ANALYSIS AND MITIGATION OF HARMONICS IN POWER DISTRIBUTION NETWORK

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Analysis and Mitigation of Harmonics in Power Distribution Network

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university

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DEDICATION

To my dear mum, my lovely wife and my two sons for their unwavering love, prayers, moral support, and encouragement during my research work. As the wise men said: One can walk fast but many can go far. May Almighty God bless you for walking with me throughout my research journey.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AIMF	Active Injection Mode Filter
ANN	Artificial Neural Network
APLC	Active Power Line Conditioner
APF	Active Power Filter
AHF	Active Harmonic Filter
ASD	Adjustable Speed Drive
BDV	Breakdown Voltage
CLP	Cold Load Pick-up
CFL	Compact Fluorescent Lighting
CoG	Center of Gravity
CPU	Central Processing Unit
CSI	Current Source Inverter
Dpf	Displacement power factor
DC	Direct Current
DI	Distortion Index
DFT	Discrete Fourier Transform

DGA	Dissolved Gas Analysis
FACTs	Flexible AC Transmissions
FFT	Fast Fourier Transform
FL	Fuzzy Logic
FMS	Ferroresonant Magnetic Synthesizer
GTO	Gate Turn-On
GOK	Government of Kenya
HHF	Hybrid Harmonic Filter
HM	Height Method
HPF	High Pass Filter
HVDC	High Voltage Direct Current
HT	High Tension
IA	Artificial Intelligence
IBJT	Insulated Bipolar Junction transistor
IEC	International Electrical Committee
IEEE	Institute of Electrical and Electronics Engineers
IEGT	Injected -Enhanced Gate Transistor
K-Factor	Rating of distribution transformer based on harmonic content

KEBS	Kenya Bureau of Standard
LF	Load Factor
LV	Low Voltage
LPF	Low Pass Filter
MF	Membership Function
MoM	Mean of Maximal
MOE	Ministry of Energy
MOSFET	Metal Oxide Semiconductor Field Transistor
ONAN	Oil Natural Air Natural
PCC	Point of Common Coupling
Pf	Power factor
PID	Proportional Integral Derivative
PHF	Passive Harmonic Filter
PLL	Phase Lock Loop
PN	Priority Number
PQA	Power Quality Analyzer
PT	Potential Transformer
PWM	Pulse Width Modulation

RMS	Root Mean Square
SAPF	Shunt Active Power Filter
SLD	Single Line Diagram
SMPS	Switch Mode Power Supply
SRF	Synchronous Reference Frame
SVC	Static Var Compensator
SVM	Space Vector Method
TDD	Total Demand Distortion
THD_i	Current Total Harmonic Distortions
THD_v	Voltage Total Harmonic Distortions
Tx	Transformer
TV	Television
VA	Voltage Ampere
Var	Voltage ampere reactive
VSI	Voltage Source Inverter

LIST OF SYMBOLS

P_{TSL}	Total stray losses
P_{EC}	Eddy current losses
P_{OSL}	Other stray losses
P_T	Total losses,
P_{LL}	Load losses
P_{NL}	No-load losses
P_{EC-O}	Winding eddy-current loss
h_{max}	Highest significant harmonic order
I_{rms}	rms current at harmonic *h* of order
I	RMS load current
N	Number of sample per fundamental period
$A(n)$	Input signal (voltage/current) at point
$\bar{A}_h$	Complex Fourier Vector of the harmonic h^{th} of the input signal
A_{hr}	Real part of A_h
A_{hi}	Imaginary part of A_h
Φ_h	Phase of the vector
i^s_d	Phase stationary reference frame currents (real)
i^s_q	Phase stationary reference frame currents (imaginary)
d^e	Synchronous rotating frame (real)
q^e	Synchronous rotating frame (imaginary)
w_e	Frequency for the harmonic order that needs to be in *rad/s*
I_h	Current of harmonic h
h	Harmonic odd orders; 3^{rd}, 5^{th} , 7^{th}
y	Fuzzy output crisp
e	Error
Δe	Rate change of error
μ	Membership function
x	Function element

A_i	Different fuzzy variables used to classify the input Ύ
C_i	Different fuzzy variables used to classify the output y
$V_{dc, max}$	Pre-set upper limit of the energy storage capacitor voltage
$V_{dc, min}$	Pre-set lower limit of the energy storage capacitor voltage
$V_{s, max}$	Maximum voltage of utility source
T	Period of the utility source
ΔI_{L1}	Change of load current (*first step*)
C_{dc}	DC side capacitor
f_h	h^{th} Harmonics, h = 2, 3, 3…
f_{ac}	Fundamental frequency of the system
D	Distortion power
T_L	Insulation aging life
T_a	Absolute temperature
e	Napierian base.

ABSTRACT

Harmonic distortions for low voltage distribution network is a research area that has not been extensively explored due to the assumption that the harmonics do not adversely affect low voltage equipment. However, field data collected shows contrarily that current harmonic generated by nonlinear residential customer loads do immensely affect distribution transformers by causing speedy deterioration of the transformers insulation. In the past few decades, there have been considerable changes on residential single phase loads in terms of power demand magnitude and appliance electrical characteristics. The main difference between the current residential single phase loads and earlier versions of a few decades ago is widespread use of electronic appliances with Switch Mode Power Supply (SMPS). These loads are rapidly increasing due to advancement of technology in semi-conductor devices and digital controllers. Such appliances generate current harmonic distortions, which stream back to the low voltage distribution network affecting installed low voltage network equipment. The adverse impact of the generated harmonic distortions are witnessed in premature failure of distribution transformers, erroneous recording of energy meters and over-loading of neutral conductors to mention just a few. This study focuses on analysis and mitigation of current harmonics distortions on distribution network. It involved measurement of current harmonics generated by domestic consumers individual appliance and combined appliances at Point of Common Coupling (PCC) and current harmonics streaming at the secondary side of distribution transformers. Transformers' oil breakdown voltage was analyzed from sampled transformers to correlate between harmonics and degradation of the oil insulation level. The failed transformers for a period of one year in one of the region was obtained and analyzed. Based on the results of the analysis that show high harmonic pollution on low voltage distribution network, a mitigation measure was devised that involved design and simulation of a single phase active filter using MATLAB–Simulink software. From this work, it was found out that loads with similar electrical characteristics aggravate harmonics and loads with dissimilar electrical characteristics attenuate harmonics. Further, the high current harmonics cause speedy degradation of transformer liquid (oil) insulation and lastly the high current harmonics observed at domestic consumers PCC emanating from current domestic appliances can be mitigated by employing a single phase shunt active filter. The designed and simulated single phase active filter, in MATLAB/Simulink environment, the distorted current waveform was noted to be sinusoidal (undistorted) after introduction of single phase shunt AHF and the current harmonic distortion levels obtained were well within the admissible level recommended by IEEE 519-1992, a power quality standard for power utilities and industries.

CHAPTER ONE

INTRODUCTION

1.1 Background

1.1.1 Aspects of power quality

Power quality has progressively been raising great concern largely due to modern microprocessor controlled load equipment and power electronic devices, which are sensitive to poor power quality supplies in the past 20-30 years Roger, S. (2002). Furthermore, end users are more conversant with power quality issues such as transients, voltage collapse and voltage swell/dips. With this knowledge together with existing standards, the power users compel power utilities to provide quality power that meets the stipulated power quality standards (IEEE Std., 1995)-(Iagar, 2014). . Among the listed power quality issues, voltage collapse (short or sustainable interruptions) and voltage sags/dips have been identified as the most common problems that cause major outcry from the power customers. Presently, the current harmonic distortion (despite of the fact that it has negative impacts on a low voltage distribution network) has not been extensively studied and investigated. This is mainly because the effects of the current harmonic distortions are not immediately observable but its adverse effects are evident such as early loss of life of distribution transformers. For instance, degradation of transformer insulation is a slow process, which is aggravated by high level of harmonic distortions subjected to the concerned equipment.

Under normal conditions, generators are expected to produce voltages that are close to sinusoidal waveform. However, due to presence of nonlinear loads that generate harmonic distortions waveform, the effective waveform is thus distorted (non-sinusoidal) as shown in Figure 1.1. Harmonic distortions usually stream back to the power network through a service cable (i.e. cable supplying power customers from power utility grid to PCC) because the cable usually has less impedance compared to the other loads connected to the power system. The harmonics therefore affect both the residential loads together with installed power network equipment.

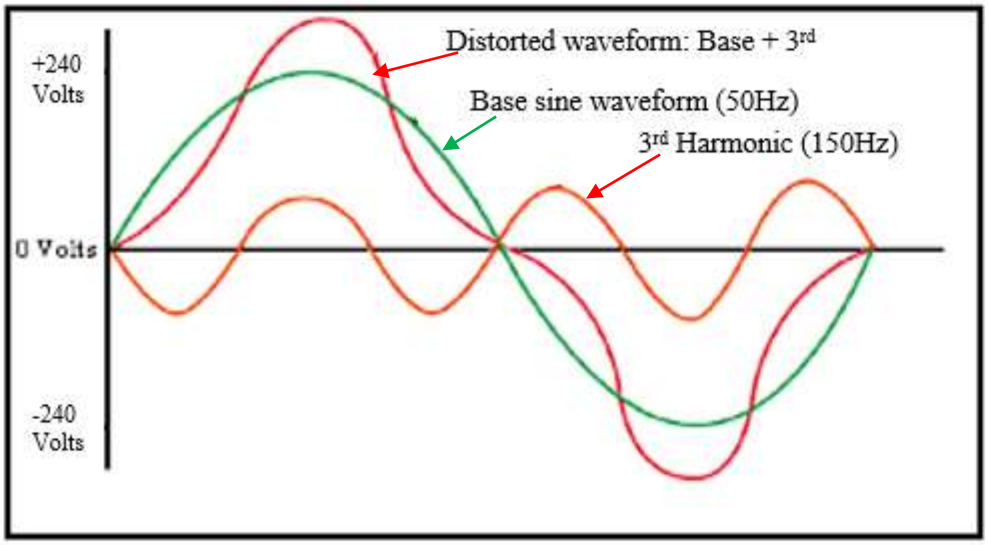


Figure 1.1: Non-sinusoidal waveform due to presence of harmonic distortions

The commonly known sources of the harmonics in a low voltage distribution network are nonlinear residential loads which include: TV sets, computer CPU and monitors, battery chargers, refrigerators, fans with electronic regulator, CFL lamps, washing machines, hot water systems, water pumps, air conditioners, driers, microwaves, UPS and transformers (due to nonlinear magnetization core) among others. In commercial and industrial loads, sources of harmonic distortions include power electronic converters, adjustable speed drives, high voltage DC-links, Static Var Compensators (SVCs) and rotating machines (Purushothama, 2012).

Harmonic distortions generated by nonlinear loads are known to cause serious detrimental effect on both loads and power network. Harmonics result to malfunction, reduced efficiency and reduced operational life span especially for sensitive loads and measuring equipment. Moreover, the presence of harmonic distortions on a low voltage network causes substantial additional thermal power loss (I^2R losses) on both distribution transformers and low voltage network conductors including over-loading of neutral conductors due to homopolar (triple-n) harmonic frequencies.

1.1.2 Distribution transformer and main causes of transformer failure

(a) Distribution transformer

A distribution transformer is a key component in the power system as it enables connection of electricity to residential and commercial loads. Distribution transformer failure is quite costly and results to reduced revenues for the power network operator. Before the advent of Switched Mode Power Supply (SMPS) based appliances, lifespan for a distribution transformer operating at normal ambient temperature and loading was more than forty years (Farooq et al., 2011). However, currently, substantial number of distribution transformers fail a few years after commissioning. This has necessitated research to investigate the root cause of the distribution transformers premature failure. For instance, in Kenya, the failure rate is approximately 10-12% per annum (equivalent to approximately 3,600 per year (2018 report)) while in India it is estimated to be 15% (Shah, 2012). These failure rates are far above the failure rate of 1-2% in most developed countries. This could be attributed to few nonlinear loads at the distribution level resulting to minimal harmonic cancellation since some of nonlinear loads possess similar electrical characteristics. Generally, loads are said to have similar electrical characteristics when the voltage and current phase displacement angle are almost equal. This also implies that they have almost equal power usage efficiency, which is depicted by the operating power factor. As a result, high harmonics are injected to the power supply network, as there is minimal damping of harmonic distortions where there are few nonlinear loads connected.

The push to increase energy access across the globe has resulted to connection of more residential customers to the grid at the low voltage network. This has led to drastic increase in number of installed distribution transformers and consequently the reported increase of transformer failure rate. Therefore, it is pertinent to investigate the root causes of the premature failure of transformers because this has contributed to a massive loss of capital investment and revenue to the power utilities. Further, it causes an outcry from public in general due to lack of a stable and reliable power supplies. Figure 1.2 depicts the number of distribution transformers failures in sampled regions, over a period of one year due to various causes.

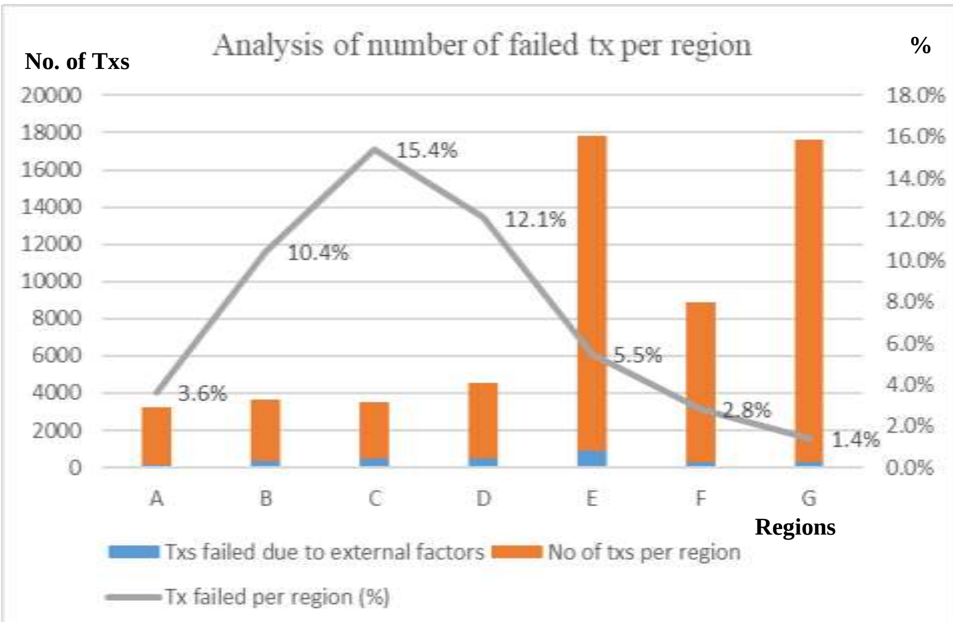


Figure 1.2: Percentage of the number of failed distribution transformers per region

From the Figure, it is seen that 3 regions (B, C and D) have the highest number of distribution transformer failure (in %) due to external factors such as phases overload and/or conductor high impedance short circuit. It can also be due to harmonics streaming from nonlinear loads. Region G is observed to have the highest installed distribution transformers as well as having the lowest transformer failure rate (in %). This region is characterized by having many commercial and industrial consumers. The GOK report on nation electrification shows that 93% in urban areas and 56% of rural areas are connected to the national grid (GOK electricity connectivity report -

(b) Main causes of failure of distribution transformers

Transformer failure can be attributed to several causes but the main causes that contribute to premature transformer failure are shown in Figure 1.3 (Venkatesh, 2008) . As depicted in Figure 1.3, it is difficult to identify the specific transformer failure cause due to many independent variables involved. For instance, a sustainable fault due to low voltage conductor short-circuits or a high impedance earth fault could have devastating degradation to transformer insulations if the low voltage (LV) fuses do not operate within a reasonable time.

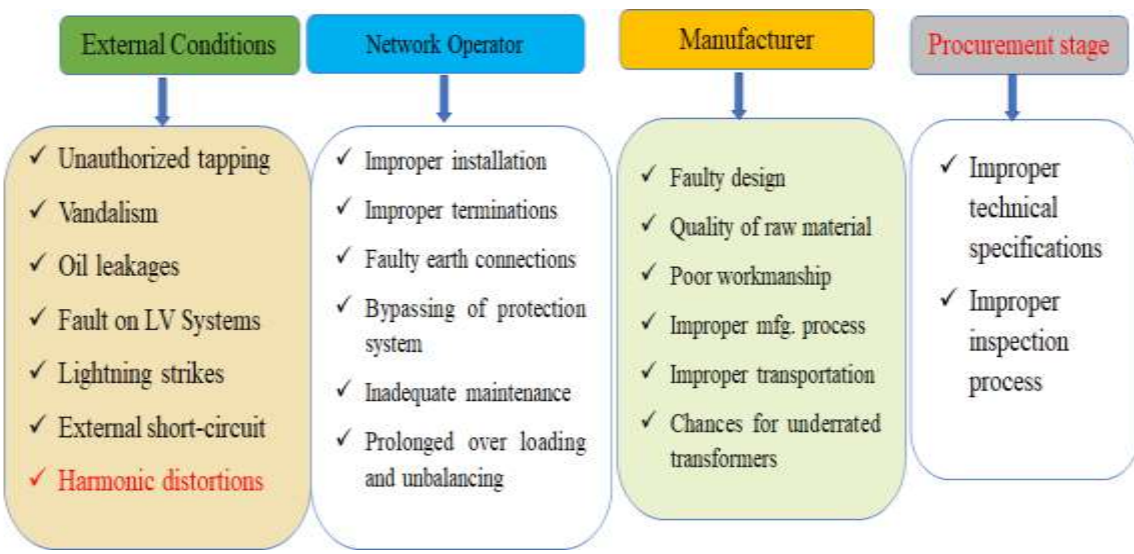


Figure 1.3: Main causes of transformer failure

Figure 1.4 shows the number of failed distribution transformers due to assorted reasons shown earlier in Figure 1.3. Region A to F present regions as per power utility management administration structure. It can be seen from Figure 1.4 that the fault on a LV network contributed to the highest number of failure of distribution transformers followed by the transformer internal defects. The internal defects are mainly associated with faulty copper windings whose cause could not be established. However, research has shown that continued heating of transformer windings due to presence of the harmonic distortions results in winding insulation breakdown thus diminishing transformer service life.

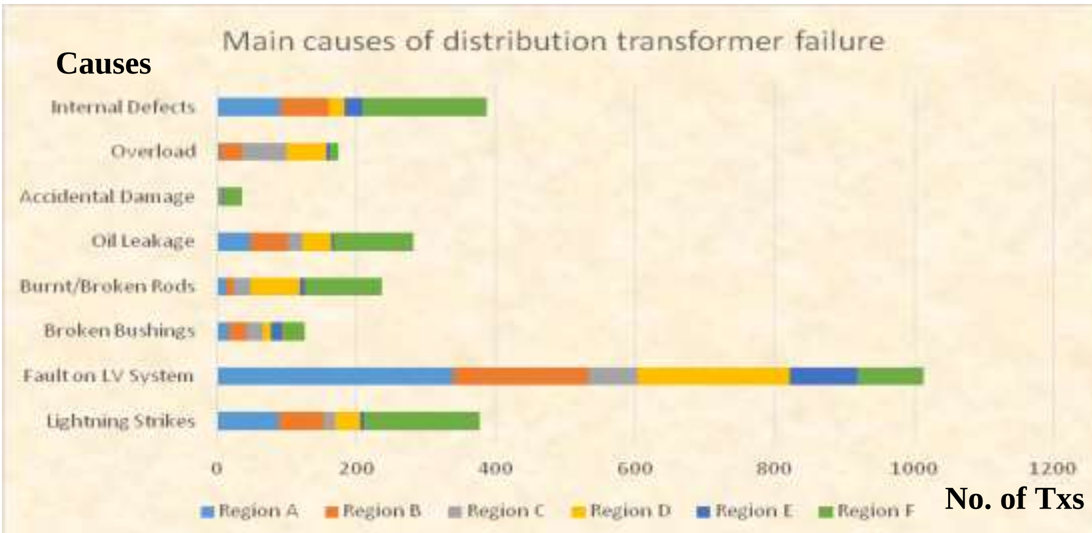


Figure 1.4: Transformer failure statistics based on specific causes (Mehta, 2011)

The study has shown that a transformer overloaded 100% continuously with power supplies containing over 25% THDi, the life span decreases from approximately 40 years to 40 days (Mehta, 2011) . Similarly, research also shows that the loading capacity of a transformer needs to be derated approximately by 35% when supplying compact fluorescence lights (CFLs) than one supplying incandescent bulbs Gunda, Sudheer, & Sarma, 2012). .

It has been globally noted that due to relative low cost of distribution transformers (as compared with power transformers), very little deliberate efforts are made by utility companies to investigate the root cause of distribution transformer failure. Lack of such investigation, as noted by the author (Khatavkar, 2009), could be one of the reasons why more failures happen immediately or within a short time span after replacing a faulty transformer.

It is pertinent to point out that approximately more than 60% of all connected loads in one of the power utility belong to the category of domestic power consumers (Venkatesh, 2008). Domestic loads, unlike commercial and industrial loads, are often connected to the power source for few hours within a day (i.e. have load factor of 20-25%) and have almost definite statistical duty cycles (Mehta, 2011)-(Mehta, 2011). Load factor (LF), which is a ratio of average demand over designated period of time and peak load occurring in that period, shows the % of duration of the loads on power supplies for specified period of time (e.g. a month). It is thus important to note the following regarding harmonics generated by nonlinear loads:

i. Nonlinear loads with similar electrical characteristics exacerbate the current harmonic distortions (loads with almost or have equal voltage and current angle displacement (almost or equal power factor)).
ii. The Wattage (heat) dissipated due to harmonic distortions increases at square of frequency

With the increased use of domestic appliances with switch mode power supplies, that inherent generate harmonics such as CFL and LED bulbs, microwave among others, it is expected that harmonics levels in distribution system will increase and hence the study of the effect of harmonics on distribution network become the objective of this study. The results obtained clearly shown that distribution transformers oil insulation is adversely affected by high current harmonic pollution.

1.2 Problem Statement

With increase in the use of nonlinear loads in domestic consumers such as compact fluorescent lights (CFLs) and light emitting diodes (LEDs) bulbs, whose penetration level continue to rise, the generated harmonics are expected to negatively affect the installed distribution equipment such as distribution transformers, neutral conductor and electronic switching devices (circuit breakers). There has been an assumption that nonlinear residential loads have insignificant adverse impact on the power system compared to commercial or industrial loads, which are characterized by high power ratings and high load factor. However, distortions caused by low rated nonlinear residential loads cannot be ignored, as the current harmonic distortions are well known to degrade electrical equipment's insulation, elevating heat within the equipment, which results in premature equipment failure.

A review conducted revealed that there is inadequate data collected on harmonic distortions emanating from residential appliances. Therefore, it was imperative to carry out harmonic distortions measurement on modern nonlinear loads and assess their impacts on distribution transformer liquid (oil) insulation and corresponding transformer failure rate. Thus, lack of enough data on harmonic distortions on low voltage distribution network gave the basis of this research. Due to current high rate of premature failure of distribution transformers, which is suspected to be caused by harmonic distortions, this study has devised a mitigation measure of reducing the current emanating from modern residential nonlinear loads streaming to low voltage network. The thesis proposed installation of a single phase shunt AHF at domestic consumers point of common coupling.

1.3 Justification

Power consumer loads have evolved technologically compared to those that existed 15-20 years ago. As the result, they have adversely affected installed distribution equipment on low voltage network. Measurement data at the low voltage distribution network is very important since it aids in determining the level of harmonic distortion emanating from residential loads. The data also provides insights on the effects of harmonic distortions which are known to degrade liquid (oil) insulation.

Owing to the above, it is important to collect and analysis data and establish the effect of harmonic pollution on distribution system and devise a mitigation measure of reducing the harmonics in distribution network to be within the admissible levels specified in the power quality standards.

1.4 Objectives

1.4.1 Main objective

To investigate the effects of harmonic distortions due to domestic appliances and develop a mitigation measure to improve quality of power supplies for domestic consumers

1.4.2 Specific objectives

The specific objectives of this study were as follows:

i. To investigate the level of harmonic distributions due to single phase nonlinear loads at point of common coupling of domestic consumers.
ii. To investigate the effects of harmonic distortions on distribution transformer liquid (oil) insulation and failure rate.
iii. To design and simulate a single phase active harmonic filter using SRF method and fuzzy logic controller for the harmonics mitigation on low voltage network.
iv. To validate the designed model in MATLAB-Simulink environment and evaluate the performance of simulated single phase active harmonic filter.

1.5 Research Scope

Power systems are categorized by voltage levels globally into: high voltage (132 KV) and above), medium voltage (above 11 KV and (<132 KV) and distribution voltage (< 415 V) power system. The scope of this work was to investigate and analyze harmonic distortions generated by modern nonlinear appliances commonly found in domestic consumers. Further, the study also entailed the investigation and analysis of the impacts of harmonic distortions on the liquid (oil) of distribution transformers and the subsequent distribution transformer failure rate. To mitigate harmonic distortions emanating from single phase nonlinear loads, a single-phase shunt active current harmonic filter was designed and simulated in a MATLAB-Simulink environment for domestic power end users. The designed AHF is proposed to be installed at the PCC of domestic power end user between single phase supply (service cable) and the non-linear loads. The work did not cover practical implementation of designed single phase filter because it was beyond the scope of the study. However, the author recommends development of a practical approach to implement a single phase shunt AHF for domestic consumers as the rating of the parameters used in the design of the active harmonic filter correlate with appliances ratings mainly found at domestic power end users.

1.6 Contributions

From this study, the following are the contributions to the body of knowledge;

It has for a long time been assumed that the effect of harmonics generated by domestic nonlinear loads on the power distribution system is negligible, that is, can be ignored. However, with more and more proliferation of nonlinear domestic loads by the consumers, this assumption may no longer be correct. Furthermore, in recent times there has been a notable increase in the failure rate of the distribution transformers, especially those supplying domestic consumers. This work, therefore sought to establish the effect or the relation of the increase of harmonics streaming from domestic loads and the notable high failure rate of the distribution transformers. By practically measuring the harmonics on the live low voltage distribution network and analysis of the measured harmonics data, this work has established a strong relation between the increased harmonic distortions and the notable increase of distribution transformers failure rate and devised a mitigation measure.

1.7 Outline

This thesis contains five chapters, namely: Chapter 1 that highlights introduction, background of the study, problem statement, justification, objectives and the scope of the research study. Also contained are the contributions to the body of knowledge from this work. Chapter 2 contains literature review and the research gaps. Chapter 3 is research methodology giving methodologies employed to investigate harmonic distortions at various points of low voltage network. It also provides equipment used to carry out the harmonics data measurements. Lastly, this chapter contains detailed design of proposed single phase shunt active harmonic filter and methodology of validation of the designed model and performance evaluation of the simulated single phase shunt active harmonic filter. Criterion for selection of adopted method for the main components of active harmonic filter are presented and discussed. Chapter 4 contains results and discussion of the field measurement at various points of distribution network. It also contained results and discussion of MATLAB-Simulink simulation of nonlinear and linear loads. Lastly, the chapter present validation of the designed model and performance evaluation of simulated single phase shunt AHF. Chapter 5 is the last chapter of this thesis that contain conclusions drawn from the study and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter has explored in-depth on issues related to power quality, harmonic distortions and various mitigation methods of harmonic distortions both on three-phase and single-phase power system. Previous research studies done in relation to improvement of the quality of power supplies to power end users has been explicitly explored. Also presented in this chapter is a summary of research gaps identified from previous research studies. Lastly, the design of active harmonic filter fundamental components are presented.

2.2 Background Information on Harmonics

The study of harmonic pollution in the power system is likely to have commenced in 1916 when Steinmetz studied harmonics in three-phase power system (Khatavkar, 2009). Steinmetz proposed use of delta windings to block the 3rd harmonic current from streaming back to power source. The problems of harmonics were temporarily solved until the years 1939-40s when rural electrification and telephone were invented. As a result, harmonic frequencies in power line were inductively coupled into adjacent open wire telephone circuits causing audible telephone interference. This problem was solved by employing twisted pair cables, burying cables and advent of fiber optics. However, with the introduction of electronic devices, which draw non-sinusoidal currents in form of pulses, the power system of 80s and 90s was introduced to non-sinusoidal currents, which reacted with system impedance causing voltage distortions and severe parallel resonance. The main sources of harmonic currents before the advent of electronic devices were from mercury arc rectifiers used for AC to DC current rectification for railway electrification. Nowadays, the number and type of the loads that generate the harmonics has risen sharply and will continue to upsurge (Dugan, McGranaghan, &

Beaty, 1996). This provides the reason why many research studies are ongoing to address the current harmonics emanating from both industrial and domestic modern nonlinear loads.

There are four main phenomena of harmonics which when present in any distribution network require mitigation action as stated in (Chan, Lee, & Fung, 2007). :

i. Source of harmonics is high when the connected nonlinear loads are large loads or many nonlinear loads with similar electrical characteristics.
ii. The path in which the harmonic currents flow is too long resulting in high voltage distortion and telephone interference.
iii. The system response impedance magnifies one or more of frequencies to a greater degree and hence causing parallel or series resonance.
iv. When high rate of premature failure of system equipment such as distribution transformers are suspected to be due to the high current harmonics distortions in the network.

In this regards, due to upsurge of the number of distribution transformers prematurely failing as noted in recent time, it is worth to carry out extensive investigation to establish the effects of harmonic distortions on distribution transformers and devise an appropriate mitigation measure.

2.3 Power Quality in Power System and Power Quality Standards

2.3.1 Power quality in power system

A report showing connected loads in one of power utility revealed that domestic power end users constitute over 67% of the supplied loads (Mehta, 2011). In its annual performance growth, the domestic consumers supersede commercial and industrial power end users as depicted in Figure 2.1. From the Figure, it is clear that domestic consumers have a profound upward trajectory compared to other consumer categories. This therefore implies that there is need to investigate the emerging impacts caused by harmonic pollution emanating from modern appliances on the distribution system, especially on the power quality of supplies to the end power users.

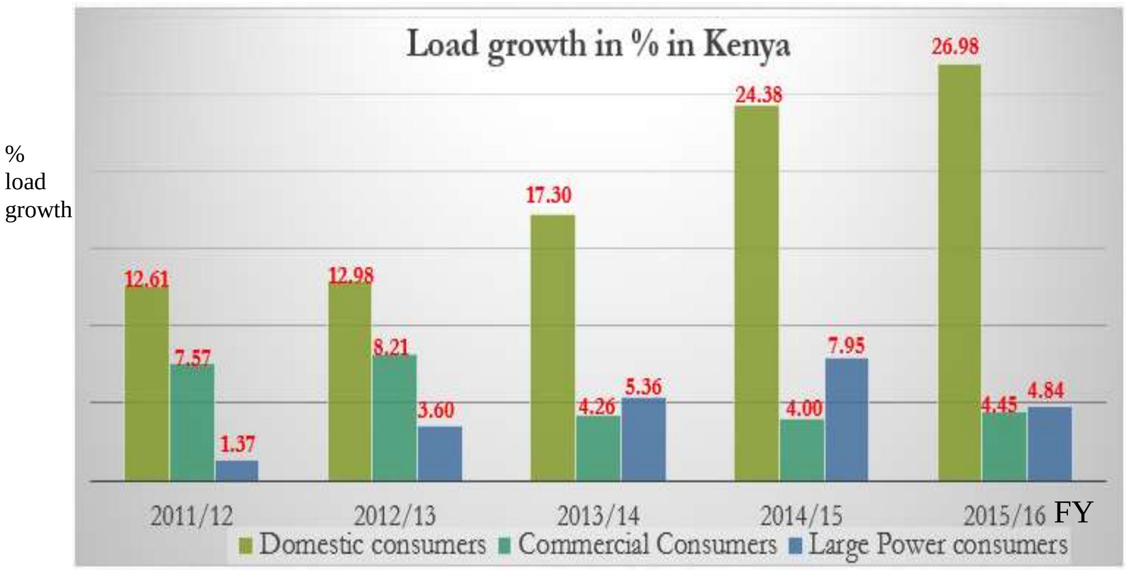


Figure 2.1: Power consumers categories growth in Kenya (Courtesy of KPLC 2016 annual report)

Power quality is a measure of the degree to which the power parameters i.e. voltage, current or frequency conform to established specifications or standards (Godbole, 2014). Good power quality, therefore, is one that maintains equipment in normal operation without malfunctioning due to external influences. These external influences can be voltage sag, swell, flickers, voltage interruptions (short, momentary or sustainable), transients (impulse or oscillatory transients), harmonic distortions (current or voltage), frequency deviations and phase deviations. The IEEE 519 power quality standard defines the term ‘power quality’ as a wide variety of electromagnetic phenomena that characterizes the voltage and current at a given time and at a specific location on the power system (Dolara, & Leva, 2012). In this study, power quality is considered to be any attributes and features that meet power customer needs, lack deficiencies that bring dissatisfaction and have desired specifications as defined by the power quality reference standards.

Voltage quality is interpreted as a quality of the power delivered by the utility (from generators) to the customer, while current quality implies deviations of the current waveform from a sinusoidal wave due to customer loads (especially nonlinear loads). The voltage quality, however, has to do with what the utility delivers to consumers and current quality is concerned with how the consumer interfere with power supplied by utility (Said, Ahmad, & Zin, 2003). The degree to which electrical power supply deviates from set levels (that is from sinusoidal waveform) indicates the quality of voltage supplied by the power utility. The ultimate measure of good power quality is determined by the performance and productivity of the powered equipment.

Stable voltage profile and undistorted (sinusoidal) waveforms are two characteristics, which are very desirable in the power system for proper operations of connected load. Poor power quality of power supplies by power utility impact negatively on power end users in operations of equipment and sustainability of production process. For this reason, power utility is required to meet certain customer expectations and maintain customer confidence by supplying a quality power to avert the ill effects of poor quality power such as malfunctioning of machines and downtime of operation processes due to lack of sufficient voltage at point of common coupling (PCC). It has been noted that residential customers suffer majorly from poor power quality due to increased use of electronic equipment such as personal computer at home. This has compelled the power utilities to provide quality power, as computers are sensitive to flickers and any other system disturbances such as voltage swell or absence of the voltage (Ndung'u, Nderu, & Ngoo, 2011). The premise of IEEE 519 standard is that there exists a shared responsibility between utilities and customers regarding the harmonic control. The standard states that maintaining reasonable levels of voltage harmonic distortion depend upon customers limiting their harmonic current emissions and power utility controlling the system impedance characteristic which may include adding shunt capacitors and/or line inductors for improving voltage profile and power stability (Ndung'u, Nderu, & Ngoo, 2014).

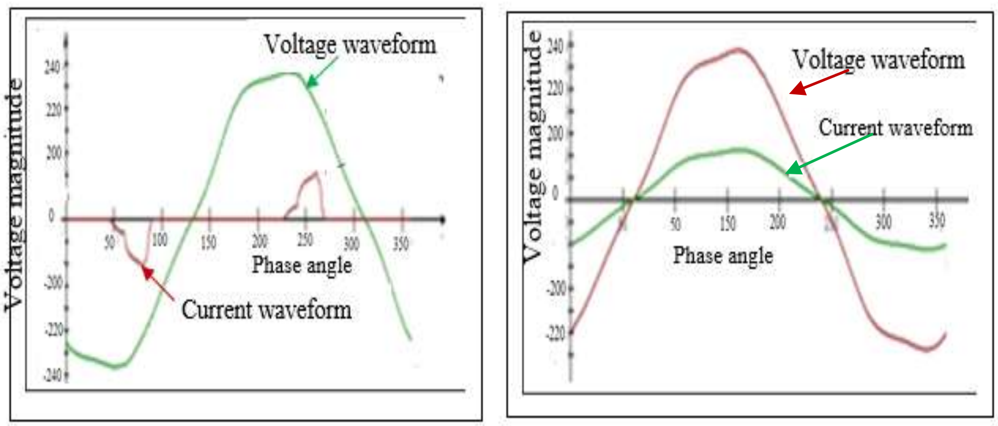
2.3.2 Power Quality Standards

There are numerous international standards that define the permissible limits of power quality in power system. However, this study compares harmonic distortions obtained at various points of power distribution system with two international standards namely: IEC 61000-3-2 often used by manufacturers of electrical devices and IEEE 519-1992, adopted by power utilities and industries. The required acceptable limits are provided in Appendix 2.

2.4 Characteristic of Modern Nonlinear Loads

The increase of current waveform distortions in the power system has solely been contributed by the power consumers recent changing from inefficient large rated linear loads to advent of more efficient smaller rated nonlinear loads such as plasma TV that retrofitted CRT-TV among others. The electronic front ends of these nonlinear loads make them more efficient than linear loads. It is pertinent to note that any switch mode power supply (SMPS) equipment installed anywhere in the system have an inherent property to generate continuous current distortions on the power source that imposes an extra loading on power utility network and installed infrastructures such as transformers and conductors. As stated in (Ranade, 2010) that even though the harmonic contribution of any domestic non –linear loads is negligible on its own, with hundreds of nonlinear loads connected on the same supply, their harmonic contributions present particular problems depending on the short-circuit capacity, impedance and layout of the power system. Such problems include overloading and overheating of installed distribution equipment and system resonance among others.

Most of modern electronic devices found in residential homes are nonlinear loads and contain SMPS that do not conduct current on full cycle of the applied voltage in AC circuits as depicted in Figure 2.2(a).



(a) (b)

Figure 2.2: Typical waveform for (a) a nonlinear load, (b) a linear load

Figure 2.2 shows waveforms displayed by a power measurement equipment for a nonlinear and linear single phase load. It is observed that the nonlinear load draws a non-sinusoidal current waveform (contains both fundamental and harmonics frequencies) despite the supply voltage being close to sinusoidal waveform (contains only fundamental signal). This characteristic of nonlinear load is what is desired to increase energy usage efficiency and hence, reducing electricity bill to the power end users. Moreover, it also enables the power utility to use least cost generators, which are cheaper to run such as geothermal and hydro generators. Furthermore, power utilities spend less in investment of power equipment and infrastructures where there are more nonlinear loads. The drawback of a linear load is that it draws full cycle current as shown in Figure 2.2(b) hence consuming more energy. (. $E = \int vi\, dt$). It is for this reason that engineers are tirelessly designing electrical devices that do not draw current continuously to save energy. The research carried out by (Bayliss, Bayliss, & Hardy, 2012) revealed that the use of efficient nonlinear loads with SMPS saved energy equivalent to 240 GWh per year in California. The author of (Jan, Afzal, & Khan, 2015) on the other hand, stated that SMPS have made harmonic distortions a common occurrence in electrical power system. References (Jan, Afzal, & Khan, 2015) -(Ndungu et al., 2017) gave the main reasons for investigating power quality supplied by power utility, which include:

(i) Increase of concern on the power quality by consumers of power supplied by power utility. Power consumers are becoming more aware of power quality issues such as voltage sag, swell, power interruptions, transients and frequency deviations, which can lead to costly litigations.
(ii) Use of microprocessor- based controls, which are sensitive to power quality variations.
(iii) Use of more efficient and low power consuming devices such as compact fluorescence light (CFL) bulbs, SMPS or Adjustable Speed Drives (ASD) but which cause increase of harmonics levels that impact negatively on the power quality.

The ability to investigate power quality enables the power utility to identify where the power supply to end power users falls below the acceptable threshold levels as stipulated by relevant power quality standards.

2.5 Harmonic Definition and Its Inherent Characteristics

2.5.1 Harmonic definition

Harmonic refers to a complex sinusoidal waveform that is a multiple of fundamental frequency of the system ($50\ \text{Hz}$ or $60\ \text{Hz}$). It can be expressed as in equation (2.1):

$$f_h = hf_{ac} \tag{2.1}$$

Where; f_h is the h^{th} harmonics and f_{ac} is the fundamental frequency of system, h =2, 3, 5

Harmonics are therefore made up of series of sinusoidal waves whose frequencies are integral multiples of frequency of the fundamental wave. The complex waveform, which is also referred to electrical noise or electrical pollution, can also contain non-integer harmonic frequencies commonly known as inter-harmonic frequencies. Total Harmonic Distortion (THD) is the most commonly used measure of the effective value of harmonic distortion. This factor is used to quantify the levels of the current flowing in the distribution system or the voltage level at the PCC. The total harmonic distortion for the voltage and current as percentage is defined in reference (Rajurkar, Nandapurkar, & Kulkarni, 2010). The reference also define the Total Demand Distortion (TDD) and how it is used to address the drawbacks of THD when used in harmonic distortions analysis.

2.5.2 Characteristics of harmonic distortions

Harmonic distortions have numerous inherent characteristics as provided in (Bayliss, Bayliss, & Hardy, 2012) and (Jan, Afzal, & Khan, 2015) . The key harmonic distortions characteristics include:

i. Harmonics follow an inverse law in the sense that the higher the harmonic order level, the lower is the amplitude hence, higher harmonic levels are usually assumed.
ii. Odd harmonics give half-wave symmetric distortion, while even harmonic and DC- component give half-wave unsymmetrical distortion. Rotating machines produce similar positive and negative half-cycles while nonlinear circuit element produces non-symmetrical current waves. This implies that rotating machines contains only odd harmonics unlike the nonlinear loads, which generate both even and odd harmonics.
iii. Inter-harmonics give unsymmetrical distortion between periods and all neutral current is because of triple-n harmonics (zero sequence harmonics).
iv. Single-phase electronic loads generate harmonics of all odd multiples of the fundamental frequency, but the dominants are triple-n (Homopolar) harmonics.

v. If an alternating voltage containing harmonics is applied to a single-phase circuit with linear (passive) elements (i.e. resistor, inductor or capacitor), the resulting current also contains harmonics.

2.5.3 Phase sequences of harmonic frequencies

Harmonics phase sequences and their effects on power system are as explicitly documented in (Rajurkar, Nandapurkar, & Kulkarni, 2010).

2.6 Sources of harmonic distortion

Globally, the dominating source of current distortions are nonlinear loads connected to the power system. However, at some location HVDC–link converters, static voltage converters (SVCs), arc furnaces and wind turbines contribute significant current distortions (Kazem, 2013). The main sources of harmonic distortions are nonlinear loads (devices with SMPS), variable speed drives (VSDs), arc welding machines, power system itself (HVDC, SVC, saturated transformer, STATCOMs and polluted insulators), and lighting with electronic switching devices such as compacted fluorescent lamp (CFL) bulbs and the power storage devices such as uninterruptible power supplies (UPS).

For nonlinear single-phase loads, they can be grouped into two types (Singh, Zadgaonker, & Singh, 2014):

i. Devices with AC/AC conversion for example light dimmers where the control circuit varies the RMS of voltage applied, and
ii. Device with AC/DC conversion. These types of devices have diodes, thyristor or transistors that facilitate AC rectification.

The diode bridge rectifier produces high harmonic distortions compared to transistor rectifier. However, transistor rectifier contains high frequency ripples. Different single-phase household loads such hair dryers, radios, TVs, computer, laptop among others, may have rectifier diodes or transistors as per designer discretion. For three-phase nonlinear loads, the rectifier can be either controlled or non–controlled. The non-controlled rectifier employs either diodes or thyristors. Figure 2.3 shows an example of a three-phase controlled rectifier. For three-phase 6-pulse rectifier, the current spectrum is dominated by odd harmonics (6±1) with decaying amplitude for higher orders. The study done by (Shepherd, Morton, & Spence, 2009). using CFL and LED bulbs found out that current harmonics are generated by power electronic converters and installed ballasts. The THD_i generated depends on the power supplied circuit topology and control strategy.

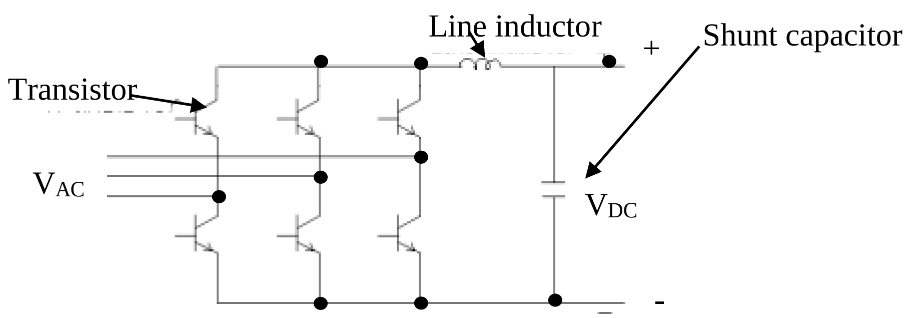


Figure 2.3: Three-phase, 6-pulse rectifier with inductive and capacitive DC-link

In addition, it was noted that the level of harmonics generated by CFL and LED bulbs are independent of the bulb technology and size. Research carried out by [35] also on energy saving bulbs shows that, lighting diversity diminishes the harmonics generated by CFL bulbs at PCC and the authors recommended hybrid of different types of lighting system in domestic houses.

2.7 Effects of Harmonic Distortions on Power Distribution System

Harmonic distortions have numerous adverse impact on power system network when their limits are beyond the admissible threshold levels specified in power quality standards. In addition to what is listed on profound effects of harmonic distortions in

(Rajurkar, Nandapurkar, & Kulkarni, 2010), reference (Uzair, Mohiuddin, & Shujauddin, 2013) added the following:

i. Harmonics produces extra eddy current losses, which cause overheating of electrical equipment such as transformers and induction motors.
ii. Accelerate aging of insulation materials including transformer oils.

With proliferation of the electronic devices in the market, the quality of life has drastically improved alongside increased power consumption efficiency. However, this has caused greater disturbances to the electrical system. Author of (Rajurkar, Nandapurkar, & Kulkarni, 2010) has shown in details the impacts of proliferation of electronic devices in the power system in two-folds: technical and economic costs.

The voltage and current harmonics are influenced by components of the power system. For instance, the voltage harmonics is reduced substantially when a capacitor is in shunt with source voltage as shown equation (2.2).

$$v = \frac{1}{C}\int i \; dt \qquad (2.2)$$

From relationship (2.2), it shows that capacitor reduces voltage distortions. On the other hand, a line inductor can attenuate the current harmonics (when inductive reactance, $X_L > X_C$). This can clearly be shown by the expression given in equation (2.3).

$$i = \int \frac{v}{L} \; dt \qquad (2.3)$$

From relationship given in equation (2.3), current harmonic frequencies are significantly reduced when an inductor is in series with harmonic source generator (Ghadai, & Das, 2014).

When, $X_L = X_C$ this condition results to a circuit resonance that is responsible for amplifying the harmonic distortions. This condition results to a minimum line impedance, which provides less hindrances to the flow of current harmonic distortions.

It is imperative noting that displacement power factor (computed as shown in (2.4) has no influence on level of harmonic distortions.

$$Pf = \frac{P}{S} \tag{2.4}$$

Where P ʃ is the power factor, is the real power and S is the apparent power.

However, presence of harmonic distortions reduces power factor as is shown in equation (2.5).

$$S = \sqrt{P^2 + Q^2 + D^2} \tag{2.5}$$

Where; *Q* is the reactive power and *D* is the distortion power (caused by harmonic distortions).

2.8 Effects of Harmonic Distortions on Distribution Transformers

A distribution transformer is one of the major electrical equipment in electricity distribution network that links the power utility and power consumers. It enables the power utility to supply electricity to consumers by stepping down high voltage to a low voltage that is appropriate for use in domestic, commercial and industrial connected loads (Singh, Zadgaonker, & Singh, 2014)-(Ghadai, & Das, 2014). In Kenya for instant, the phase voltage is 240 V.

In recent time, there has been an upsurge of distribution transformers premature failure before serving the desired and designed service life of approximately 40 years and above. Consequently, power utility incurs huge losses of revenue during outage period and replacing or repairing the faulty transformers. It is critical to note that, failure of transformer inconveniencies the power end users. This is mainly because the power supply is interrupted for prolonged period before the faulty transformer is replaced or repaired. Although there are more distribution transformers as compared to power transformers, the fault diagnosis of distribution transformers has not been given the required attention. This is due to the fact that they are not as expensive as power transformers. Research carried out by (Sinha, 2015) shows that transformers fail due to insulation breakdown which could be due to electrical, mechanical and/or thermal factors. Electrically induced factors include operation of transformer under transients or sustainable over voltage condition, exposure to lightning and switching surges, or partial discharge (corona). On the other hand, the mechanically induced factors are such as looping of the inner most windings, conductor tipping, conductor telescoping and failure of coil clamping system. Lastly, thermal induced factors include degradation of cellulose insulation of oil and insulation material of the windings. The thermal induced factors are largely due to overload beyond transformer design capacity. This could be as a result of cold load pickup (loads transformer supplies after restoration of power following a prolonged power outage), failure of transformer cooling system, poor low voltage fuse grading, high impedance faults, operating transformer in an over excited condition (under frequency) and operating under excessive ambient temperature conditions which could be due to harmonic pollution (Bartley, 2011). In a transformer, insulating papers and the transformer insulation oil are mainly vulnerable to deterioration as they are both at vicinity and in contact with copper windings that radiate excessive heat due to load current and harmonics streaming from nonlinear loads.

Research studies have shown that temperature rise causes the insulation life to decrease, while moisture acts as a catalyst. The transformer temperature rise is caused by the current drawn by the loads and harmonics generated by nonlinear loads connected to the transformer. It is observed that, harmonics elevate winding eddy current losses and stray losses which cause 50% of thermal stress of transformer resulting in breakdown of dielectric insulation materials: transformer mineral oil and insulating paper (solid insulation) (Singh, Zadgaonker, & Amarjit, 2014.

Mineral oil plays an important role of insulating and cooling of transformers. However, oil degrade mostly because of the ageing process, high temperature and chemical reaction such as oxidation. When a transformer is in service, transformer oil is subjected to different types of stresses namely thermal, mechanical, environmental and electrical stresses. Each of the stress factors contribute differently to the ageing of the insulation materials (oil and solid). When oil degrades, its ability to provide dielectric insulation diminishes and thus reduces the life expectancy of the transformer. The degradation also reduces electrical properties and cooling efficiency of the oil, while at the same time generates oxidation products such as acids and sludge, which are detrimental to the solid insulation.

From literature, transformer losses consist of no-load (core losses) and load losses as indicated in equation (2.6) (Kumar, Singh, & Husain, 2013) .

$$P_T = P_{LL} + P_{NL} \tag{2.6}$$

Where; P_T is total losses, P_{LL} is the load losses and P_{NL} is the no-load losses.

Load losses consist of P_{dc} losses (I^2R_{dc}) and stray losses, which are as a result of electromagnetic fields within windings, core clamps and tank walls. Stray losses are composition of winding eddy current losses (caused by eddy current and circulating current) and structural part. No load loss is insignificant on distribution transformer hence can be assumed. The load losses, therefore, can be expressed as in equations (2.7) and (2.8):

$$P_{LL} = P_{dc} + P_{TSL} \tag{2.7}$$

$$P_{TSL} = P_{EC} + P_{OSL} \tag{2.8}$$

Where; P_{TSL} is the total stray losses, P_{EC} is the eddy current losses and P_{OSL} is the other stray losses.

Eddy current losses include skin and proximity effects. Losses due to skin effect are directly proportional to square of both the eddy current and frequency $(I^2 \times f^2)$ as per equation (2.9):

$$P_{EC-0} = \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 h^2 \tag{2.9}$$

Where; P_{EC-o} is the winding eddy-current loss at the measured current and power frequency, h_{max} is the highest significant harmonic order, I_h is RMS current at harmonic of order h and I is the RMS load current.

An internally induced voltage that causes eddy current to flow in the ferromagnetic materials such as core, clamps and structural parts causes other stray losses in transformers. The eddy current losses increase at a rate proportional to I^2 and not proportional to. f^2. The harmonic loss factor for stray losses that relate to transformer connections and structural parts is expressed as in equation (2.10):

$$P_{OSL-R} = \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 h^{0.8} \qquad (2.10)$$

Proximity effect is as a result of current carrying conductor inducing current in a neighbouring conductor. In distribution transformer, high tension (HT) windings produce a flux density that cuts the LV windings inducing an emf that produces circulating or eddy current.

Because of complexity, to calculate the eddy current losses directly for a dry -type transformer, eddy current losses are normally estimated using equation (2.11):

$$P_{EC} = \eta P_{TSL} \qquad (2.11)$$

Where; $\eta = 0.67$.

The life of the transformer normally depends on the life of the insulation. The transformer insulation deteriorates as function of time and transformer oil temperature. Insulation aging is a thermo-chemical process in which aging progression is a highly nonlinear function of the absolute temperature which is governed by law of Arrhenius depicted in equation (2.12) (Zynal, & Ala'a, 2012):

$$T_L = e^{(A+B/T_a)} \qquad (2.12)$$

Where; A and β are constants derived by experiment for a given insulating material), T_L is the insulation aging life and T_a is the absolute temperature.

Transformer temperature is related to loading. However, the long thermal time constant of a transformer makes the relationship between load and transformer highly dynamic.

Thermal aging of transformer insulating materials depends on the chemical reactions: pyrolysis, oxidation and hydrolysis that occur within transformer. They are accelerated by increased temperature that lead to aging and decomposition of both liquid and solid insulation materials (oil and cellulose) which liberate gases within the transformer. The distribution of these gases reveal the type of fault caused the thermal stresses (corona, partial discharge, thermal heating or arcing). The references Lucian & Steffan, stated that degradation of transformer insulation depends also on oxidization process of liquid or solid insulation, cooling system of transformer and short circuit level on the connected loads. In the research study (Sneha, & Sreehari, 2015), the principal mechanism of oil aging is oxidation, which results in acids and other polar components. The oxidation products have profound effect on transformer oil. When oil is oxidized, it loses its stability and hence decomposes. In addition, its acidity level increases.

From (Sneha, & Sreehari, 2015), the following are worth noting;

i. Carboxylic acids dissolve in the oil or accumulate into a head space of transformer casing.
ii. Dissolved acid causes damage to the paper and copper windings, while volatile acids corrode the top part of the transformer container.
iii. Water, hydrogen, carbon monoxide and carbon dioxide are generated at different oil temperatures.

Hence, to deter fast aging of the transformer oil, it is imperative to maintain a low temperature within the transformer. Some of the methods employed to maintain low ambient temperature on distribution transformers are cooling fins and reduction of current harmonic distortions emanating from nonlinear loads streaming to transformer windings (Sneha, & Sreehari, 2015)

2.9 Harmonic Distortions Mitigation Methods

Previous research studies have shown that there are various measures, which may increase the expected life of distribution transformers. These measures include adequate and good design, enhanced transformer maintenance to ensure oil level of the transformer is sufficient, clearing trees, which are the main source of high impedance faults, proper fuse grading and removal of condensed water in the transformer as well as use of correct load diversity factor to avoid the overloading of the transformer (Kesler, & Ozdemir, 2010; Monfared et al., 2013; Mazumdar, Harley, & Venayagamoorthy, 2006). In addition, especially in rural setups, two phasing is avoided as it causes unbalance phase current that rises potential of neutral wire with respect to the earth. This is undesirable, as it comprises the safety issues and overloading of the neutral wire. It has been noted that the failure of many distribution transformers can be linked to high harmonic distortions circulating within transformer windings. Several methods have been proposed to mitigate or alleviate the ill effects of harmonics in distribution transformers as well as maintaining harmonic distortions in the power system within admissible levels as stipulated in the power quality standards. The following are the common methods researchers have proposed for mitigation of the effects of harmonic distortions in distribution transformers. The drawbacks for each proposed mitigation method are highlighted and how this work intends to address/improve on the proposed mitigation method.

2.9.1 Passive Harmonic Filter (PHF)

Research has shown that mitigating the harmonics at the source significantly reduces the profound impact of the harmonics in the low voltage network. The PHF is one of the conventional methods employed to eliminate or reduce the harmonics at the source, as stated in (Msigwa, Kundy, & Mwinyiwiwa, 2009). The PHF is one of the oldest (traditional) method used to mitigate the harmonics at the source generated by nonlinear loads. The PHF employs passive electrical elements: capacitors, inductors and resistors. They are usually connected in series or in shunt. The series configuration offers high impedance to voltage harmonics hence preventing/blocking them from reaching the connected loads, while shunt configuration diverts the flow of harmonic currents emanating from nonlinear loads by means of offering low-impedance path parallel to the ground. The PHF has a drawback of causing resonant conditions in the network circuit they are installed in. This is influenced by dynamics of the source impedance and the frequency variations of the power distribution system that affect their filtering characteristics. A tuned filter, for instance, requires extensive system analysis to prevent resonance problem. Furthermore, PHF are less costly and easier to install notwithstanding are bulky and they need large installation space.

Another common type of passive filter is a series line reactor, which is an economical means of increasing the source impedance. Using the series line reactor, research has shown that the current harmonic distortions can be reduced by up to 60% (Kumar, & Gopalakrishnan, 2013) . One main drawback of series line reactor is that it has to carry the full load current drawn by the connected loads, hence maximum load must be known in advance to enable proper sizing of the inductor. This poses a challenge of determining the maximum loads at conception of system for correct sizing of the line reactor. Further, series reactor may need to be replaced when the loads increases beyond the rating of the inductor as the system is always dynamic. Other types of PHF include tuned harmonic filter, parallel-connected resonant filter, series-connected resonant filter, and neutral current filter-used to block triple-n frequencies. The main challenge of passive filters is that they are designed for specific harmonic orders and hence may cause resonance problems in the power system (Kasimvadi & Rao, 2012). The technique to overcome some of the challenges caused by passive filter is use of a hybrid harmonic filter that consists of both passive filter and active harmonic filter. However, hybrid harmonic filters are expensive hence not commonly used. The AHF proposed in this study requires small installation space as it consists of mainly electronic components. This will also make it affordable as most of the electronic components are readily available and their prices are competitive.

2.9.2 Phase shifting winding method

Authors of (Sunitha, & Kartheek, 2013) proposed use of shifting of windings as one of the method of mitigating harmonic distortions on power distribution system. This involves separating the electrical supply into two or more outputs. Each output is phase shifted with respect to each other with appropriate angle for the harmonic pairs to be eliminated. The concept is to displace the harmonic current pairs in order to have a 180^0 phase shift to cancel each other out. The details of phase shifting are well elaborated in (Sunitha, & Kartheek, 2013).

Figure 2.4 shows single line diagram (SLD) used in mitigating 5^{th} and 7^{th} harmonic distortions, which are most dominant harmonic orders in three phase nonlinear loads with PMW of 6 pulses as an example of how the method is employed to cancel the harmonic distortions. From Figure 2.4, two different step-down distribution transformers with different phase shift (one with zero phase shift and the other 30^0 phase shift respectively) supplies nonlinear loads. The resultant waveform at the common bus becomes close to a sinusoidal waveform as 5^{th} and 7^{th} harmonic cancel each other.

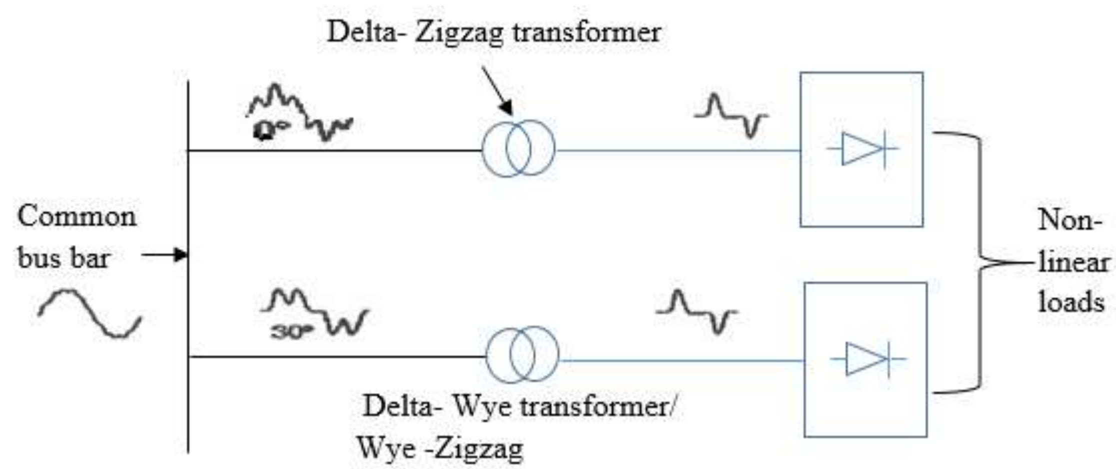


Figure 2.4: Single Line Diagram (SLD) for mitigation of 5^{th} and 7^{th} harmonic distortions

For various harmonics cancellation and mitigation, Table 2.1 shows the phase shift required within the windings of a transformer.

Table 2.1: Phase shifting required for harmonic mitigation or cancellation

S/No.	Harmonic order	Sequence	Phase shift required	Solution mode
1	3	Zero	180^0	Cancellation
2	5	-	30^0	Mitigation
3	7	+	30^0	Mitigation
4	9	Zero	180^0	Cancellation
5	11	-	15^0	Mitigation
6	13	+	15^0	Mitigation
7	15	Zero	180^0	Cancellation

From Table 2.1, it is clearly shown that using phase shifting technique, homopolar harmonics can be completely eliminated, while other harmonic orders can be mitigated or reduced within the transformer using this method. This method is expensive and almost unpractical to implement on LV voltage distribution network as more than one transformers are required. It is practical mainly in commercial and industrial setups. Hence, a better method needs to be devised to mitigate the harmonic distortions on low voltage distribution system.

2.9.3 Zigzag transformers

Zigzag transformers have been employed to attenuate the level of harmonic distortions within the transformer as authored by Rao Nasini et al, 2009. The zigzag connected transformer has three windings on each limb of the core, one on primary side and two on secondary side as shown in Figure 2.5.

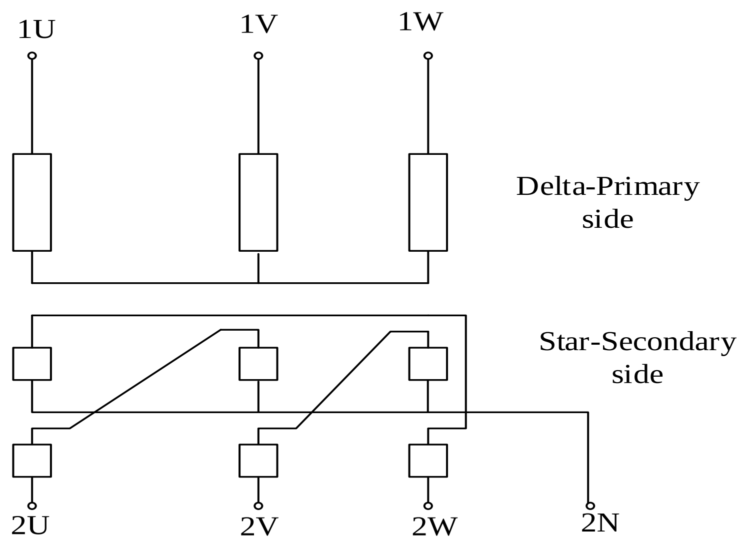


Figure 2.5: Zigzag transformer windings connection

Both windings on secondary side are of equal turns and wound in opposite directions. This gives a zero-phase displacement between primary and secondary i.e. primary and secondary windings are in phase. This type of transformer is commonly used for cancellation of triple-n harmonics and for creation of a missing neutral connection from an ungrounded three-phase system to permit the grounding of the neutral wire to an earth reference point. The main drawback of this method is it only cancels homopolar harmonic frequencies, hence does not eliminates other harmonics generated by nonlinear loads which may cause system resonance.

2.9.4 Use of *K-factor* transformers

The *K-factor* rated distribution transformers are designed to tolerate the heating effect of current harmonic distortions as stated in (Davudi, Torabzad, & Ojaghi, 2011). The amount of harmonics produced by a given load is represented by the term *K-factor*. For instance, *K-4* transformer indicates transformer has ability to accommodate 4 times the eddy current losses as compared to a *K-4* transformer (i.e. *K-4*) transformer can tolerate load up to 100% at 50 Hz, 16% of 3rd harmonic, 10% of 5th harmonic, 7% of 7th harmonic and 5.5% of 9th harmonic). The higher the '*factor*' the higher the harmonics present, hence the more harmonic current the transformer must be designed to tolerate thermal stress caused by electrical pollution. Distribution transformers with *K-Factor* have been in use since 1990. The *K-Factor* is obtained by using equation (2.13):

$$K - factor = \frac{\sum {I_h}^2 h^2}{I_1} \tag{2.13}$$

Where; I_1 is the rms current, I_h is the current of harmonic h, h is the Harmonic odd order: 3rd, 5th, 7th etc. An example is as shown in Table 2.2.

Table 2.2: Calculation of *K-Factor* transformer

h (Order)	$\mathbf{I_h}$	$\mathbf{{I_h}^2}$	$\mathbf{h^2}$	$\mathbf{{I_h}^2 h^2}$
1	1	1	1	1
3	0.15	0.0225	9	0.20
5	0.1	0.01	25	0.25
7	0.1	0.01	49	0.49
K-Factor				**1.94**

From Table 2.2, *K-Factor* is the transformer required to be installed to supply a nonlinear load of 1 A, generating above current harmonic distortions. However, *K- 4* is the minimum *K-Factor* among the standardized *K-Factor* transformers and hence recommended for this kind of installation. Other standardized *K-Factor* rated transformers are 9, 13, 20, 30, 40 and 50.

A linear load has *K-Factor* of 1. The higher, *K-Factor* the higher the ability of a transformer to withstand the additional heat generated by the harmonic current. It is worth mentioning that the *K-Factor* transformers do not mitigate the harmonics, but are able to tolerate thermal stress caused by the presence of harmonics at secondary side of the transformer and neutral conductor. Some of the *K-Factor* transformers and applications as per transformer manufacturer-Claude Lyons Group are as listed below:

i. *K-1*: Resistance heating, motors, control transformers (mostly linear loads)
ii. *K-4*: Welders, induction heaters, fluorescent lighting, load with solid-state controls.
iii. *K-13:* Telecommunications equipment
iv. *K-20:* Mainframe computers, variable speed drives, sub circuits with loads of data processing equipment, and desktop computers.

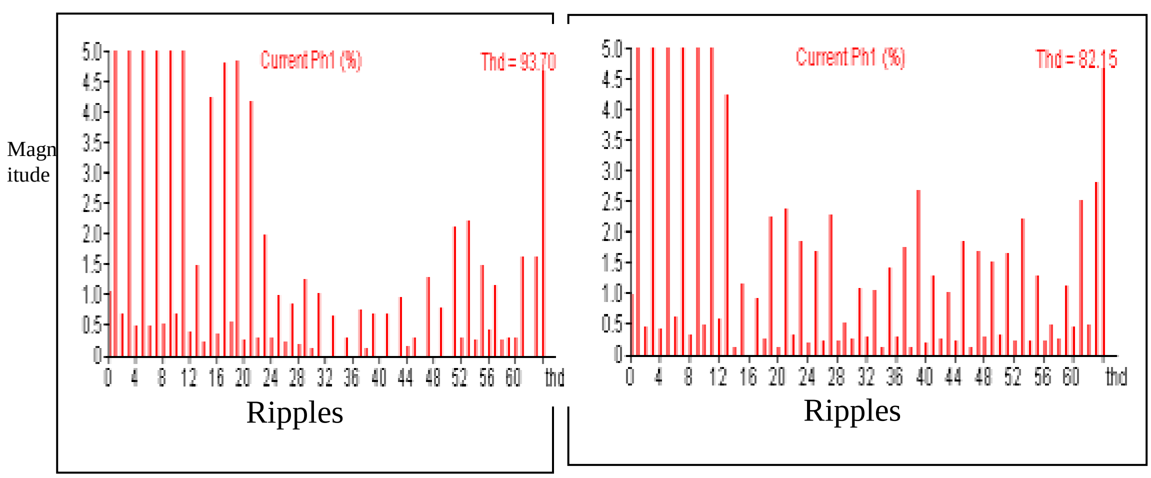
A *K- Factor* rated transformer has distinctive features. Use of *K- factor* transformers do not offer solution for all the challenges associated with harmonic distortions in distribution system. Some of the challenges that *K- factor* transformer cannot eliminate include voltage and current resonance as well as overload of neutral conductor due to zero sequence harmonic orders. The *K- factor* transformers are expensive. Hence, there is need to devise an affordable mitigation method for LV distribution network.

2.9.5 Increase of converter pulses

Use of higher pulse numbers of converter circuits has currently gained popularity as reported in [57]. It involves designing converter circuits with 12-pulses, 18 pulses and 24 pulses rectifiers to eliminate the lower order harmonic distortions. As a result, the dominant harmonics therefore become,12±1, 18±1 and 24±1 respectively. The higher the number of converter pulses, the lower the total harmonic distortions level. This is primarily because low harmonic frequencies (3^{rd}, 5^{th} etc.), which usually have high magnitude, are eliminated. Research has shown that a 6-pulses rectifier will produce approximately 25% THD_i , a 12-pulses rectifier will produce about 12% THD_i and an 18-pulses rectifier will produce approximately 5% THD_i. The main drawback of increasing converter pulses is increase in cost of converter. Furthermore, it is not possible to eliminate current harmonics streaming back to the power utility service conductors by increasing device's converter pulses.

2.9.6 Low harmonics level electronic devices

Low harmonics level electronic devices have front-end rectifier that employs forced-commutation (pulse width modulated) devices such as IGBTs, MOSFET, GTO and IEGT (Injected-Enhanced Gate Transistor) rather than electronic devices such as diodes or thyristors (also known as natural commutation devices) for AC/DC power conversion. Research has shown that the devices with IGBT or IEGT exhibit less harmonic current distortions as compared to those with diode at front-end rectifier (Mazumdar, 2006) and (Cherian, Bindu, & Nair, 2016). This is illustrated in Figures 2.6(a) and 2.6(b).



(a) (b)

Figure 2.6: Harmonic spectrum; (a) CRT- TV and (b) Plasma –TV

From Figure 2.6, it is observed that there is a reduction in THD_i from 93.7% to 82.15% from old technology to new TV–plasma, but with an increase of ripples, which have undesirable effects such as heating electronic components that may cause digital circuits to malfunction. Low harmonic devices technique generate ripples as noted, hence a better solution is desired that does not inject ripples in a LV distribution network.

2.9.7 De-rating electrical equipment

De-rating electrical equipment implies overrating the equipment to more than its optimal rating/size required, as is highlighted by Carami P. et al (Musa, et al., 2017). For instance, installation of a 75 mm^2 cable instead of 50 mm^2 cable. This is because harmonic currents add extra loading (has high I_{rms}) as shown in equation (2.14).

$$I_{rms} = \sqrt{1 + THD_i^2} \tag{2.14}$$

As a result, system components such as cables, conductors, circuit breakers and transformers may have to be oversized where high levels of current harmonic pollution are expected. Adopting this method makes the power distribution system expensive, as the equipment with high rating are generally more expensive.

2.10 Related Research on Distribution Transformer Harmonics Mitigation

From literature review presented in this chapter, it is noted that there are numerous research studies carried out on harmonic distortions in the power system. It has also been established that the study of harmonic distortions started more than century years ago (since 1916), therefore it is a field that has attracted profound attention of many researchers. This section gives a summary of related studies that focused mainly on mitigation of harmonic distortions on a low voltage distribution network. The study carried out by Michael S. Witherden, (2007), focused on adverse effects of CFLs on power quality of a low voltage network. The research scope was limited to the effects of different type of CFLs on low voltage distribution network. The study proposed endorsement of stringent measures already enshrined in IEC 61000–3-2, which most lighting industries have been lobbying not to be implemented. Further, the study also suggested introduction of a power quality correction unit at domestic power consumers' PCC. Introduction of an active filter in every low-power electronic-based appliances may increase exorbitantly the price of the household appliances. It is for this reason that this study proposed an active harmonic filter to be installed at PCC rather than on each individual appliance. Ming-Yin et al., Gunda, Sudheer, & Sarma, 2012), conducted a survey in an office building of harmonic currents generated by computers. From the study, the field measurement data obtained revealed high neutral current, which was due to additional current caused by zero sequence harmonic orders (triplen harmonic orders). The researcher proposed oversizing of the neutral conductor as a mitigation measure of high harmonic pollution caused by office equipment such as computers, fax machines, printers among others. The proposed method only addressed one problem of harmonic distortions, problems such as system resonance and overheating of equipment due to harmonic distortions cannot be addressed by oversizing of neutral conductor. Godbole P. (Khatavkar, 2009), carried out a study on low voltage distribution network. The research was conducted in a steel industry that was installed with induction furnaces. From the site data measurements obtained, harmonic distortions were noted to increase apparent power hence reducing power factor. The author mainly dwelled on industrial nonlinear loads and their impacts in power factor but no mitigation measures were proposed in this study. Gupta A. et al (Singh, Zadgaonker, & Amarjit, 2014) , evaluated distribution transformer losses supplying nonlinear loads. In their study on 100kVA three phase transformer supplying nonlinear loads, they demonstrated two types of losses associated with harmonic distortions at no load and on load. The authors proposed uprating of the transformer and use of *K - Factor* for mitigating harmonic distortions streaming from the nonlinear loads. High rated and *K - Factor* transformers are generally exorbitantly costly. A similar study was done by Ahia H. et al. (2011) on effects of harmonic distortions and mitigation in a distribution network. The study focused on commercial loads; computers and telecom equipment. From field data measurements, the authors proposed deployment of phase shifting transformer as one of the methods of alleviating the impacts of harmonic distortions on a low voltage network. The drawback of this solution is that only few orders of harmonic distortions are eliminated while the rest are mitigated as depicted in Table 2.2. Zynal H et al. (Bartley, 2011), modelled a 2 KVA three-phase transformer in MATLAB-Simulink environment.

The objective of the study was to establish the effects of voltage and current harmonic distortions on distribution transformers. The results obtained from the simulation indicated that both the voltage and current harmonic distortions have adverse impacts on transformer insulation oil and windings. They cause earlier failure of the transformers. The authors proposed passive filter (5^{th} harmonic filter) as one of the methods of reducing the profound impacts of both the voltage and current harmonics on distribution transformers. Passive filter has demerit of fixed filtering of specific harmonic order and its performance is adversely affected by dynamic changes of system impedance.

The above research studies mainly focused on mitigation of harmonic distortions using classical methods. Although the studies achieved the desired results, they suffered major setback of not cancelling the entire spectrum of harmonic distortions. A study that employed the modern methods of harmonic distortion was done by Sobby S. et al (2012) in which an adaptive three phase shunt active filter was designed and simulated for mitigation of harmonic distortions generated by a resistance spot welding machine. The designed shunt active harmonic filter employed proportional integration (PI) controller as well as a voltage limiter circuit to generate desired switching signal for the VSI. Due to dynamic behavior of the harmonic distortions in a low voltage network, PI controller that require actual data, may not give satisfactory results hence, why this study adopted fuzzy logic controller. Jose S. et al (2011) proposed synchronous reference frame based control method for unified power quality controller (UPQC). The objective was to mitigate the effect of voltage sag and attenuate the harmonic in power system. The designed AHF was a three phase shunt active filter that employed PI controller to maintain DC bus voltage. The PI controller is well known not to offer good results under dynamic system as earlier stated. Monfared M. et al (2013) designed an AHF using a double SRF. This method is characterized by poor performance in reactive power compensation, unnecessary complexity and high computation burden to the control system. Research done by Saitou et al (2014), extended the application of the SRF theory to single phase AHF. The author shifted single phase signal by 90^0 to generate fictitious single phase signal. This method has three demerits, which include: (i) Use of a Hilbert transformation to construct the fictitious single signal, which requires a high computation time, (ii) The algorithm is sensitive to grid frequency fluctuations and therefore any grid frequency deviations introduce an error, and (iii) Reactive power compensation is not considered in this method. Anooja et al (Anooja, & Leena, 2013), carried out a study on a single phase AHF using fuzzy logic controller for dc-voltage control. The p-q theory was employed to extract reference compensating signal. The p-q theorem, when used for single phase AHF, require signal to be shifted by 90^0 to obtain real and reactive power (α - β) components. The process of shifting the signal by 90^0 demands additional processing time for analog- to - digital conversion.

2.11 Active Harmonic Filter

The active harmonic filter also commonly referred as active power filter (APF) or active power line conditioner (APLC) was proposed as early as 1970s as per (Sunitha, & Kartheek, 2013). However, it remained at laboratory (simulation) stage because technology was not advanced enough to practically implement the compensation principle. The advent of fast switching devices such as Bipolar Junction Transistor (BJT), Insulated Gate Bipolar Transistor (IGBT) and Gate Turn-On (GTO) thyristor, spurred high interest in the study of shunt and series active power line conditioners for reactive power and harmonics compensation. In 1982, the first shunt active conditioner, which consisted of current source PWM inverter using GTO thyristor, was put into practical use for harmonics compensation.

The heart of AHF is the controller part. Control strategy plays a critical role in improvement of the performance and stability of the filter. There are two types of the control schemes employed:

i. Fast Fourier transform that calculates the amplitude and angle of each harmonic order.
ii. Time domain that carry out full spectrum cancellation by first extracting the basic frequency component (fundamental frequency 50 Hz) and then 'directing' the voltage source inverter (VSI) to inject the inverse of the harmonic waveforms.

The common reference current extraction schemes in time domain are (p - q) theory, deadbeat controller, neuro network, adaptive control, wavelet, fuzzy, delta-sigma modulation, sliding mode control, vector control, repetitive control, synchronous reference frame, and SFX control. The AHF has two controllers: reference current harmonic extraction and PWM current controller. The latter is employed in providing gating pulses, while the former is for extracting harmonic details generated by nonlinear load.

The AHF has three main steps in the principle of operations. These operations include (Ghulbet, Hinga, & Nderu, 2017). :

i. Controller detects the instantaneous load current i_l
ii. The AHF extracts the harmonic current i_{lh} from detected load current i_l by means of digital signal processing and
iii. The AHF draws the compensating current i_{AF} (= - i_{lh}) from the utility supply voltage v_s to cancel out the harmonic current i_{lh} .

The main reason why AHF is becoming first choice in most installation is that it does not cause harmful resonance with the power distribution system impedance and installed feeder shunt capacitor used for reactive compensation. However, the cost of AHF is still relatively high and mostly depends on filter rating (Kerrouche, & Krim, 2009). However, the cost for a single phase active harmonic filter is relatively cheaper and is less complex as compared to a three phase AHF.

The active power filters are categorized by the mode of connection at the PCC. The configuration depends on interfacing inductor or transformer. From the literature, there are different connections as shown in Figure 2.7 (Michael, 2007).

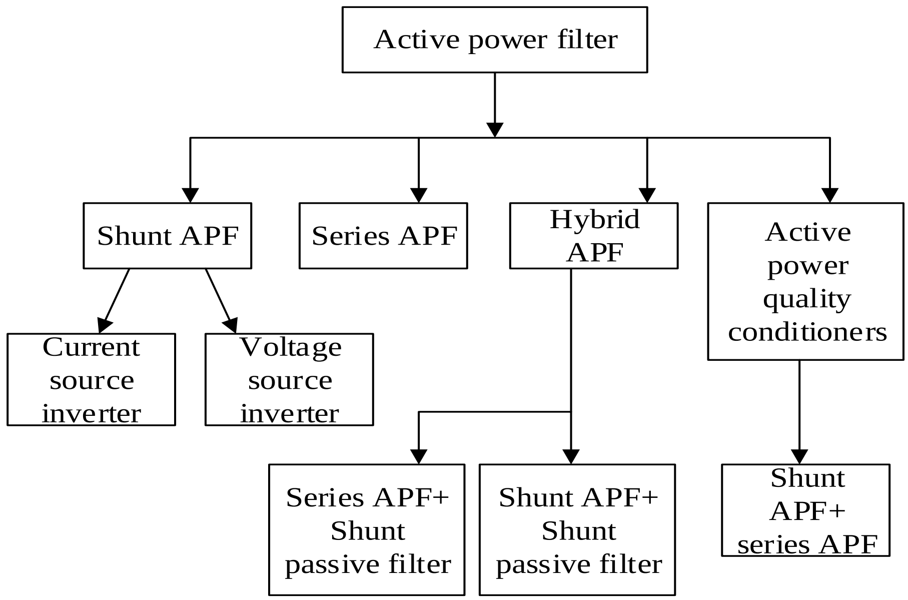


Figure 2.7: Different types of connection of active harmonic filter

2.11.1 Active harmonic filter design concept

The shunt, series and hybrid (combinations of both AHF and passive filter) have been designed for mitigation of harmonic distortions, voltage regulation and improving of the power factor at PCC. According to (Ghulbet, 2017), this wide range of applications is achieved either individually or in combination. Depending on the requirements, a control algorithm and a configuration has to be selected appropriately. The diagram in Figure 2.8 illustrates a generalized block diagram for AHF.

From the Figure, there are various methods that are used to realize each of the block sets. This study explored various technologies/techniques proposed and reasons for selecting the appropriate technique suitable for the proposed single phase shunt AHF. Figure 2.9 shows a simplified SLD circuit diagram of an active power harmonic filter.

Unlike passive filter that mitigates specific harmonic orders, mostly the dominant harmonic order, AHF cancels entire harmonic spectrum generated by nonlinear loads.

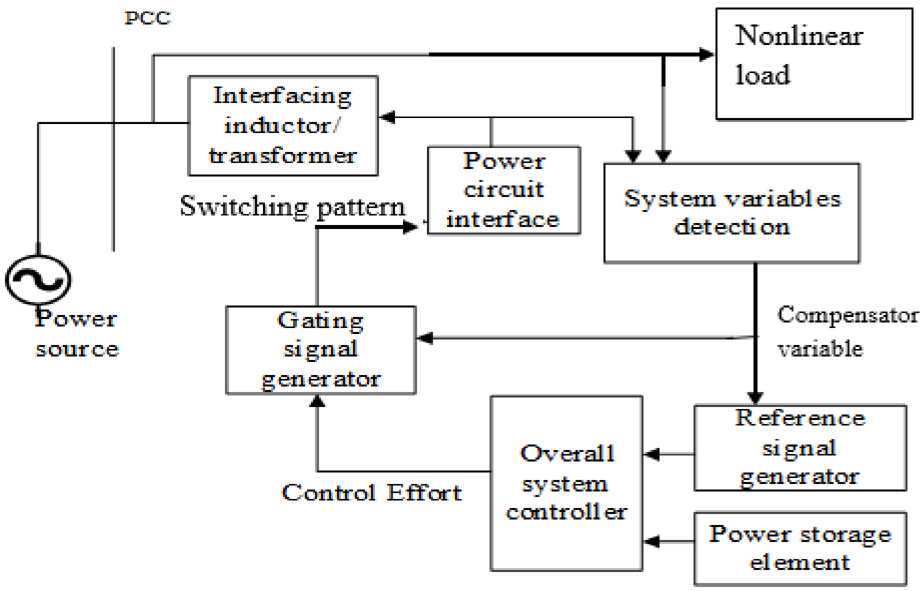


Figure 2.8: Block diagram of active harmonic filter

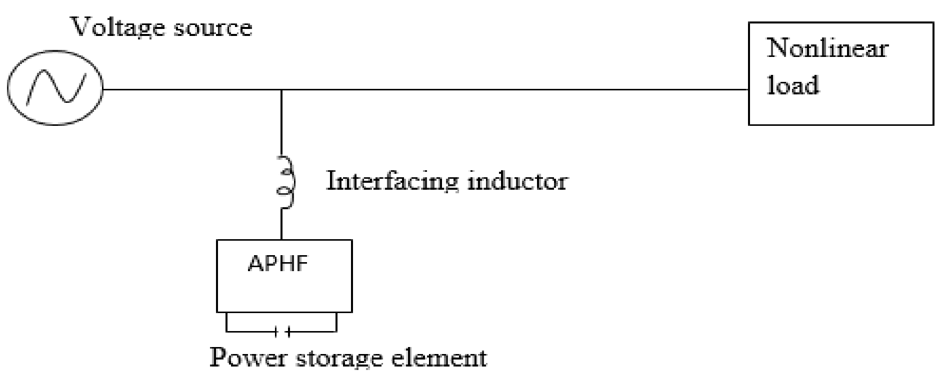


Figure 2.9: Equivalent circuit diagram of AHF

2.11.2 Components of active harmonic filter design

The subsequent sections present determination of the main components that constitute a typical AHF design. These are system variable detection, reference signal extraction, power storage element, AHF internal controller, gating switching signals and DC-bus controller.

(a) System variables detection

There are numerous methods used for signal conditioning for the voltage and current. Voltage can be sensed by use of direct connection, potential transformers (PTs), Hall Effect or voltage divider. Current can be sensed using direct method, current transformers (CTs), Hall Effect sensor, Rogowski coil, optical isolation amplifiers or shunt resistor (Kerrouche, & Krim, 2009). The current details required to be conditioned include; load current (and harmonic current), compensation current and dc-link current, while voltage details required include AC source voltage, DC-bus voltage and voltage across the interfacing transformer or inductor.

(b) Reference signal extraction techniques

There are many techniques used to estimate or extract and/or detect the magnitude of harmonic distortions and phase angle streaming from nonlinear loads. The techniques can be either in Frequency domain or Time domain. Example of Frequency domain methods are such as Fast Fourier transforms (FFTs), Discrete Fourier Transform (DFT), Wavelet method and Recursive Discrete Fourier Transform (RDFT). On the other hand, time domain approaches employed include; synchronous reference d- q- o theory, synchronous detection algorithm, multiple adaptive feed-forward cancellation (MAFC) algorithm, sine–multiplication theorem and instantaneous reactive power p –q theory. From the literature, the main advantage of frequency domain is its ability to identify and select individual harmonic distortion to be mitigated. However, drawbacks of the Frequency domain that makes it unpopular as first choice include large memory required to store Fourier coefficients, time delay due to sampling and computation of Fourier coefficients (at least two cycles are required to be computed), more computation power and is less precise hence not appropriate for real time application at dynamically varying loads installation. Notwithstanding, with advancement of microprocessor memory which has greatly improved, heavy computational burden will be less of a challenge in near future (Michael, 2007).

Frequency domain extraction technique employing discrete Fourier transform is expressed as given in equations (2.15)-(2.17) (Ghulbet, 2017). :

$$\bar{A}_h = \sum_{N=0}^{N-1} A(n)\,\mathrm{Cos}\left(\frac{2\pi.h.n}{N}\right) - j\sum_{N=0}^{N-1} A(n)\,\mathrm{Sin}\left(\frac{2\pi.h.n}{N}\right) \tag{2.15}$$

$$|\bar{A}_h| = \sqrt{A_{hr}^2 + A_{hi}^2} \tag{2.16}$$

$$\Phi_h = arctan\left(\frac{A_{hi}}{A_{hr}}\right) \tag{2.17}$$

Where; *N* is the number of samples per fundamental period, *A(n)* is the input signal (voltage/current) at point $\bar{A}_h$ n, is the complex Fourier Vector of the h^{th} harmonic of the input signal, A_{hr} is the real part of A_h, Ahi is the imaginary part of $\bar{A}_h$, $I\bar{A}_hI$ is the amplitude of the vector and Φ_h is the phase of the vector.

From equations (2.15) – (2.17), it is clearly shown how the details of individual harmonic frequencies (magnitude and phase angle) are extracted. However, more than one sample is required before obtaining the desired results of identifying the harmonic frequencies present in the network. It is important to point out that once the harmonic distortions are detected and isolated, they are reconstructed back in time domain to generate compensation signal for the controller. On the other hand, the time domain algorithm is the most employed technique in extracting the reference signal. This is mainly because of its numerous inherent advantages such as less time to compensate the current harmonics and reactive power and further, it gives superior results than its counterpart extracting algorithms in a frequency domain.

Extracted signals need to be conditioned to obtain the compensating signals that is inverse of identified harmonic waveforms. This is mainly achieved by use of digital filter. There are different types of digital signal filters. The most common are namely: Butterworth, Chebyshev I and II (Inverse), Bessel and Elliptical filters. Each of these signal filters has unique response in terms of signal magnitude and time response (Sobly, et al., 2008). Table 2.3 gives a summary of each type of the filter.

Table 2.3: Common digital signal filters and their characteristics

Filter type	**Magnitude discrimination**	**Time response**	**Equiripples in passband**	**Equiripples in stopband**	**Transition band**
Butterworth	Better	Better	Monotonic	Monotonic	Wide
Chebyshev I	Better	Worst	Present	Monotonic	Shorter
Chebyshev II	Best	Better	Monotonic	Present	Shortest
Bessel	Worst	Best	Monotonic	Monotonic	Shorter
Elliptic	Better	Better	Present	Present	Shorter

This work used an inverse Chebyshev type filter mainly because of its inherent excellent performance in magnitude discrimination and shortest transition band. Figure 2.10 shows Chebyshev II type HPF digital filter.

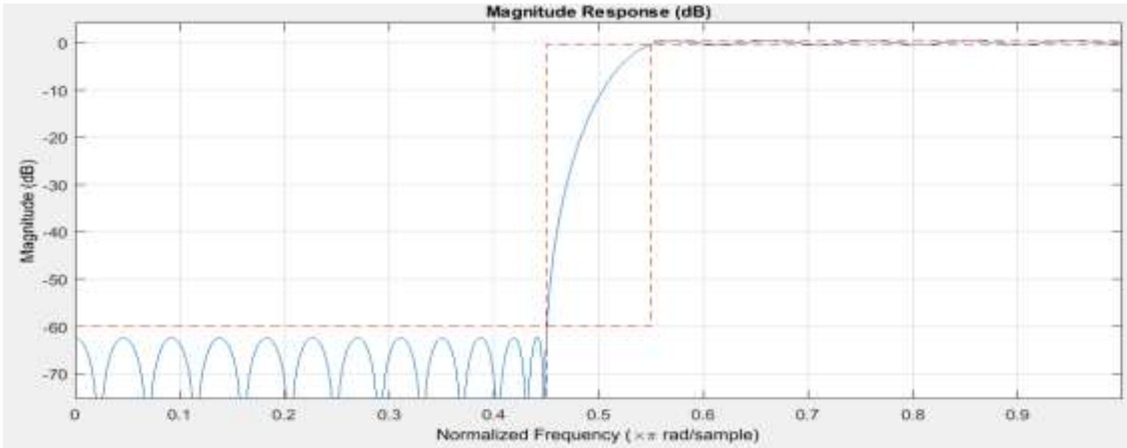


Figure 2.10: HPF magnitude response for Chebyshev II filter

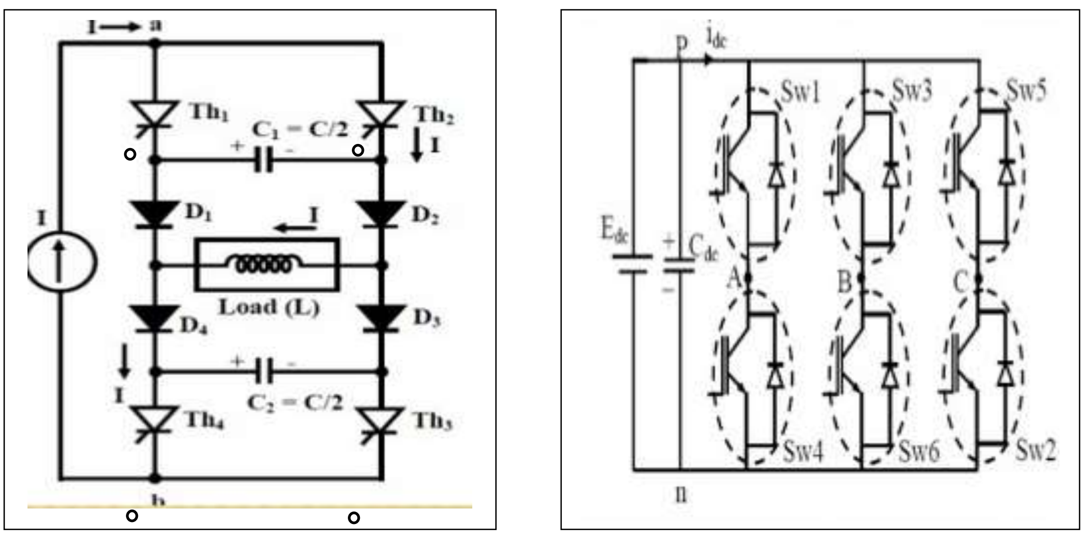
It is worth to note that the filter has monotonic response in pass-band frequencies and equi-ripples in stop-band which depends on the order of the filter. Further, the filter magnitude response is of 6^{th} order (by counting the number of complete cycle of equi-ripples in stop-band).

The selection of the best extraction method is an important factor that enable designer of AHF to obtain good accuracy reference current especially in a dynamic system (Musa, et al., 2017). If there is an error when estimating reference signal, the overall performance of AHF is degraded in such a way that not even a sophisticated control algorithm can correct it. This was the conclusion made after a debate that deliberated on which part of AHF the designer should critically focus on during the designing stage. Other subtle areas the active harmonic filter designers should also pay attention include the detection method accuracy, the speed, filter stability and ease of application.

(c) Power storage element

There are two types of storage elements used in an active power filter. The selection depends on the type of inverter used i.e. current source inverter (CSI) employs inductor and voltage source inverter (VSI) uses capacitor as storage element. The CSI has a predetermined current, while load impedance determines the output voltage. It should be pointed out that CSI has problem at light load as it exhibit sluggish performance and instability. They use Gate- On electronic element such as Thyristor as switching devices. The CSIs are less common due to bulkiness and high cost of inductor. However, they are employed where a constant current is the most important consideration (Msigwa, Kundy, & Mwinyiwiwa, 2009) . Figure 2.11shows typical circuit diagrams of CSI and VSI respectively.

The inverter switching causes power losses to occur at DC-side of the inverter. This causes the DC-bus voltage, that is, the capacitor voltage to decrease. It is therefore necessary to restore and maintain a constant voltage level of 1.5 phase voltage for compensation of harmonic distortions only. However, when compensating both harmonic distortions and reactive power, the voltage required is twice the nominal voltage.



(a) (b)

Figure 2.11: Typical circuit diagram; (a) CSI, (b) VSI storage element

Various methods for regulating the dc capacitor voltage have been proposed in the literature (Sunitha, & Kartheek, 2013). They can be classified as linear and nonlinear methods. Linear methods include proportional integral (PI), proportional derivative

(PD), and phase lock loop (PLL). The linear methods require complete knowledge of the system and more calculations of parameters time. They also require a robust system whose output does not change significantly under the influence of change in the inputs because the linear methods operate within a narrow window of uncertainty conditions. Nonlinear methods on the other hand include; fuzzy logic, bang-bang, and neural network. These methods do not need the prior system information and they provide a good rapid response under dynamic loads.

(d) AHF internal controller

The internal controller of AHF constitutes a controller that generates the gating signal of VSI with capacitor as storage element. Various methods have been proposed to control inverter gate signal device. Among the methods include; hysteresis current controller, which could be either fixed or adaptive hysteresis controller, artificial neural network (ANN), fuzzy logic (FL) and genetic algorithm (GA) or hybrid of any of the mentioned methods. Further, some designs employ pulse width modulation (PWM), which could be single PWM or multiple PWM. The multiple PWM employs triangular, sinusoidal or periodic sampling. Proportional integral control and sliding mode control has also been proposed. This research uses hysteresis current controller due to the advantages it has over the other inter-loop controllers. These include: fast current controllability, quick response current loop, inherent peak current limiting capability, unconditional stability and more importantly gives accurate results (Musa, et al., 2017).

The switching pulses of hysteresis current controller are in such a way that the peak to peak gating signal are limited to a specified band determined by H as shown by Figure 2.12.

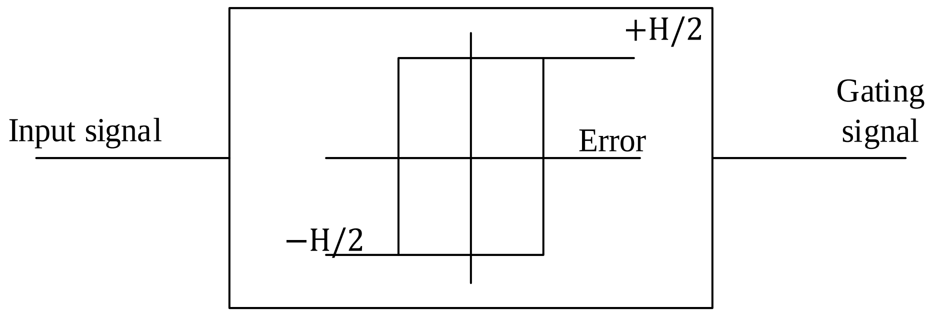


Figure 2.12: Switching hysteresis current controller

(e) Gating signal switching devices

Gating signal is mainly used to switch bipolar junction transistors (BJTs), which are commonly used for low power rating at relatively low switching frequencies. This implies that, the power lost at dc-side of inverter is minimal. Insulated gate bipolar transistors (IGBTs) are commonly employed for medium power rating at average switching frequency. Most of the industrial and commercial building, active harmonic filter uses IGBTs. The IGBTs have relatively high-power rating than BJTs. For a three phase, VSI using Thyristors as the switch devices are preferred (Sunitha, & Kartheek, 2013).

(f) DC- bus controller for AHF

The DC-bus voltage regulator is one of critical components in AHF as it stabilizes operation of active harmonic filter. This is because AHF performance is adversely affected by external disturbances from power grid, load fluctuations and system parameters changes (Kerrouche, & Krim, 2009). For these reasons, selection of an appropriate DC-bus voltage regulator is of paramount to make the AHF insensitive to system disturbances/fluctuations, robust and more importantly to have a fast dynamic response. Regulation of DC-bus voltage involves balancing between power flow into the filter and the losses inside the filter. The DC-bus controller therefore compensates the active power losses that occur due to switching activities and conduction losses associated with the gating devices. There are two widely used gating devices; the insulated gate bipolar transistors (IGBTs) and bipolar junction transistors (BJTs). The IGBTs have low power losses and can be switched at moderate high frequencies compared with BJTs gating devices, hence the reason why this study adopted IGBTs for the PWM inverters in the designed active harmonic filter.

The DC-controllers as noted in literature can be achieved by use of proportional integral (PI), proportional integral derivative (PID) or fuzzy logic controller (FLC). In (Rajurkar, Nandapurkar, & Kulkarni, 2010), advantages and disadvantages of each of the method has been explicitly provided. This study opted to use fuzzy logic controller to control the DC-bus voltage of inverters of the proposed single phase AHF because of many inherent advantages the fuzzy logic controller have over the PI and PID controllers which are documented in (Rajurkar, Nandapurkar, & Kulkarni, 2010). It is important to point that, this study present a single stage FLC, unlike neutro-fuzzy approach that requires two-stage FLCs. As result, the proposed control scheme has reduced amount of fuzzy membership functions and control rules, which consequently reduces the computation time and memory size of the rule base.

A fuzzy logic is an approach that involves artificial intelligence (AI) invented by Professor Zadeh (1965) of University of California at Berkley. Unlike classical sets that deal with crisp values or definite boundaries, fuzzy set contains elements, which have varying degrees of membership in the set. The fuzzy set uses a universe of discourse as its base, which contains an infinite number of degrees of membership. Fuzzy logic has been widely employed in many fields such as economical modeling, biological analysis and control engineering. Due to rapid development of fuzzy technologies, different fuzzy control strategies have been developed such as PID-fuzzy control, sliding-mode fuzzy control, neural-fuzzy control and adaptive fuzzy control. This has been spurred by many inherent advantages of fuzzy logic controller such as robustness, customizability, reliability and high efficiency (Parthasaradhy, Padhan, & Chinmaya, 2014).

The aim of fuzzy logic is to make decisions based on number of predefined rules rather than numerical calculations. It has an aggregation of rules based on the input state variables condition with a corresponding desired output. These defined rules are from knowledge of an expert in that related field of application. Fuzzy logic is expressed as:

$$\text{IF } x \text{ is } A_i \text{ THEN } y \text{ is } C_i$$

Where; x is the input (*state variable*) and y is the output of the system, A_i is the different fuzzy variables used to classify the input x, while C_i is the different fuzzy variables used to classify the output y.

The IF part is used to capture knowledge by using variable conditions, while THEN part gives the conclusion or output in linguistic variable form. Fuzzy inference system is characterized by three steps, which are fuzzification, fuzzy rule evaluation (fuzzy inference engine) and defuzzification. The three steps are related as illustrated in the fuzzy inference system shown in Figure 2.13.

The fuzzification converts crisp variables to fuzzy variables. This is realized by two processes; membership functions (for input and output elements) and linguistic variables. Different membership functions waveform that are currently widely used include; triangular, trapezoidal, Gaussian, bell-shaped sigmoidal and S-curve waveforms. For system with significant dynamic variations within a short period of time, triangular or trapezoidal waveforms are preferred (Kumar, & Gopalakrishnan, 2013) .

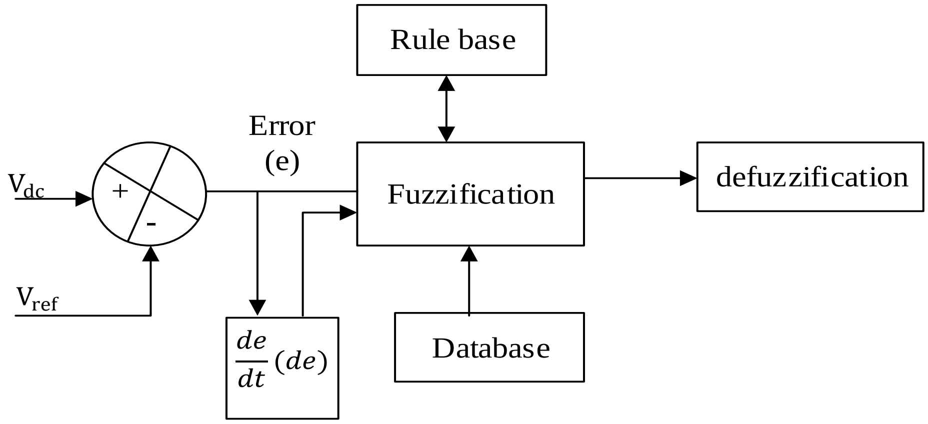


Figure 2.13: Block diagram of Fuzzy logic control technique

However, for a system, that needs very high control accuracy, a Gaussian or S-curve waveforms are employed. On the other hand, fuzzy rules describe the relationship between the fuzzy input and fuzzy output. Each fuzzy rule approximates a limited number of elements of the function hence entire function is approximated by set of fuzzy rules.

The last process of fuzzy inference system is defuzzification which converts the fuzzy output back to crisp or actual output. There are three main defuzzification methods; mean of maximal (MoM), Center of Gravity (CoG) and Height Method (HM). The most employed defuzzification methods is CoG the reason been that it considers the entire shape of the output membership function. The mathematical expression of CoG is given by equation (2.18):

$$CoG(y) = \frac{\Sigma_x \mu_y(x) x_x}{\Sigma_x \mu_y(x)} \tag{2.18}$$

Where; y is the fuzzy output crisp, μ is the membership function and x is the function element.

Defuzzification can be either off-line or on-line. The off-line implies all input and output membership functions, fuzzy rules and the lookup table are developed based on estimations of the real application prior to the implementation of the fuzzy logic system. On the contrary, all input and output membership functions and the lookup table are developed in real time based on the current actual input and output for an on-line defuzzification (Ghulbet, 2012).

2.12 Summary of Research Gaps and Proposed Solution

2.12.1 Research Gaps

From the literature review, the following gaps have been revealed:

i. Research on the effects of harmonic distortions emanating from modern domestic appliances on low voltage distribution network has been limited due to assumption that nonlinear residential loads have insignificant impact on the power system. Research has widely focused on commercial and industrial loads. This research therefore focuses on investigating harmonics emanating from different residential loads.
ii. The harmonic distortions emanating from nonlinear residential loads would greatly affect the adjacent distribution transformers. Consequently, this research also entails investigating the effects of nonlinear residential loads on the LV side of distribution transformers by determining and analyzing the harmonic levels together with their correlation with distribution transformer failure rate
iii. Harmonic distortions are also known to affect and contribute to degradation of transformer oil. This research also involved obtaining and analyzing distribution transformer oil samples to determine the adverse effects of harmonic distortions on transformer oil.
iv. There is need to develop mitigation measures for harmonic distortions emanating from LV distribution network with much focus on single phase as opposed to conventional three phase methods employed. This research involves design and

implementation of active filter as a way to alleviate the effects of the harmonic distortions.

2.12.2 Proposed solution

Based on previous studies on harmonic distortions mitigation measures, use of SRF method to extract compensating signal for a single phase shunt active filter has not been fully explored. It is observed that SRF method has been widely employed in design of a three phase active harmonic filter. It is for this reason that the proposed single phase shunt AHF used a synchronous reference frame (harmonic synchronous reference frame) method, due to its inherent advantages such as less processing time and its performance is not affected by voltage unbalance (hence possible to use fictitious signals). It is also worth to mention that, use of an artificial intelligent (AI) controller, that is, fuzzy logic controller (FLC), to regulate DC-bus voltage of single phase shunt active harmonic filter was novel as most previous authors adopted conventional methods such as PI and PID controllers for DC –bus voltage control for AHF. This study adopted the FLC for DC-bus voltage control across the voltage source inverter mainly because of its inherent merits such as;

i. The FLC is known to mimic human behavior and hence offer a better results in a dynamic condition as does not require accurate mathematical models of a system.
ii. Power network system is complex and nonlinear in nature and its behavior are not well understood, that is, are potentially ill defined hence approximation of the output, by use of FLC, suffice.
iii. The FLC is more adoptable to parameters variations, non-linearity and load disturbance hence guarantee a better and a fast solution.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter presents the approach adopted in harmonic data measurement at various points of LV distribution system. It provides steps carried out to measure the harmonics data at various points of distribution network and power quality equipment used. The approach adopted in gleaning transformer oil samples and instruments employed to analyze the oil samples are presented. Data collection of transformer failure rate was conducted at North Eastern region, Kenya. It also gives methodology on the design of the fundamental components of the proposed single phase shunt active harmonic filter using MATLAB-Simulink block-sets software. Lastly, validation of the designed model and performance evaluation of the proposed single phase shunt active harmonic filter is presented.

3.2 Investigation of harmonic distortions due to Domestic nonlinear loads

In order to exhaustively study effects of harmonic distortion, two scenarios were considered; first, harmonic distortion contribution from individual nonlinear loads and secondly contribution due to several nonlinear loads combined.

3.2.1 Harmonic distortions emanating from individual nonlinear loads

Harmonics injected back to LV network generated by domestic individual loads were obtained by carrying out current harmonic distortion measurements at domestic consumer's PCC. The measurements were carried out by use of a power quality measuring equipment shown in Figure 3.1. The data measured using the power quality measuring instrument was THD instantaneous and power factor (leading or lagging) as shown in Figure 3.1(a) and 3.1(b) respectively. Measurement was done at PCC as recommended in IEEE 519, standard. Each appliance was powered individually and corresponding instantaneous harmonic distortions and power factor values noted. Figure 3.2 depicts the measuring device connection at domestic power end user's point of common coupling.

(a) (b)

Figure 3.1: Power quality measuring equipment (a) Harmonic distortions data display, (b) Pf data display

Figure 3.2: Connection of measuring equipment at point of common coupling (PCC)

Figure 3.3 shows a single line diagram (SLD) on how the harmonics data was obtained from individual appliance at domestic power user's PCC.

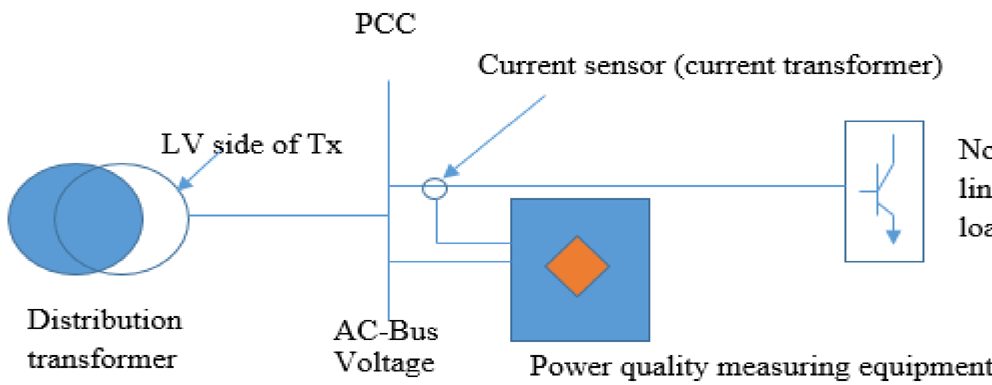


Figure: 3.3: SLD showing connection for an individual domestic appliance

3.2.2 Harmonics emanating from combined multiple appliances

Current harmonic distortions and pf for multiple (combined) appliances were measured using the same equipment employed for individual loads. Figure 3.4 depicts connection and combination of the appliances. For instant, load A could present a computer monitor screen while load B presents a central processing unit (CPU).

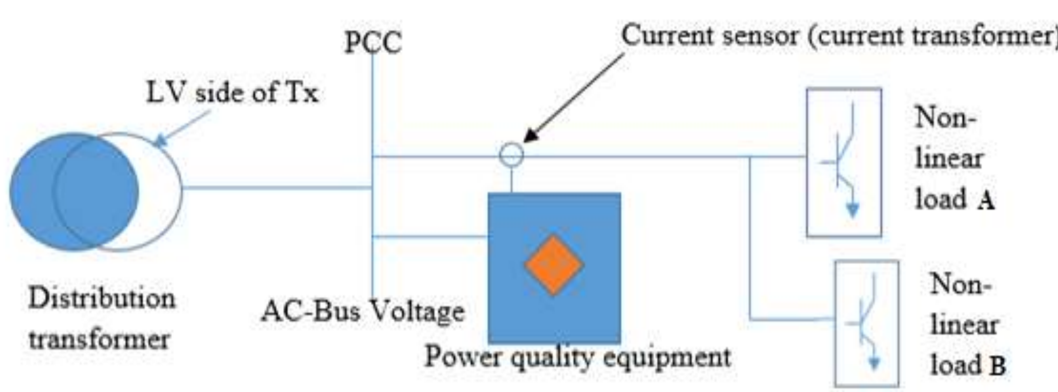


Figure 3.4: SLD showing connection for multiple appliances

3.2.3 Analysis of harmonics data obtained for individual load and multiple loads

Analysis of the obtained data, which was presented in a table form, was carried out using graphs generated from an Advanced Microsoft Excel as analysis data tool. Each appliance THD generated and Pf was noted, same for multiple loads. Effective and Pf of combined appliances were also noted. Analyses of combined appliances was carried using the following principle.

i. Appliances with similar electrical characteristics (equal or almost same pf-lagging or leading)
ii. Appliances with dissimilar electrical characteristics (with different displacement phase angle)
iii. Loads that are usually used in pairs such as TV and decoder (GoTV decoder), and
iv. Combination of inductive loads (lagging Pf) and capacitive loads (leading pf)

3.3 Investigation of harmonic distortions effect on distribution transformer LV side, oil and transformer failure rate.

The effects of harmonic distortions streaming to LV distribution transformers was investigated threefold; first the harmonic distortion levels on the LV side of distribution transformer, secondly effect on the distribution transformer oil and third, effect on distribution transformer failure rate. Analysis of each of the three cases was also performed.

3.3.1 Investigation of harmonic distortions levels on LV side of distribution transformer

The current harmonic distortions levels at the secondary side of sampled distribution transformers supplying different loads were measured. The sampling of the transformers was based on the most dominant loads supplied by the transformer (i.e., transformer supplying mainly domestic power consumers' loads and one that supplies mainly commercial consumers' loads). All the sampled transformers were three phase transformers, 11000/415/240 V. Table 3.1 shows additional information for the sampled distribution transformers. The substation local power supplies distribution transformer was selected as control transformer due to the following reasons;

i. Being the longest serving among the sampled distribution transformers (41 years of the service at time of data collection)
ii. With no oil leakage observed, it was considered as 'healthy' transformer

Among the sampled transformers, none was from repair workshop and point of service was their first installation as noted from transformers' manufacturer data nameplate and the company's record. All the sampled transformers were pole mounted distribution transformers. It is worth noting that the length of the service conductors from distribution transformers to the connected loads varied. The length was longest for the transformers supplying domestic consumers and least for the substation transformer. Furthermore, the length of conductor and service cable have no effects on the measured current harmonic distortion at domestic premise's PCC (see Figures 3.3 and 3.4). A Power Quality Analyzer (PQA) was logged at LV side of each of the transformer for two consequent weeks to capture all possible scenarios of the connected loads' usage patterns. The data aggregation period was five (5) minutes to have good resolution and an accurate data. Figure 3.5 shows the PQA used in field harmonics data gathering.

Table 3.1: Details of sampled distribution transformers

No.	**Manufacturer**	**Year of Manufacturer**	**Date of installation**	**Dominant loads**	**Location**
1	Dong Manufacturer	2007	02/2008	Commercial	Ruiru Town
2	Vijah Electrical Ltd	2010	10/2010	Urban domestic loads	Ruiru Toll
3	Pan - Africa	2012	12/2012	Rural domestic loads	Gatundu-Kiamwangi
4	Stromberg	1978	07/1978	Substation local power supplies	Roysambu 132/66 kV substation

The PQA shown in Figure 3.5 can be set (configured) to measure the most common power parameters (power frequency, apparent power, displacement power factor etc.) as well as the current and voltage harmonic distortions up to 63rd harmonic order.

Figure 3.5: PQA employed in measurement of current harmonics at LV side of sampled distribution transformers

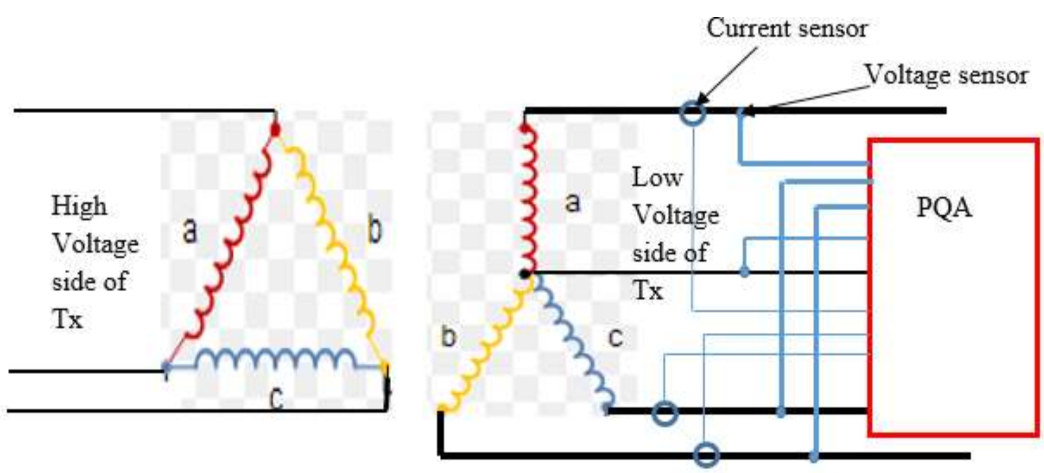


Figure 3.6: Connection of PQA at LV side of sampled distribution transformers

The connection of PQA at LV side of distribution transformer was as shown in Figure 3.6. It is imperative to note the PQA was connected in parallel with connected loads. Further, the current was conditioned by stepping down to a maximum of, 5 A i.e. the maximum current input for PQA device (i.e. CT clamps were rated 120/5 A). On the other hand, no conditioning was done on the voltage since it was directly tapped from the secondary side of the transformer to the measuring equipment as shown in Figure 3.6. The transformer rating does not influence the results of current harmonic distortions measured because current harmonic data is obtained at LV side of the transformer as shown in Figure 3.6 before streaming to the transformer windings via LV transformer fuses. Harmonics measurement was carried out as specified in IEEE 519 standard.

3.3.2 Investigation of effects of harmonic distortions on the distribution transformer oil

Test samples of oil from the transformers harmonic distortion levels were measured (logged). This involved opening of distribution transformer oil drainage tap, which is ordinarily permanently sealed (to prevent oil siphoning by vandals) and some via temperature gauge pipe, depending on flexibility to access the oil test samples. The test samples were packed in glass containers as shown in Figure 3.7 and tightly sealed to prevent external contamination. The considered transformers cooling mechanism is based on natural oil natural air-cooling system (i.e., Oil Natural Air Natural (ONAN) cooling method) without oil conservator as depicted in Figure 3.8.

Figure 3.7: Samples of transformer oil in a well labelled and tightly sealed glass containers

The oil BDV analysis was carried out at Kenya Power Company Isiolo road high voltage laboratory, one of the reputable high voltage laboratories in Kenya.

Figure 3.8: Oil natural air natural (ONAN) transformer cooling method

3.3.3 Investigation of effects of harmonic distortion on distribution transformer failure rate

For a duration of one year, the data of all the failed distribution transformers installed in one of the regions that constitutes four counties (A, B, C and D) was obtained. The reasons for selecting this region for data collection on the failure of distribution transformers were;

i. The transformers' failure data was readily available
ii. It was easier to classify the nature of loads the transformer was supplying before failing as the author was conversant with the region setups than any other region as segmented by the power operator
iii. Some of failed transformers could easily be identified in storage yard for further analysis, if there was a need, as the region was at vicinity of transformers singled out for harmonic distortions data collection

3.3.4 Analysis of harmonic distortions effects on distribution transformer LV side, oil and transformer failure rate

Based on data collected on the three distinct cases at the distribution transformer, i.e., harmonic levels at the low voltage side of distribution transformer, transformer oil and transformer failure rate, analysis was carried out as detailed in subsequent subsections.

(a) Analysis of harmonics distortions levels at low voltage side of the transformers

The analysis of the harmonics data gathered at LV side of the distribution transformers were analyzed using Advanced Microsoft Excel software. Based on data obtained using data logger, harmonics up to 9^{th} order harmonics were found to be sufficient to carry out analysis as higher harmonic orders were found to be insignificant in magnitudes (harmonic magnitude diminishes as frequencies increase). The data obtained was also time stamped to assist in establishing specific occurrences for both high and low harmonics. Time stamping also helped in determining harmonic distortion magnitude profile within a given week.

(b) Analysis of sampled distribution transformer oil as a result of harmonic distortions

Figure 3.9 shows the instruments used to analyze transformer oil's BDV and moisture content respectively. It is worth noting that there is no instrument available to identify the color of the oil, hence oil sample's color identification was analyzed by bare eyes observation.

The oil BDV values result were analyzed by computing the average of 10 samples measured by breakdown voltage machine as shown in equation (3.1):

$$Y = \sum_{j}^{N} x_j \tag{3.1}$$

Where; Y is the average of individual oil sample, x is BDV values obtained, $j = 1\ldots N$ and $N = 10$.

(a) (b)

Figure 3.9: Transformer oil test equipment; (a) BDV machine, (b) Oil moisture analyzer

(c) Analysis of Distribution transformers' failure rate resulting from harmonic distortions

Analysis of transformer failure rate data obtained from the selected region involved determining the estimated number of distribution transformers on LV network installed in each of the county for correlation between high current harmonic distortions streaming to the secondary side of distribution transformer and failure rate of distribution transformers. Transformer failure cause/s data was not available at the time of carrying out this study and therefore, an assumption was made that the causes of the transformer failure were similar in all counties and only varied based on specific residential load

3.4 Design and Simulation of a Single Phase Active Harmonic Filter based on SRF method and fuzzy logic controller

3.4.1 Design of single phase active harmonic filter

The design of the single-phase shunt AHF, using MATLAB-Simulink simulation for ameliorating high current harmonic pollution generated by nonlinear loads in domestic rural setup, involved: (i) determining of the voltage level supplying single phase at domestic power consumers, and (ii) the level of current harmonic distortions streaming from the nonlinear loads as obtained in simulated AHF. It is worth to mention that the orders of harmonic frequencies were not crucial while designing the active harmonic filter reason been that the active harmonic filter cancels the entire spectrum of harmonic distortions. In this work, shunt active harmonic filter topology was employed. The advantages of using shunt active harmonic filter compared to other types of active harmonic filters include:

i. Does not carry the full load current, and
ii. Is less expensive than series active harmonic filter types, which needs transformer for interfacing with the main circuit.

The basic components required to be designed and determined were namely; interfacing inductor and DC- link power storage (dc capacitor), fuzzy logic controller, hysteresis current loop controller and synchronous reference frame method for extracting compensation signal. There interconnection for aforementioned fundamental components of AHF are as depicted in Figure 3.10.

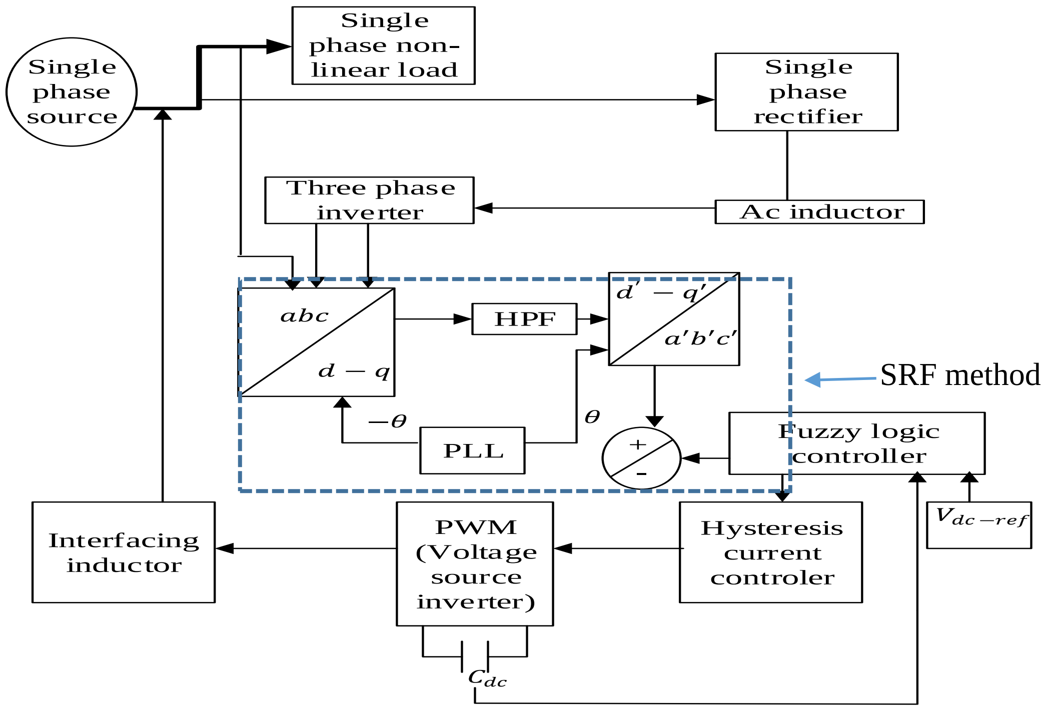


Figure 3.10: Main components for design of a single-phase active harmonic filter

3.4.2 Design of synchronous reference frame for extraction of AHF compensation signal

Signal extraction is an important function for proper operation of AHF. When there is an error in extraction of compensating signal, no available method can correct that error. In this regards, this work paid a great attention of ensuring that errors are eliminated during extraction of compensating signal. For this reason, the proposed AHF used synchronous reference frame as method of extracting compensation signal. The SRF has inherent benefits than other Time domain methods which include;

i. The reference currents are derived directly from the real load current without considering the source voltages
ii. The generated reference current is not affected by voltage imbalance
iii. It increases the compensation robustness and performance of AHF

iv. By use of fictitious signals, this method can be employed to realize a single-phase active power harmonic filter

The SRF involves transforming real currents into a synchronous reference frame. The reference frame is synchronized with the AC mains voltage and rotates at the same frequency (in this case 50 Hz). In this study, the author opted to focus on improvement of accuracy in extraction of the compensating signal to achieve high performance filter for single-phase active harmonic filter by use of synchronous direct- quadrature (d-q) frame method.

There are two types of synchronous $d-q$ frame; fundamental and harmonic frames. The basic philosophy of the synchronous frame is to transform signal in coordinates (stationary reference frame) into a direct- quadrature coordinates (rotating reference $a-b-c$ frame). Fundamental $d-q$ frame, for instance, the frame rotates with fundamental angular frequency making the fundamental currents to appear as dc components and the harmonics as ac signal. Figure 3.11 illustrates a three-phase $a-b-c$ stationary system transformed into a direct axis (d) and quadrature axis (q) rotating coordinate system (commonly known as Park transformation).

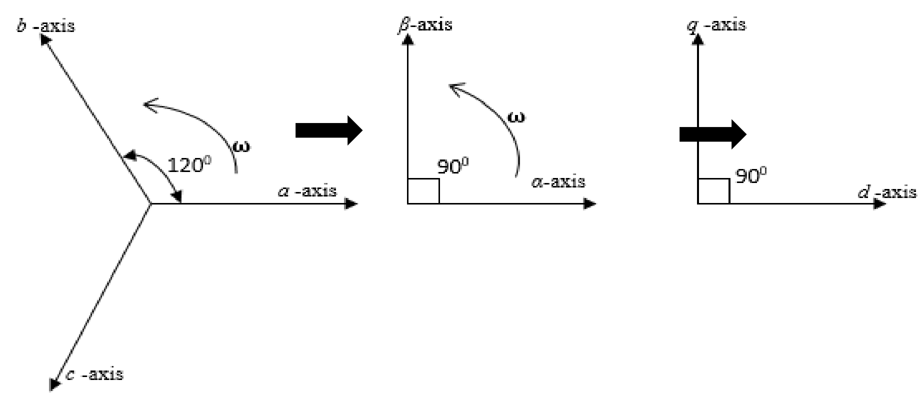


Figure 3.11: Park's transformation that transforms a three-phase *a-b-c* stationary system into a direct axis (*d*) and quadrature axis (*q*) rotating coordinate system

From the Figure, the axes *a*, *b*, and *c* are fixed on the same plane and are separated from each other by $\frac{2\pi}{3}$ radians (120^0). $\alpha - \beta$ are orthogonal axes with α – *axis* being synchronized with α – *axis* a, b, c of plane and the β- *axis* being orthogonal to α – *axis*.

Clarke transformation transforms (ɑ, ƀ, c) to real and imaginary currents as shown in equation (3.2). This transformation is important because it is in direct axis (d) and quadratic axis (q) rotating coordinate system the signal can effectively be controlled to get the desired reference signal. The real part of the space vector is equal to instantaneous value of the direct-axis current component, i_α and imaginary part is equal to quadrature- axis component, i_β. The Park Transformation realizes Clarke transformation currents from the stationary to the rotating reference frame. Derivation of the matrix elements are presented in Appendix 5; Clarke and Park transformation.

$$\begin{bmatrix} i^s{}_d \\ i^s{}_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.2}$$

The three phase currents for the proposed AHF are obtained by considering the single phase current supplying single phase load and two phases from conversion of a single phase to a three phase current using DC converter into a three phase inverter. The current $i^s{}_d$ and $i^s{}_q$ are transformed to synchronous rotating d^e - q^e frame by unit vector cos ω_e and sin ω_e using equation (3.3).

$$\begin{bmatrix} i^e{}_d \\ i^e{}_q \end{bmatrix} = \begin{bmatrix} \cos\omega_e & \sin\omega_e \\ -\sin\omega_e & \cos\omega_e \end{bmatrix} \begin{bmatrix} i^s{}_d \\ i^s{}_q \end{bmatrix} \tag{3.3}$$

Where; ω_e is the frequency for the harmonic order that needs to be isolated (example 150 Hz to isolate 3rd order harmonic) in *rad/s*.

The d^e - q^e reference frame components of ω_e appear as dc quantities and all other harmonics are transformed to ac quantities as in (3.4).

$$\begin{bmatrix} i^e{}_d \\ i^e{}_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d^e & \tilde{i}_d^e \\ \bar{i}_q^e & \tilde{i}_q^e \end{bmatrix} \quad (3.4)$$

Where; $\bar{i}_d^e$ (fundamental) and $\tilde{i}_d^e$ (distorted) represent the fundamental and harmonic components of the d- frame load current.

Using a high pass filter, the dc component is eliminated. The ac component of the current is transformed back to the stationary reference frame using equation (3.5).

$$\begin{bmatrix} i^{s'}{}_d \\ i^{s'}{}_q \end{bmatrix} = \begin{bmatrix} \cos\omega_e & \sin\omega_e \\ -\sin\omega_e & \cos\omega_e \end{bmatrix}^{-1} \begin{bmatrix} \tilde{i}_d^e \\ \tilde{i}_q^e \end{bmatrix} \quad 3.5$$

The reference current $i^{s'}{}_{d-ref}$ and $i^{s'}{}_{q-ref}$ are given by equation (3.6)

$$\begin{bmatrix} i^{s'}{}_{d-ref} \\ i^{s'}{}_{q-ref} \end{bmatrix} = \begin{bmatrix} \sin\omega_e & \cos\omega_e \\ -\cos\omega_e & \sin\omega_e \end{bmatrix} \begin{bmatrix} \tilde{i}_d^e \\ \tilde{i}_q^e \end{bmatrix} \quad (3.6)$$

The components from the stationary reference frame are transformed back to a three-phase reference frame (using Clarke transformation) by employing equation (3.7).

$$\begin{bmatrix} i'_a \\ i'_b \\ i'_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^{s'}_{d-ref} \\ i^{s'}_{q-ref} \end{bmatrix} \quad (3.7)$$

These extracted reference currents are utilized for the generation of switching pulses for the inverter.

Figure 3.12 illustrates the above transformation process.

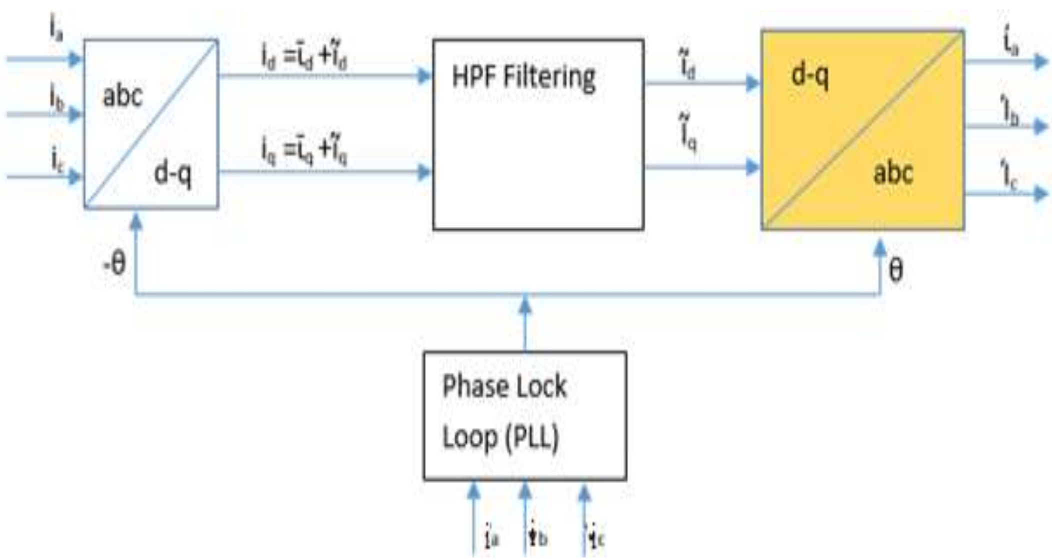


Figure 3.12: Clarke transformation that transform stationary reference frame back to a three- phase reference frame

Where; ө =2πf, and f = 50 Hz

From Figure 3.12, PLL generates the synchronous frequency that extracts the desired frequency. High pass filter (HPF) or low pass filter (LPF) is used depending on the frequencies to be eliminated. In the proposed filter, HPF is employed to isolate fundamental 50 Hz from the rest of the harmonic present within the network. The process of extracting only fundamental frequency is what is referred to as fundamental *d –q* frame otherwise is termed as synchronous frequency *d –q* frame. This implies that only the selected harmonic will be a dc signal while other frequencies including the fundamental will be ac signal. More details on SRF formulations are available in (Monfared, 2013) and (Musa, et al., 2017). The ac signal is removed using HPF. For proposed AHF, a cutoff frequency (ω_0) of 45 Hz was set in the filter design to filter out fundamental frequency (50 Hz).

3.4.3 Design of a FLC for DC- bus voltage regulation

To have a stable and insensitive AHF that can mitigate harmonic distortions on low voltage network that is characterized by a dynamic system, this study employed fuzzy logic controller to maintain dc- bus voltage within acceptable limit of ±5% of nominal capacitor voltage. The error (*e*) and rate of change in the error (Δe) form the inputs of fuzzy logic controller variables. A truncated triangular membership function, shown in Figure 3.13, was used due to inherent advantages such as simplicity, easy to implement and therefore the reason to be adopted in the proposed AHF. The arrangement shown in the Figure 3.13 ensures that all the possible values of (*e*) and (Δe) are considered. This results to minimum fuzzy rules as well as reducing computation time. In Figure 3.13, N is a Negative, Z is Zero and P is Positive.

The truncated trapezoidal membership function is defined by equation (*3.8*).

$$\mu_x = f(x) = \begin{cases} \left\{ Max\left(min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}, \right), 0 \right) \right\} \\ 0, \qquad\qquad\qquad\qquad Otherwise \end{cases} \tag{3.8}$$

Where; μ_x is the Fuzzy value.

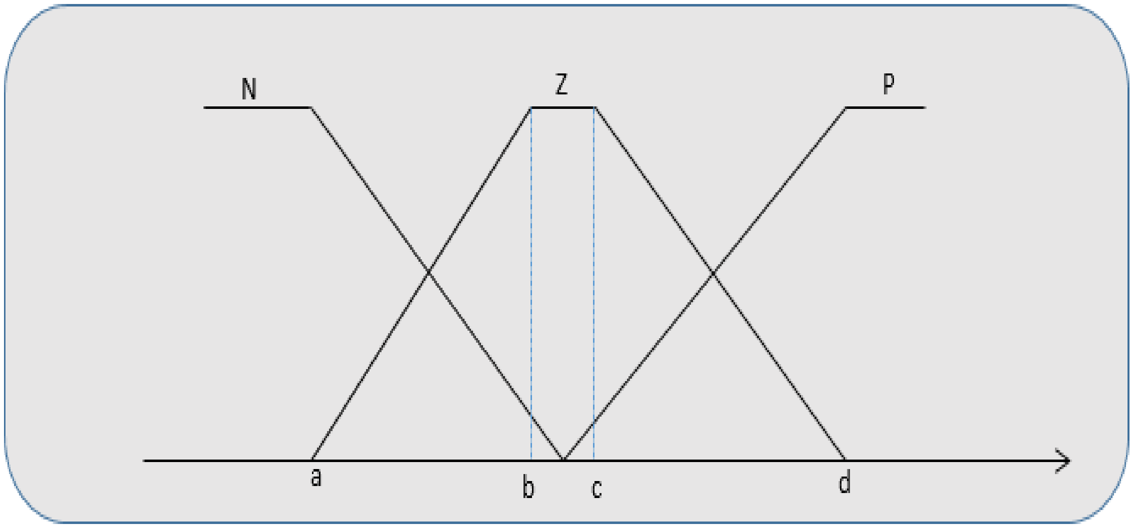


Figure 3.13: Truncated trapezoidal inputs membership function

The purpose of a fuzzy logic controller is to sustain, at the steady state, the real power supplied by the source to be equal to the real power demands of the load plus a small power to compensate the losses in the active harmonic filter PWM section. Under this condition, the DC-bus capacitor voltage is maintained at a reference value. However, when the load changes, the real power and the mains get disturbed. The DC-bus capacitor compensates for the difference between the supplied power and load power demand. If a small DC-bus capacitor voltage is less than the reference voltage, the real power supplied by the source will not be sufficient to supply the load power demand. To ensure that the DC-bus capacitor voltage remains fairly constant even after change of the load and due to transient, a fuzzy logic controller has been used to perform this duty. Since fuzzy control rules are derived from a heuristic knowledge of system behavior, neither precise mathematical modeling nor complex computations are needed as it applies in linear control techniques such as PI and PID. Further, this approach is potentially able to extend the control capability for dynamic conditions, where PI or PID do not gives satisfactory results, as fuzzy logic controller is capable of handling non-linearity and also is more robust.

A detailed block diagram of fuzzy logic controller (FLC) which is used to regulate the DC-bus capacitor voltage of the AHF is shown in Figure 3.14 while Figure 3.15 shows the flow chart specifying the algorithm followed in the design of the FLC for use with the AHF. Input variables of the fuzzy controller are capacitor voltage error **(*e*)** and rate change in voltage error (Δe).

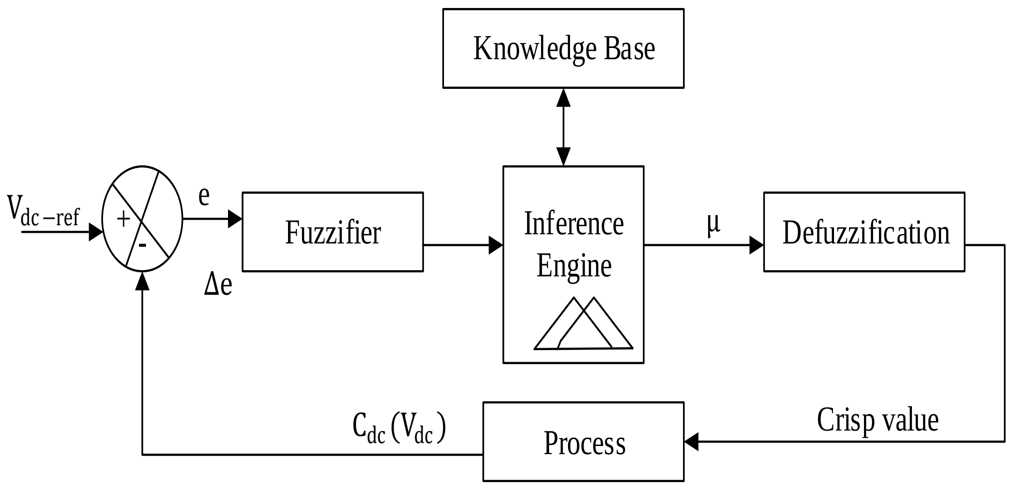


Figure 3.14. A block of fuzzy logic controller

The knowledge base with rules of the fuzzy logic controller contain linguistic words that define the output of fuzzy logic controller. The rules use the input membership values of each fuzzy variable as weighting factors to determine their influence on the fuzzy output set, task that is performed by inference engine.

In this AHF design, the fuzzy logic database rules used are shown in Table 3.4 where nine (9) rules, that described the relationship between the fuzzy inputs (error and rate of error) and fuzzy outputs, are defined. Few membership functions are selected based on the acceptable precision, that is, 'good enough' solution so as to reduce the complexity and in addition increase the speed of FLC. More rules imply high costs of implementation, less efficient and difficulty to fine tune the controller which involves adding/reducing fuzzy logic rules or altering membership function.

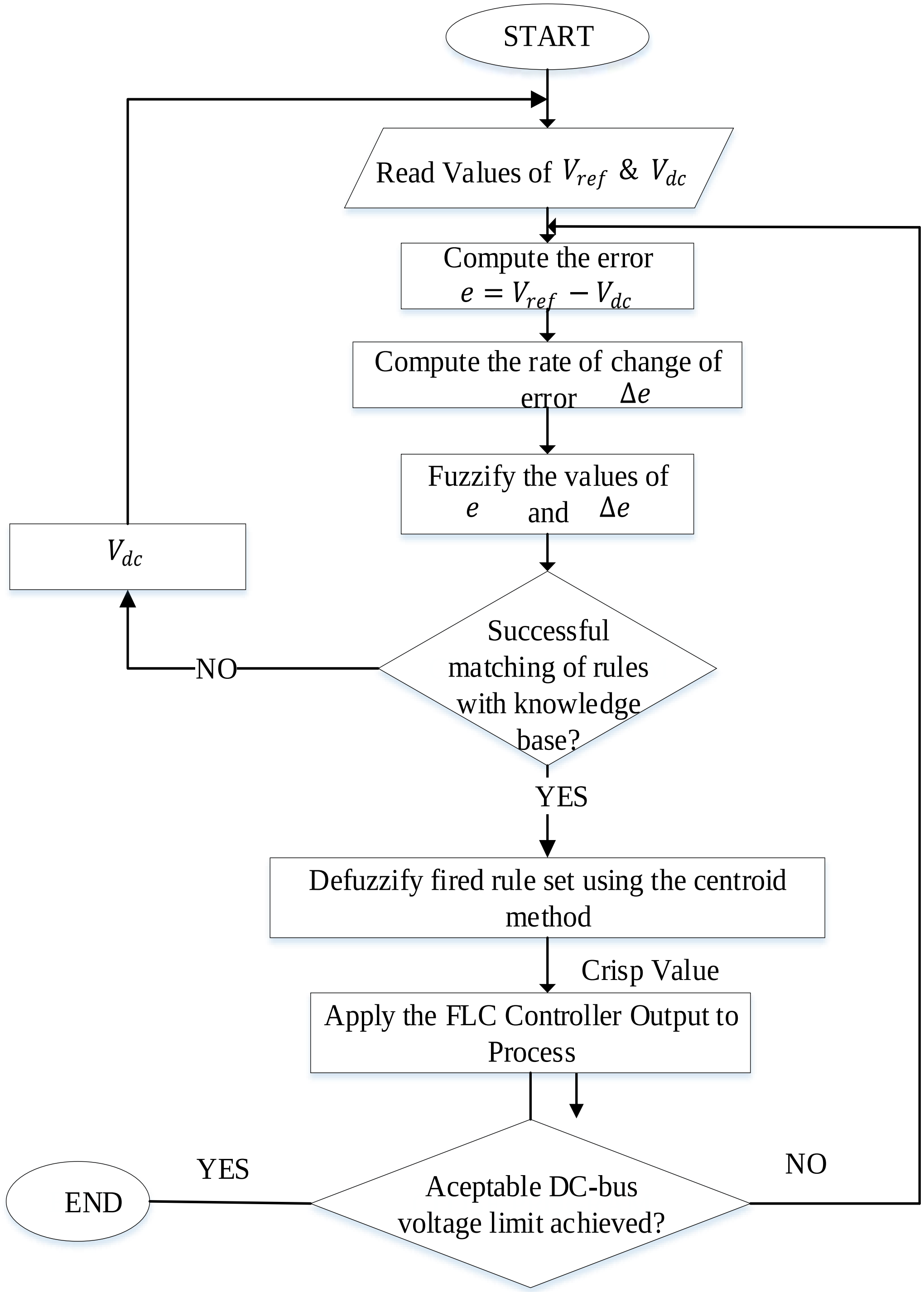


Figure 3.15: Flow chart for fuzzy logic controller

Below are the nine rules used in this FLC shown in Table 3.2.

1. If (error is N) and (rate of error is P) then (output is N)
2. If (error is N) and (rate of error is Z) then (output is Z)
3. If (error is N) and (rate of error is N) then (output is N)
4. If (error is Z) and (rate of error is P) then (output is Z)
5. If (error is Z) and (rate of error is Z) then (output is Z)
6. If (error is Z) and (rate of error is N) then (output is Z)
7. If (error is P) and (rate of error is P) then (output is P)
8. If (error is P) and (rate of error is Z) then (output is P)
9. If (error is P) and (rate of error is N) then (output is P)

Table 3.2: Fuzzy logic database control rules

Error / Rate of error change	Negative	Zero	Positive
Positive	**Decrease**	Zero	Increase
Zero	Zero	Zero	Increase
Negative	Decrease	Zero	Increase

For example, if the rate of error change is **Positive** that is, if the voltage across the DC-bus of VSI is higher than the reference voltage, and the error is **Negative**, then the FLC **Decreases (Negative)** the pulses of hysteresis loop controller and hence there is less power Watt loss across the VSI inverters. Consequently, the voltage across the DC-bus voltage increases to the reference voltage. This applies to the other rules within the fuzzy logic database shown in Table 3.2.

Figure 3.16 is FLC based voltage control scheme for generating switching pulses.

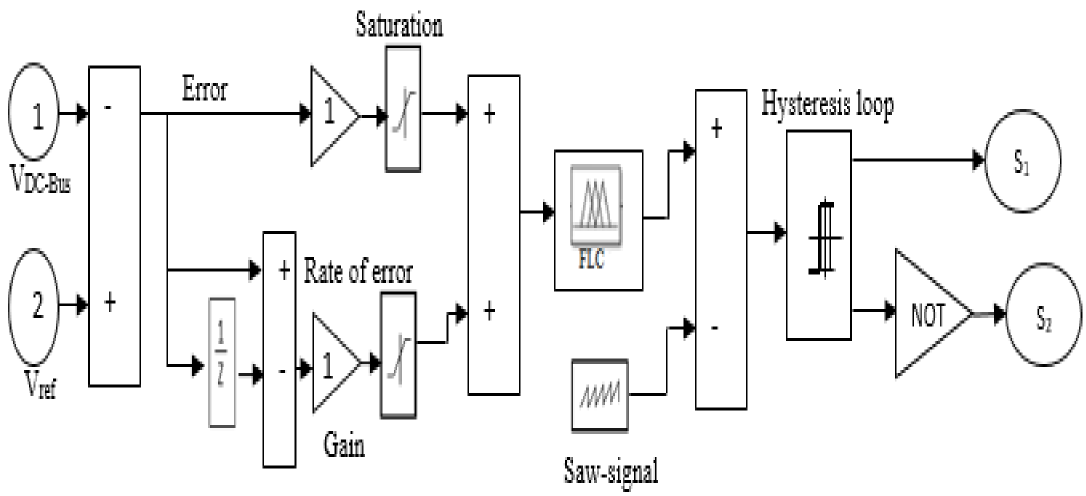


Figure 3.16: FLC based voltage control scheme for generating switching pulses

From the Figure, the rate of change of error is derived from the error signal and is determined by unit delay block on the control path. The error and change of error signals are scaled down by saturation block that enforces the upper and lower bounds on the signal. The result from the saturation blocks functions forms an input for the FLC. The output of FLC is employed in generating switching signals for VSI as detailed in 2.11.2(d) and 3.4.4(c).

To evaluate the antecedent, which involves fuzzification of inputs, Fuzzy operator AND (*min*) was used to get the consequent (commonly known as implication). This implies that if antecedent is true to some degree of membership function, then the consequent is also true to that same degree.

The logic product (AND operator) of each rule is combined or inferred before being passed on to the defuzzification process for crisp output generation as per the equation (3.6). After the evaluation of each antecedent in each rule, the resultant value of that

rule is implied for the consequent part of the rule by the selected operator. In this study, the center-of-gravity (centroid method) is employed as the defuzzification method to convert the fuzzy output back to crisp output. An off-line defuzzification, where the membership functions and fuzzy rules are prior determined before implementation of the control system, was employed in this design.

In this work, fuzzy logic controller is employed mainly due to its good dynamic responses under perturbation system. It was observed harmonic distortions level for low voltage network fluctuate drastically at domestic premises PCC. It is interesting to note that domestic power users keep on switching on and off their appliances (without any order/sequence). For instant, microwave is operated within a few minutes, a table room bulb is switched on, a kitchen bulb is switched off, water dispenser switched off and so on. At any given moment, only few different electrical appliances are powered on.

3.4.4 Determination of other fundamental components of proposed AHF

(a) AHF input signals conditioning

The proposed AHF, direct connection to sense both the voltage and current was opted. This is because the nominal AC voltage at domestic consumers' PCC is 240V and the domestic connected loads are of low ratings, hence the current drawn by the loads do not require any further conditioning i.e. scaling/stepping down to lower values.

(b) Mathematical modeling of interfacing inductor and dc- side capacitor (C_{dc})

(i) Interfacing inductor (*L*)

The main function of interfacing inductor (*L*) is to suppress the harmonics caused by the switching operations of VSI as well as acting as a buffer between the supply terminal voltage and PWM voltage generated by the shunt AHF. Furthermore, without interface inductor, it is not possible to connect a sinusoidal voltage supply to a non-sinusoidal output of the VSI. The inductor is also used to limit the magnitude of current spikes during commutation as it acts as commutation impedance, hence preventing the switching devices (IGBTs) from 'seeing' excessive rate of current change. Therefore, calculation of required *L* rating is paramount for proper operation of VSI, which translates to the performance of the active power filters. The aim is to reduce the ripples of the filter current (compensating current). If a small value *L* of is used, large switching ripples are injected into the supply current, while large value of does not allow proper tracking of the compensating currents to the desired values and also makes the active harmonic filter unnecessarily expensive and bulk. To determine maximum ac-link inductor, inductor differential equation (3.9) is used:

$$\frac{\partial i}{\partial t} = \frac{\Delta V}{L_F} \tag{3.9}$$

The maximum L_f selected should achieve the lowest average switching frequency. Further, the maximum $\frac{\partial i}{\partial t}$ of the load should be less than instantaneous $\frac{\partial if}{\partial t_{max}}$ generated by the AHF.

Considering a switching frequency f_c, the maximum $\frac{\partial i}{\partial t}$ of the current to be compensated and the ripple current Δi, the inductance value can be obtained by evaluating equation (3.10):

$$L_{max} = \frac{\Delta V_{max}}{4\Delta i_{fc}} \tag{3.10}$$

The maximum L_F for a system with a DC reference is obtained by evaluating equation (3.11).

$$L_F = \frac{\left(\frac{V_{dc}}{\sqrt{2}}\right) - \left(\frac{V_{ac}}{\sqrt{2}}\right)}{\sum_1^n (n * \omega * I_n)} \tag{3.11}$$

Where; I_n is the current of nth harmonic order, n is the harmonic order and w is angular velocity.

To obtain the correct rating of interfacing inductor, equation (3.10) was used because the deigned AHF contained a dc reference. The values of each parameter used are as follows:

V_{ac} = 230 V (Nominal single phase voltage), V_{dc} = 315 V (1.5 of nominal (230V)), and $n = 3, 5, 7, 9$ $\omega = 50$ Hz values of I_n were as shown in Table 3.3 (obtained from the designed AHF in MATLAB – Simulink environment).

Table 3.3: Harmonic order simulation currents (A) results

No	Harmonic order current	I_n	MATLAB Value (A)
1	3rd	I_3	0.094
2	5th	I_5	0. 069
3	7th	I_7	0.063
4	9th	I_9	0.035

Substituting each value in equation (3.10), resulted in. L_F = 0.18 mH

(ii) DC - side capacitor (C_{dc})

Due to active power losses associated with switching activities and conduction losses in gating devices, dc storage is required to compensate the power losses. For this reason, an energy–storage capacitor is used for this purpose. The energy–storage capacitor value computed (selected) should be sufficient to compensate for power losses in AHF. Using the energy–balance concept, the capacitor values of the load current are given by the equations (3.12) to (3.14):

$$\frac{1}{2}C_{dc}\left(V^2{}_{dc} - V^2{}_{dc-ref}(t)\right) = \Delta EC(t) = \frac{1}{2}V_{s-max}\Delta I_L T \quad (3.12)$$

The required energy –storage capacitor voltage value is obtained on the basis of the following two situations:

To increase the real fundamental component of the load current (C_{dc1}), equation (3.13) is used:

$$\frac{1}{2}C_{dc1}\left(V^2{}_{dc} - V^2{}_{dc,min}(t)\right) = \Delta EC(t) = \frac{1}{2}V_{s,max}\Delta I_{L1} T \quad (3.13)$$

Where; $V_{dc,\,min}$ is the pre-set lower limit of the energy storage capacitor voltage, $V_{s,max}$ is the maximum voltage of utility source, T is the period of the utility source and ΔI_{L1} is the change of load current (first step).

To reduce the real fundamental component of the load current (C_{dc2}), equation (3.14) is used:

$$\frac{1}{2}C_{dc2}\left(V^2{}_{dc,max} - V^2{}_{dc,ref}(t)\right) = \frac{1}{2}V_{s,max}\Delta I_{L2} T \quad (3.14)$$

Where; $V_{dc,max}$ is the pre-set upper limit of the energy storage capacitor voltage.

In this study, equation (3.13) is used to determine the value of C_{dc} to ensure that the dc-link of VSI is maintained at ±5% of the nominal voltage.

Substituting the following circuit parameter values in equation (3.13):

V_s = 230 V (single phase nominal AC voltage),

$V_{dc\text{-}ref}$ = 300 V (Pre- set lower limit of the storage capacitor voltage allowed),

$V_{s\text{-}dc}$ = 345 V (Pre- set upper limit of the storage capacitor voltage, which is 1.5 times V_s),

T = 0.02 s (one waveform cycle time (50 Hz)), and

$\Delta I_L = 0.378\text{ A}$ (obtained from MATLAB-Simulink simulation)

The required capacitor size for DC-bus voltage = 0.06 mF**.**

The capacitor voltage rating 400 V of was used due to the fact that the maximum voltage across the capacitor was expected to be maintained at 345 V by the proposed fuzzy logic controller (FLC).

(c) Internal controller loop adopted method

The hysteresis loop controller is used to generate the switching signals for the IGBTs. The IGBTs were adopted due to their inherent low power losses and relatively high frequency switching capability. High frequency switching capability of IGBT implies ability of the filter to cancel high harmonic distortion orders and hence mitigation of wide range of harmonic spectrum. Internal control loop has two outputs i.e. S_1 and S_2. The S_2 is negated from S_1 by use of NOT operator as shown in Figure 3.16.

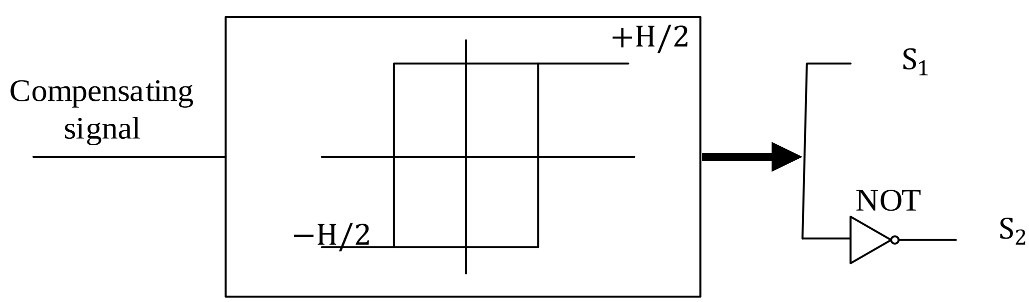


Figure 3.16: Hysteresis controller for gate signal of voltage source inverter

The two signals are connected to a pair of IGBTs of voltage source inverter (VSI) that generates the cancellation harmonic distortions signal that has opposite sign of the harmonic distortions generated by nonlinear single phase load(s). The switching logics are as follows:

If reference signal < (½H) upper switch is OFF (S_1) and lower switch is ON (S_2)

If reference signal > (½H) upper switch is ON and lower switch is OFF

To reduce glitches (noises), a buffer was added at the output of S_1 and S_2.

(d) Active harmonic filter parameter ratings

Table 3.4 shows the value of each parameter used in design of the proposed single phase shunt AHF. The ratings indicated in Table 3.4 (500 Watts and 150 Var) are for typical nonlinear loads found in many domestic dwellers such as TV, video players among others.

Table 3.4: Values/rating of parameters used during simulation

No	**Parameter**	**Value**
1	Resistive load	500 Watt
2	Capacitive load	150 Var
3	Inductive load	150 Var
4	VSI capacitor	0.06 mF
5	CSI inductor	0.05 H
6	Interfacing Inductor	0.18 mH
7	Fundamental frequency	50 Hz
8	AC voltage	230 V

3.4.5 Simulation using MATLAB-Simulink

(a) Simulation of SRF

To employ this technique in a single-phase system, which has a single signal, two additional signals were required. To realize the two additional required signals (fictitious signals), this study employed CSI and a three-phase inverter to generate the fictitious signals. The circuit diagram shown in Figure 3.17 is a MATLAB-Simulink block-sets used in generating the two fictitious signals.

From Figure 3.17, the following are worth noting;

1. A 2-level PWM generator provided the pulsing signal for universal IGBT bridge gate inputs.
2. A line inductor was used to block high frequencies from reaching the voltage ac source that are generated by universal IGBT bridge

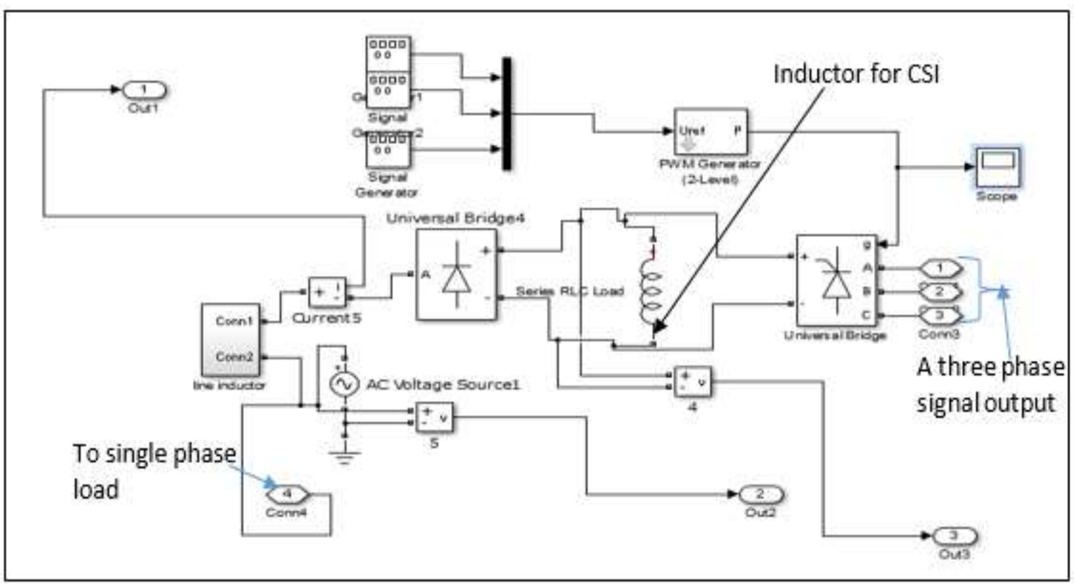


Figure 3.17: Generation of fictitious signal using MATLAB- Simulink block-set

iii. Only two (1 and 2) of the three phase signals were utilized from a 3 phase universal bridge to realize three phase signals for park transformation (the other signal was from single phase loads). The generation of three phases from a single phase supply is as illustrated in Figure 3.18.

iv. Terminal marked “conn4” supplies a single phase loads

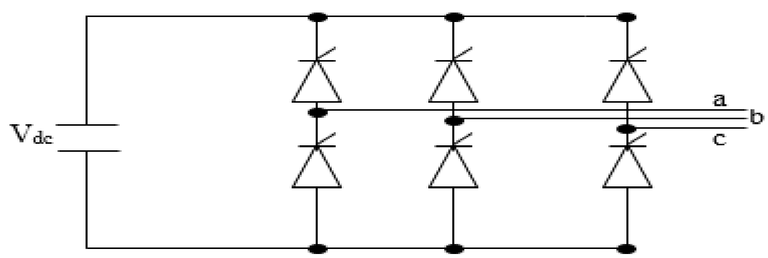


Figure 3.18: Generation of three phase from a single phase supply

(b) Simulation of FLC

i. Membership functions (MFs) for error input variables

The MFs for error input to FLC was as shown in Figure 3.19.

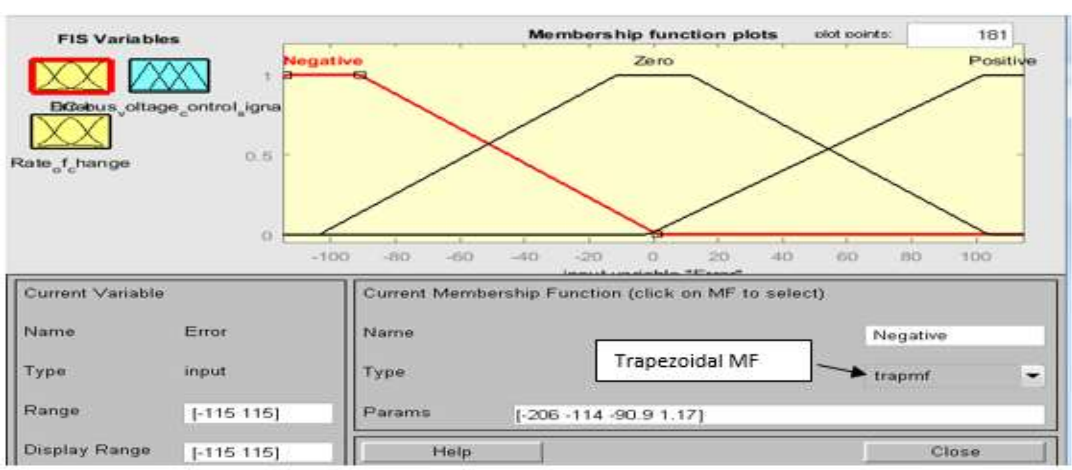


Figure 3.19: Membership functions for FLC Error input

From Figure 3.19, the universe of discourse (range) error is between -115 V to 115 V. The threshold voltage across the capacitor should be maintained at constant voltage of 345 V. A trapezoidal MF (truncated triangle curve) with Negative, Zero and Positive variables is used because of ease of implementation and wide range of point's coverage. Moreover, trapezoidal MF gives better results when there are significant dynamic variations within a short period of time.

ii. Membership functions for rate of change of error input variables

Figure 3.20 shows the mapping of MFs for the rate of change of error. The mapping is for the entire universe of discourse (range), which is between -50 to 50. Three MFs are used: Negative, Zero and Positive and they mapping in universe of discourse as shown in Figure 3.20.

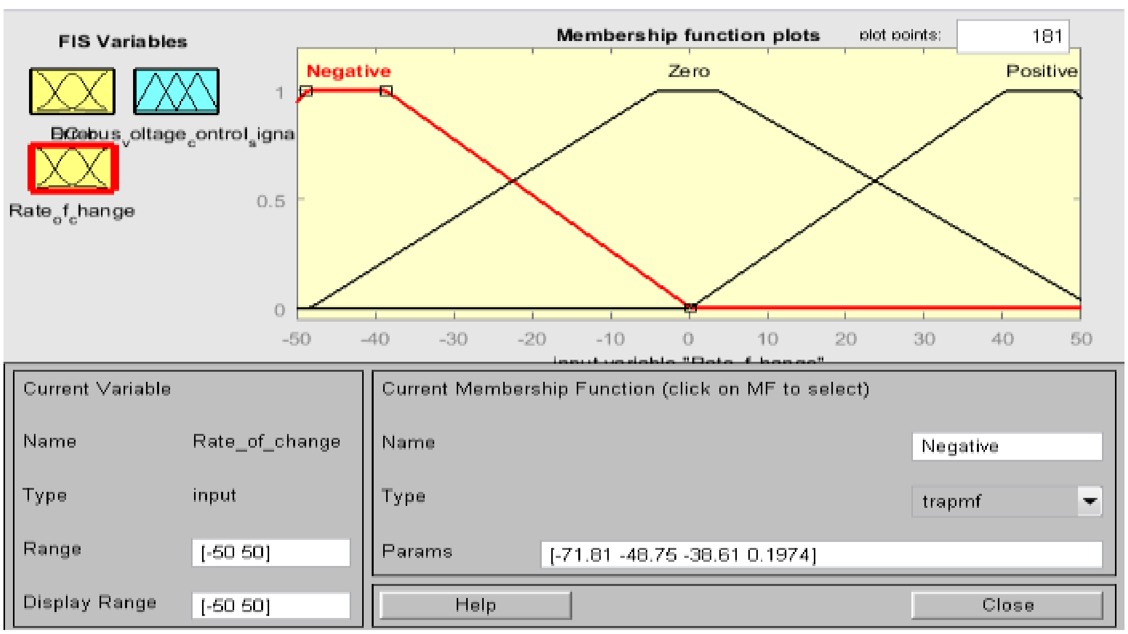


Figure 3.20: FLC map of MFs for the rate of change of error

iii. MFs for output fuzzy variables

The membership functions are as shown in Figure 3.21. The universe of discourse range between -10 to 10 as shown in the Figure. A trapezoidal MF is used for output fuzzy variables. Three linguistic fuzzy variables: Decrease, Zero and Increase are used and their mapping is as shown in Figure 3.21.

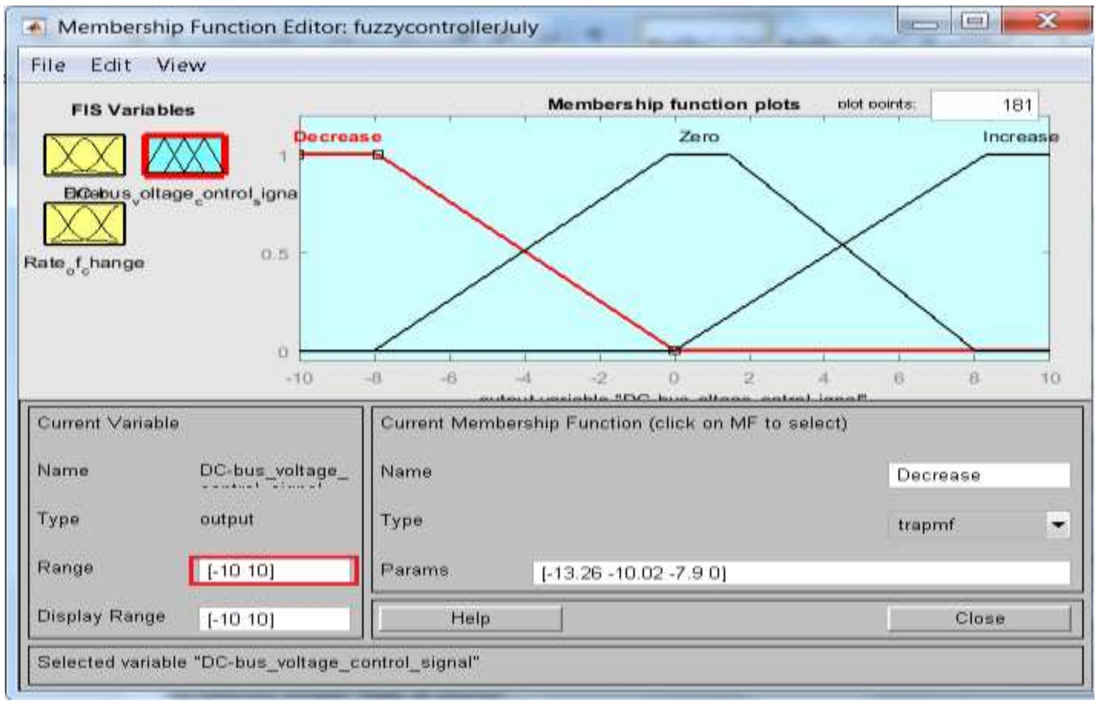


Figure 3.21: Trapezoidal MFs for Output fuzzy variables

iv. Fuzzy logic database rules

Figure 3.22 shows the nine rules of membership functions and implication (AND) method employed to realize the fuzzy logic control rules explained in Table 3.4.

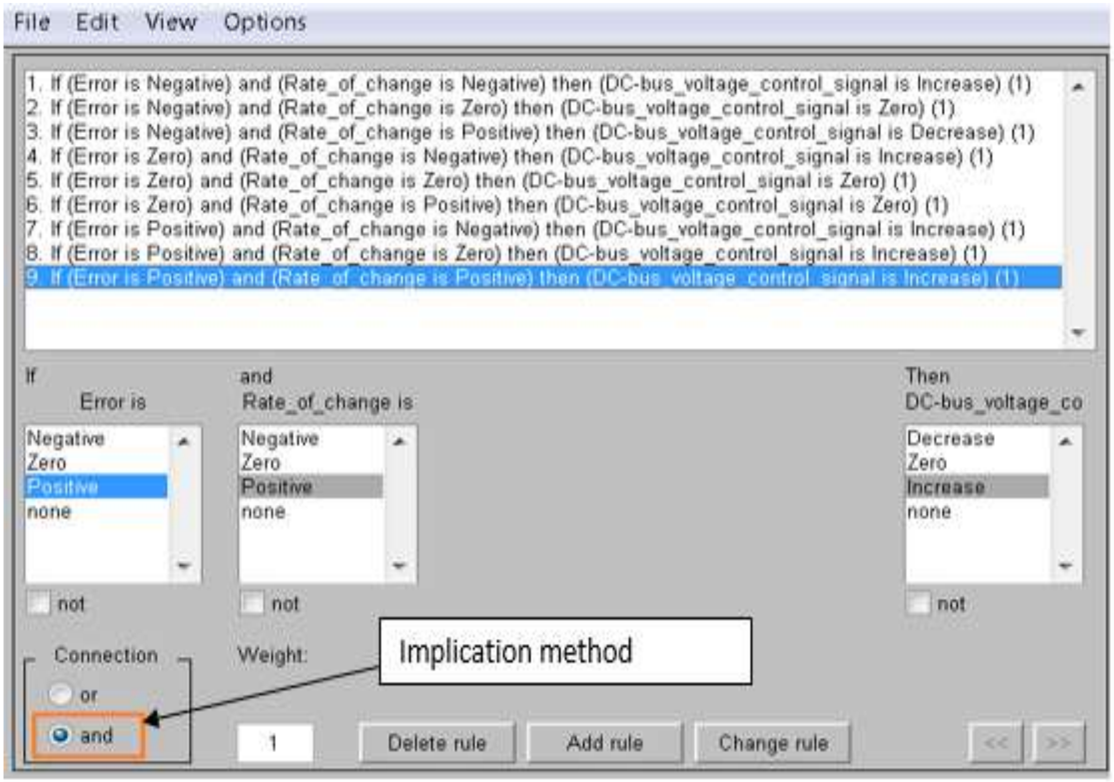


Figure 3.22: Membership function of nine (9) rules and implication method

v. Defuzzification

Defuzzification is the last process of fuzzy inference system (FIS). After fuzzy aggregation process, there is a fuzzy set for each output variable to be defuzzified by converting the fuzzy output back to crisp or classical output. Figure 3.23 shows the defuzzification process. The crisp value **2.19,** which is a **Positive** value, implies that the fuzzy logic controller needs to inhibit further decline of the voltage across the capacitor by decreasing pulses of the hysteresis gate signals of VSI. The error input to fuzzy logic controller was positive error (57.5) with minimal change of error.

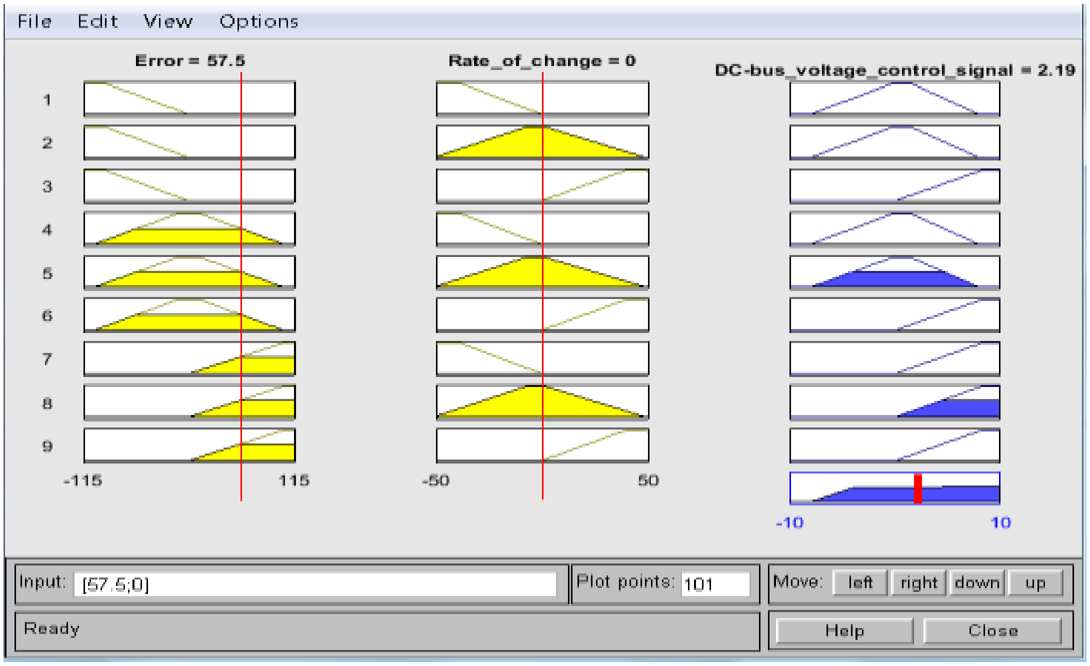


Figure 3.23: Defuzzification process using COG membership function rules

(c) Simulation of nonlinear and linear loads

The purpose of this simulation was to compare and analyze the THD_i obtained from single phase linear and nonlinear loads in a MATLAB-Simulink environment. Further, the resultant THD_i for combined (multiple) loads were also noted and analyzed. This was to confirm the field measured data that shown that nonlinear loads of similar electrical characteristics have additive current harmonic distortions and opposite have damping effect. The single-phase loads simulated in MATLAB-Simulink environment were; a nonlinear load with natural commutation devices (diodes), a nonlinear load with forced-commutation devices (IGBT) and a linear load (resistive).

3.5. Model Validation and Performance Evaluation of Proposed Active Harmonic Filter

The MATLAB- Simulink model was validated from the waveforms observed from various types of nonlinear loads (capacitive and inductive nonlinear loads) and linear load. Due to presence of harmonic distortions, the expected waveforms were distorted (non-sinusoidal) waveforms for nonlinear loads and sinusoidal waveform for a linear load. The performance evaluation of simulated AHF was by analysis of resultant waveforms, after AHF was connected, generated by different types of nonlinear loads and a linear load. Further, harmonic distortion levels obtained after connection of AHF are compared with the admissible (set) harmonic distortion limits recommended in IEEE 519-1992 international standard for power system network as well as a with another previous similar simulated AHF results obtained.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses results of analysis of the harmonics and power factor data measured at the domestic PCC for individual and combined domestic appliances. It further presents results of analysis of harmonics data collected at secondary side of distribution transformers and comparison of harmonics levels measured at LV side of distribution transformers with relevant power quality standards. Computed distribution transformers Watt-losses due to current harmonic distortions, BDV results from sampled transformer oil, and analysis of the number of failed distribution transformers data are also presented. Lastly, the chapter presents validation of the model and performance evaluation of the designed and simulated single phase active harmonic distortions filter.

4.2 Harmonic Distortions Levels and Power Factor for Individual and for Combined Domestic Loads

The harmonic distortions and power factor for individual and combined appliances were measured at point of common coupling (PCC) of a domestic consumer. The subsequent section gives the measurement results obtained.

4.2.1 Harmonic distortions and Pf characteristics for individual domestic loads

The results of harmonics and pf measured for individual domestic loads are as shown in Table 4.1. An equipment with lagging power factor is classified as an inductive load, while an equipment with leading power factor is classified as capacitive load. The data in Table 4.1 is further displayed graphically in Figure 4.1.

Table 4.1: Measured THD_i values and Pf for individual domestic loads

No.	Device	THD_i	P.F	Capacitive/ Inductive
1	Laptop	84.28	0.52 (Leading)	Capacitive
2	TV (Plasma)	74.35	0.52 (Leading)	Capacitive
3	TV Decoder	54.85	0.55 (Leading)	Capacitive
4	Video player	65.77	0.36 (Leading)	Capacitive
5	Energy saver bulb (A)	62.31	0.68 (Leading)	Capacitive
6	Energy saver bulb (B)	80.72	0.55 (Leading)	Capacitive
7	LED bulb	86.01	0.47 (Leading)	Capacitive
8	Phone Charger	50.54	0.36 (Leading)	Capacitive
9	CPU	35.75	0.45 (Leading)	Capacitive
10	Monitor	13.89	0.82 (Leading)	Capacitive
11	Dispenser	3.12	0.99 (Leading)	Capacitive
12	Radio	52.54	0.82 (Lagging)	Inductive
13	Microwave	36.08	0.9 (Lagging)	Inductive
14	Fridge	15.78	0.71 (Lagging)	Inductive
15	Fluorescent Tube (FT)	9.72	0.49 (Lagging)	Inductive
16	Water pump	3.41	0.98 (Lagging)	Inductive

Figure 4.1 shows the measured current harmonic distortions level and the power factor for each of domestic loads under investigation.

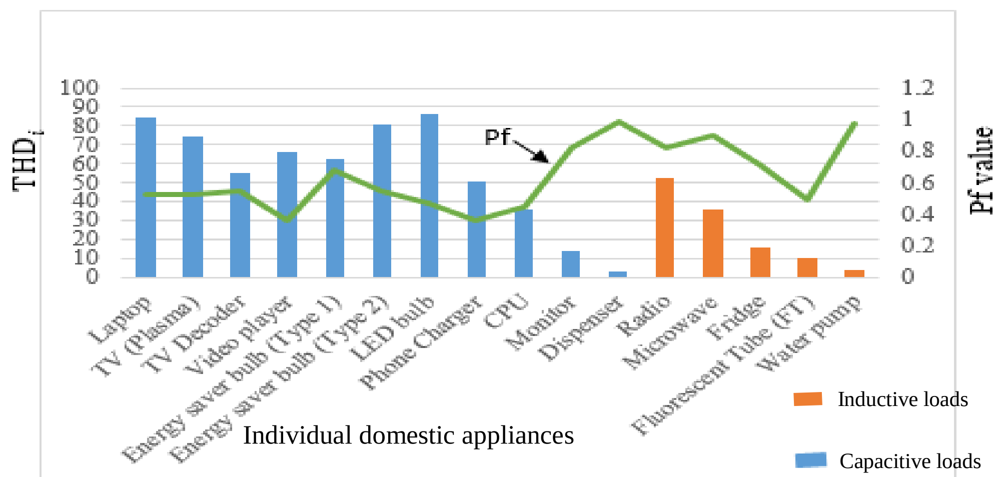


Figure 4.1: Results of harmonics levels and pf characteristics for individual domestic loads

From Figure 4.1, it is clearly seen that majority of the domestic appliances are capacitive nonlinear loads (approximately 70% of the domestic appliances under investigation). It is further observed that appliances with lagging pf (inductive loads) have a better pf than their counterpart capacitive loads. This implies that most of electronic devices, the smoothening capacitor for AC- DC power converter is over rated hence generates more reactive power than what is absorbed by low pass filter (series inductor), that is, $X_c >> X_L$ for AC- DC power converter for the most of domestic loads.

From Figure 4.1, it is observed that most of the residential loads are basically capacitive and nonlinear, hence, they generate substantial harmonic distortions which stream, via service line, to the low voltage distribution network. As result, the generated harmonics affect the installed equipment such as distribution transformers, feeder shunt capacitors and switching devices (circuit breakers and line auto closers).

4.2.2 Harmonics levels and power factor for combined (multiple) domestic loads

The harmonic distortions and power factor data measured for multiple domestic loads are shown in Table 4.2.

Table 4.2: Measured THD_i and Pf for multiple domestic loads

No.	Devices	THD_i	P.F	Capacitive/ Inductive
1	F.T + Water Pump +Fridge	10.52	0.84 (Lagging)	Inductive
2	Laptop +TV + V. player +TV Decoder	77.13	0.61 (Leading)	Capacitive
3	Energy saver + LED bulb + CPU +Monitor	38.94	0.86 (Leading)	Capacitive
4	Radio + Micro-wave +LED bulb +Laptop	34.04	0.91 (Lagging)	Inductive
5	E. Saver + FT +TV + LED bulb + V. player +TV- decoder	45.01	0.74 (Lagging)	Inductive
6	All devices with inductive pf	23.6	0.91 (Lagging)	Inductive
7	All devices with capacitive pf	16.61	0.98 (Leading)	Capacitive
8	CPU + Monitor	33.76	0.85 (Leading)	Capacitive
9	TV (Plasma) +Decoder	81.24	0.56 (Leading)	Capacitive
10	T.V plasma + Video player	77.36	0.61 (Leading)	Capacitive

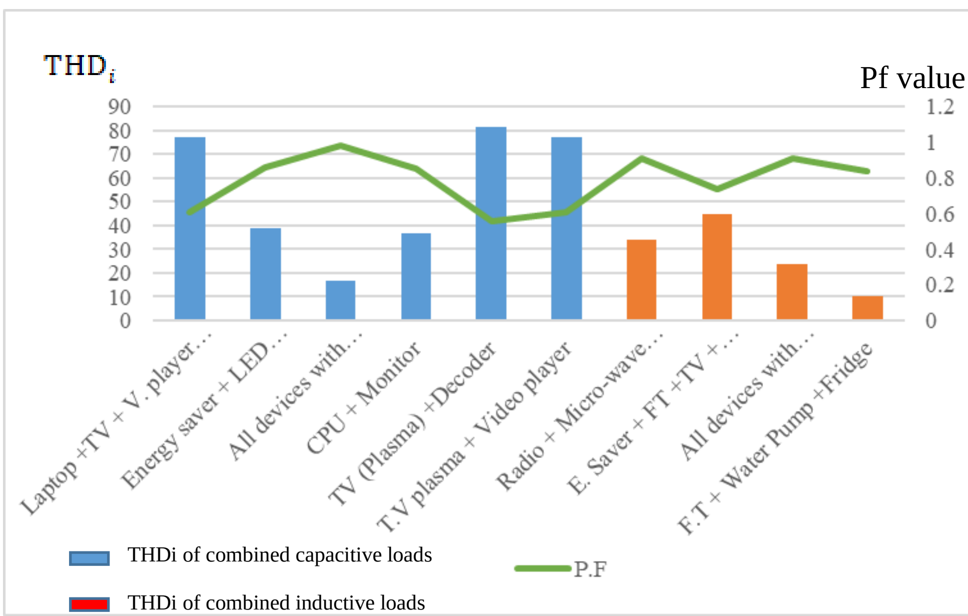


Figure 4.2 (a): Harmonic distortions levels and power factor for multiple (combined) domestic loads

Figure 4.2(a) represent harmonic distortions levels and power factor for multiple (combined) domestic loads. From Figure 4.2(a), it is noted that there is reduction in total harmonic distortions and a significant improvement on power factor with combined appliances compared with individual appliance as depicted in Figure 4.1. The effect is more amplified when a resistive linear load (for instance water dispenser) is combined with any nonlinear load. It is further observed that inductive loads with low harmonic distortions equally provide damping of harmonics. This is as expected due to the fact that resistive loads draw a sinusoidal current waveform, hence the resultant waveform tends to be a sinusoidal waveform. This also applies to a device or equipment with low harmonic distortions.

Figure 4.2(b) shows the effects of combining particular domestic loads on the harmonics and power factor. From Figure 4.2(b), it is observed that when nonlinear loads with similar electrical characteristics are combined, the effective harmonic distortion is amplified, while pf remains fairly constant. On the contrary, nonlinear loads with dissimilar electrical characteristics are found to attenuate the effective harmonic distortion and improve the power factor.

Based on the data analysis for the combined (multiple) domestic loads, it can be concluded that nonlinear loads with similar electrical characteristics when combined amplify the harmonic distortions and do have little improvement on effective pf. However, the opposite is noted for nonlinear loads with dissimilar electrical characteristics where it is observed to attenuate the harmonics and improve significantly the effective pf. This is because no phase shifting occurs when phase angle is almost equal. The phase shifting is one of the methods of mitigating harmonic distortions in power system as earlier shown in Table 2.1.

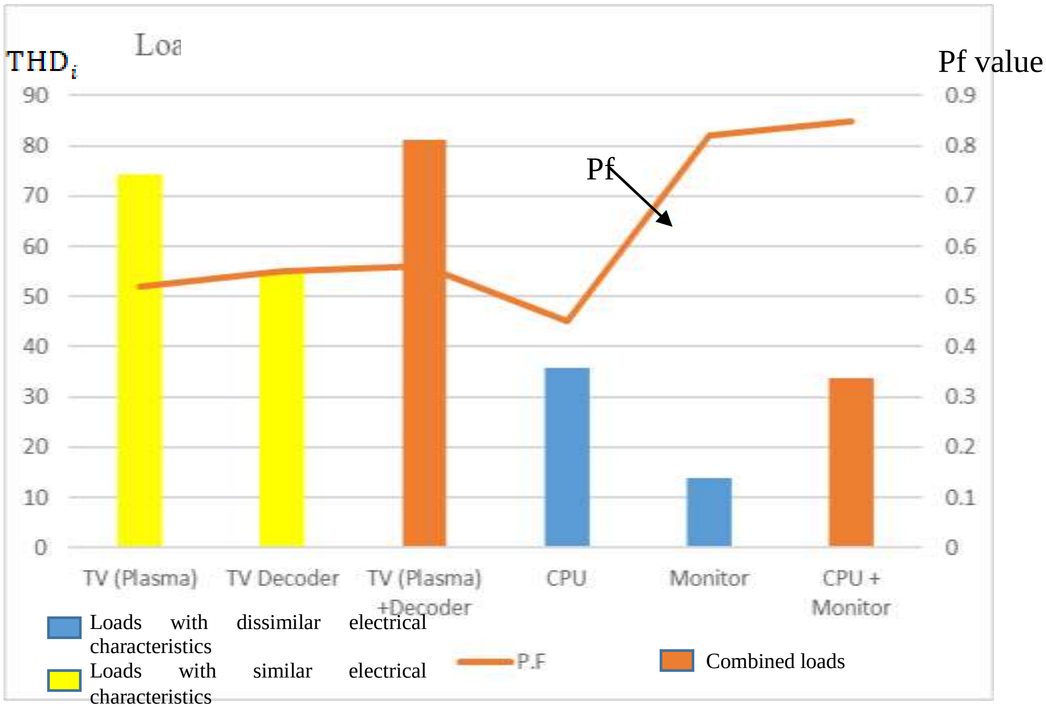


Figure 4.2(b): Harmonic distortions levels and power factor for similar and dissimilar electrical characteristics

Results shown in Figure 4.2 (b) clearly shows that a power distribution system with few installed domestic loads is likely to have high harmonic distortions streaming to secondary side of distribution transformers, mainly because of minimal harmonic cancellation that occurs due to few connected loads and also due to nonlinear loads of similar electrical characteristics. Based on this observation, it is possible to compensate for harmonic distortion through combination of various load types. However, it is difficult to influence consumer load combination and a more robust method to alleviate harmonics is required. To determine the effects of injected harmonics in distribution network, harmonic distortions levels were measured on LV side of sampled distribution transformers. The section hereunder presents the data obtained.

4.3 Effects of Harmonic distortions on Distribution Transformers Insulation, oil and transformer failure rate

The main objective for carrying out measurement of the harmonic distortions data on LV side of distribution transformers was to investigate the harmonic pollution levels at LV windings of the sampled distribution transformers. Further, to compare the harmonics measured with IEEE 519-1992 and IEC 61000-3-2 international standards. The current harmonics data obtained also enabled the computation of the total stray losses, also referred as Watt-losses, for each of the sampled transformer. This was necessary in order to determine the Watt- losses due to current harmonic distortions. Watt-losses are responsible for the elevation of the winding temperature of the transformer which is highly a nonlinear function governed by law of Arrhenius (Zynal, & Ala'a, 2012). That is, the higher the Watt-losses, the higher the ambient temperature of the windings that consequently result in high rate of insulation deterioration of transformer oil.

For the harmonics to affect the distribution transformers, the likely effects will be on the transformer windings or the transformer oil characteristics. Therefore, this research investigated the effects of the harmonic pollution on the transformer oil properties. To establish the effect of harmonic distortions on oil insulation degradation, distribution transformer oil from sampled live transformers was extracted and the BDV values, moisture contents, and oil colour were measured and determined. Lastly, the number of failed transformers from four counties that constitute the region of study of the utility power distribution operator was obtained for correlation to the failure rate of distribution transformers supplying domestic consumers in rural setups. Comparison was carried out with respect to distribution transformers supplying domestic consumers in urban setups.

4.3.1 Harmonic distortions levels on LV side of sampled distribution transformers

The harmonic distortions data measured at LV side of distribution transformers is shown in Table 4.3. A sample of the raw data of distribution transformers harmonic distortions downloaded from power quality analyzer is shown in Appendix 6. In this work, distribution transformers are grouped into three categories depending on type of consumer loads they supplies. These are namely; (i) commercial transformer supplying power to commercial consumers with high rated and high load factor loads, that is, loads that draw high current from the power system and operate for long period, for instant an induction motor, (ii) domestic consumers (urban setup) transformer that supplies power to domestic power end users with many low rated appliances and high load factor. Example of such domestic appliances are fridge, TV and so on, and (iii) domestic consumer (rural setup) transformer supplies domestic consumers with few low rated appliances and low load factor. An example of such domestic appliances are radio and mobile chargers. Table 4.3: Current harmonic order levels and total voltage harmonic dsitortions at secondary side of the sampled distribution transformers

Transformer installation	**Rating of distribution TX (kVA)**	THD_v	**Harmonics order current (A)**			
			3rd Harmonic	**5th Harmonic**	**7th Harmonic**	**9th Harmonic**
Commercial	200	2.38	5.1	2.4	2.3	1
Domestic consumers (urban setup)	100	5.8	2.08	0.66	0.48	0.26
Domestic consumers (Rural setup)	100	2.5	6.46	4.7	2.5	2.2

Figure 4.3 shows graphically the cumulative harmonic current (A) for each harmonic order at LV side of distribution transformers presented in Table 4.3.

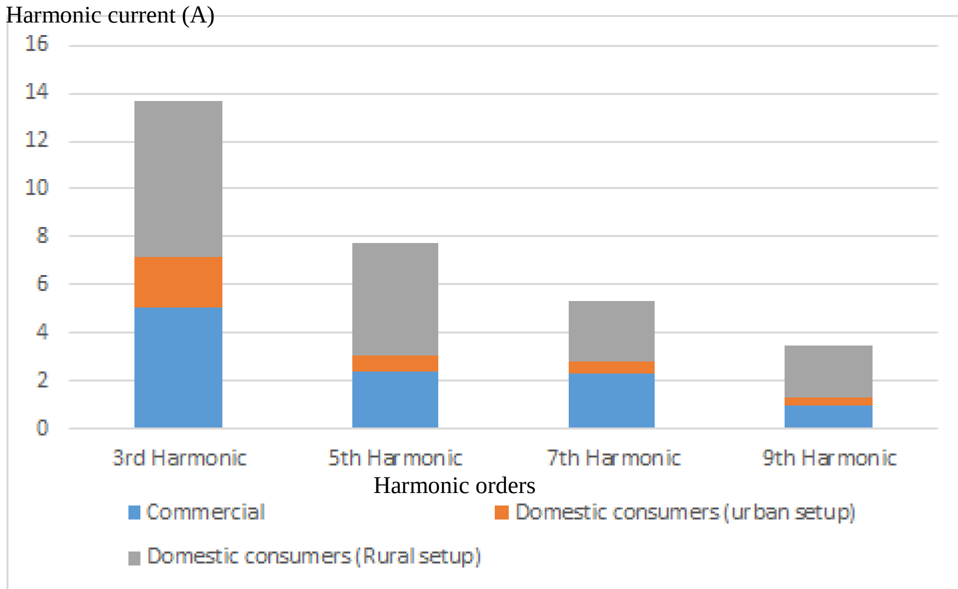


Figure 4.3: Current harmonic orders for sampled distribution transformers

From Figure 4.3, the followings are observed:

i. The individual current harmonic distortion levels diminish as harmonic order increases. This is as expected because harmonic orders follow the diminishing law (Bayliss, Bayliss, & Hardy, 2012)..

ii. The distribution transformer supplying predominantly few nonlinear and low rated loads or transformers installed in a domestic consumer (rural setup), where subsequent sections will be referred as rural setup, have the highest individual current harmonic distortions, while transformer supplying multiple nonlinear loads or transformers installed in a domestic consumer (urban setup), where subsequent sections will be referred as an urban setup, have the lowest current harmonic distortions. The results obtained were as expected due to the fact that in a rural setup there is minimal harmonic cancellation because of few installed loads whereas, in an urban setup there many connected loads and hence high attenuation of harmonic distortions due to load combination.

Figures 4.4(a) to 4.4 (c) show profile data of harmonic currents captured by PQA for duration of two weeks for 3rd, 5th and 7th harmonics orders. The other harmonic orders were noted to have insignificant current harmonics level, hence their effect was ignored.

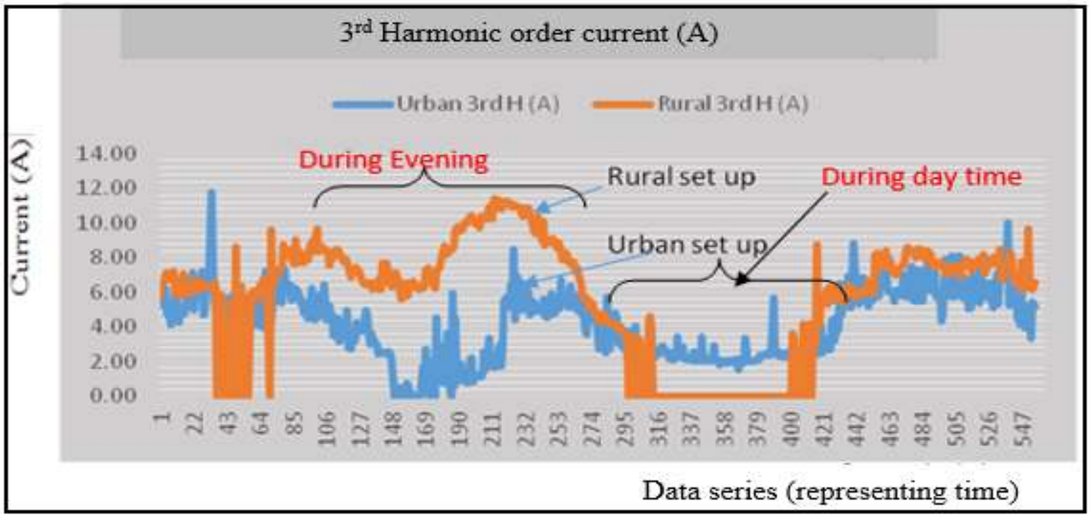


Figure 4.4 (a): 3rd Harmonic order current results obtained for duration of 2 weeks

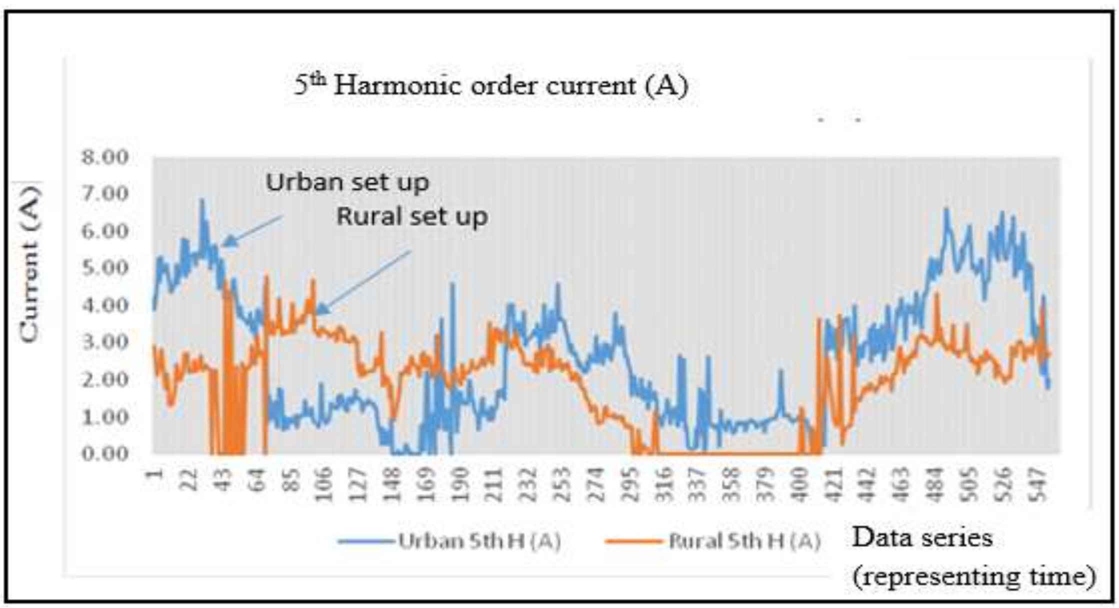


Figure 4.4(b): 5th Harmonic order current results obtained for duration of 2 weeks

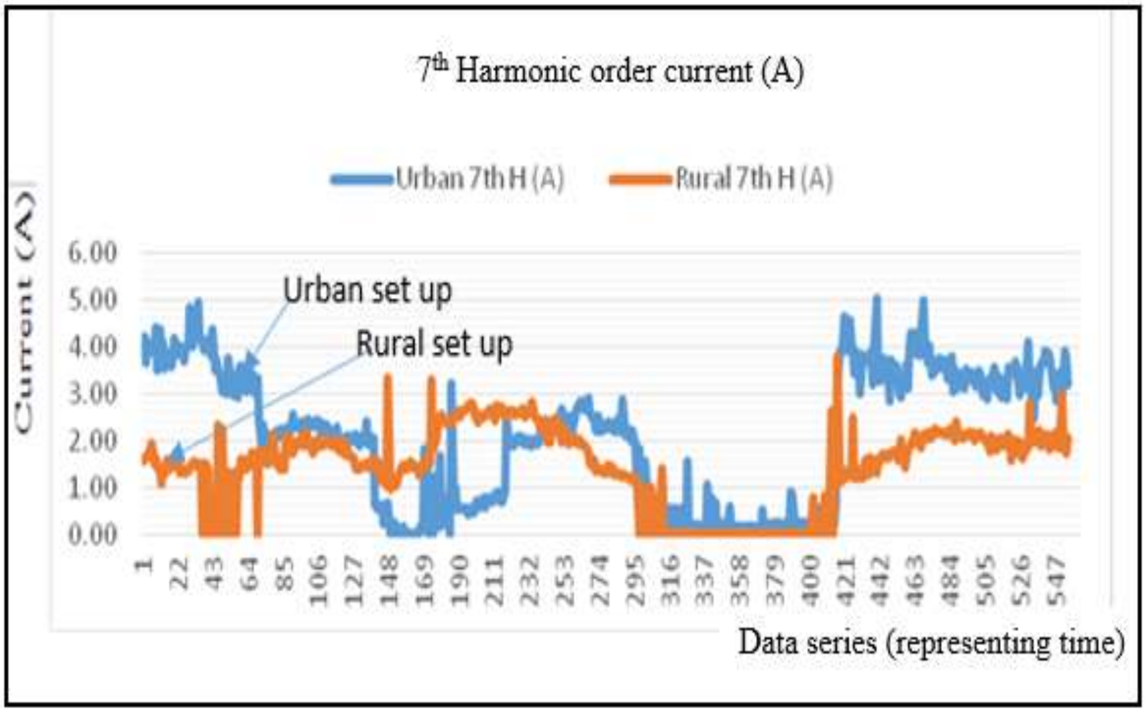


Figure 4.4(c): 7th Harmonic order current results obtained for duration of 2 weeks

From Figures 4.4(a) to 4.4(c), it is clearly seen that the level of current harmonic distortions depend on the time of the day. It is observed that the distribution transformer supplying power to domestic consumers in a rural setup have high current harmonic mostly at night (when the distribution lines are lightly loaded) as compared to the distribution transformer supplying power to domestic consumers in an urban setup. This can be explained by the fact that in most of rural setups of developing economies, there are few nonlinear loads such as security lighting devices and mobile chargers to mention a few of nonlinear loads that are connected as compared to urban setups where there are many nonlinear loads connected. It is also further observed that there are incidences when current harmonics are zero (from 10:00am to 12:00pm) for distribution transformer in a rural setup. This corresponds to the time when there were no loads connected.

From the harmonic distortions measured at secondary side of the distribution transformer, it can be inferred that distribution transformers supplying loads to domestic consumers in a rural setup are subjected to higher current harmonic distortions compared with transformers installed in urban and commercial setups. This is considered to be due to the fact that domestic power end users in rural setups usually have few domestic appliances that are normally individually powered, hence rarely do they have multiple (combination) loads supplied simultaneously. It is also observed that third harmonic current is higher for distribution transformer installed in a rural setup than one in an urban setup, which is presumed to be mainly due to the fact that single phase nonlinear loads that dominate rural setups are known to generate homopolar (odd harmonic orders multiple of 3) harmonic orders, where 3^{rd} harmonic order is predominant. From harmonics data obtained at secondary side of sampled transformers, it was important to compare results with relevant power quality standards to establish if the transformer harmonics levels are within the recommended and admissible harmonics limits. This study compared the harmonics results obtained with IEEE 519 and IEC 61000-3-2 standards, which are reputable and also enforced power quality standards by many power utilities and industries.

(a) IEEE 519 -1992 standard comparison

In this section, the field harmonics data is compared with the limits stipulated in IEEE 519-1992, a power quality international standard (see limits admissible in Appendix 2: Table 1a: Permissible harmonic current of nonlinear domestic equipment). Table 4.4 shows the computed values of percentage current harmonic level to maximum load current. The current harmonic distortions results obtained at secondary side of the distribution transformers shown in Table 4.3 are used.

Table 4.4: Computed THD_i and IEEE 519 levels recommendation

Type of setup TX is installed	Max. load current (A)	Harmonic orders' current	% current harmonic level to Max. load current (A)	Measured THD_v%
Domestic - Rural setup	75	8.64	11.53	2.5
Domestic- Urban setup	77	2.27	2.94	3.8
IEEE 519 standard recommended current and voltage in % respectively			15.0	5.0

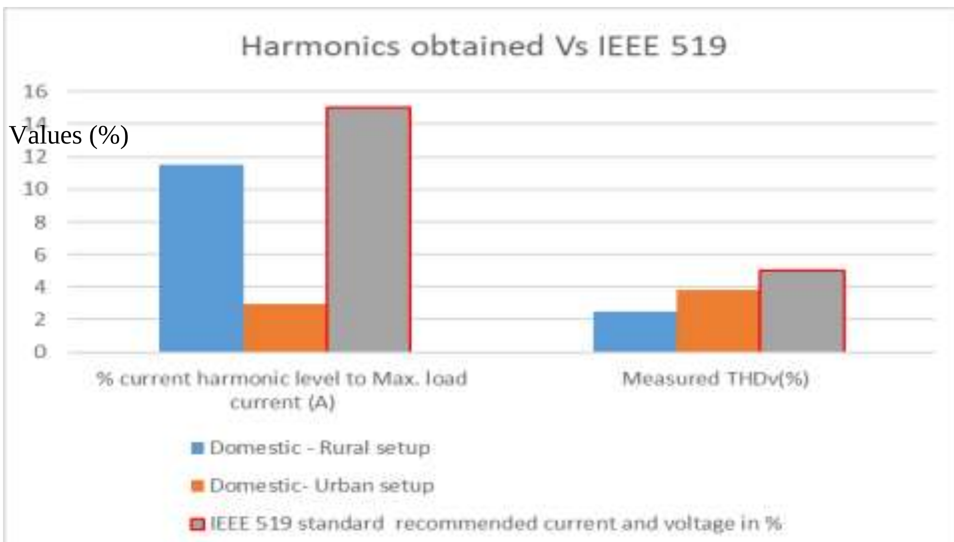


Figure 4.5: Harmonics levels at LV side of distribution transformers compared with IEEE 519 standard limits

Figure 4.5 shows results for the current harmonic distortions and voltage harmonic distortions at LV side of distribution transformers and comparison with admissible limits stipulated in IEEE 519 power quality standard.

From the results shown in Figure 4.5, voltage and current harmonic distortions are both found to be within admissible recommended limits stipulated in the IEEE 519 standard. However, in the distribution transformer supplying domestic consumers in a rural setup, the current harmonic distortions are noted to be almost four times higher than what is noted at the distribution transformer supplying nonlinear loads in an urban setup. It can be deduced that, transformers supplying rural setups are subjected to high harmonics pollution compared with other power consumer setups.

(b) IEC 61000-3-2 standard comparison

Table 4.5 shows the results obtained after computation of harmonic distortion results obtained at LV side of the distribution transformers and compared with the admissible levels stipulated in IEC 61000-3-2 standard.

Table 4.5: Results of harmonics levels at LV side of TX Vs IEC 61000-3-2 Permissible harmonic current % requirements

Transformer installed location	**Individual current harmonic orders as % to average transformer current loading**					**Average Transformer demand in kVA**	**Average Transformer current loading (A)**
	2nd	**3rd**	**5th**	**7th**	**9th**		
Commercial setups	1.73	2.93	1.38	1.32	0.58	124.8	173.83
Domestic - Urban setups	1.88	11.42	2.69	1.96	1.06	17.6	24.51
Domestic - Rural setups	13.23	30.51	22.2	11.81	10.39	15.2	21.17
IEC- 61000-2-3 Permissible harmonic current %	2	30*p.f= 27 (Pf = 0.9; Kenya grid code recommendation)	10	7	5	-	-

Figure 4.6 shows the comparison of the results of individual current harmonic orders as percentage of average transformer current loading with IEC 61000-3-2 limits. From the Figure, it is noted that the distribution transformer supplying few nonlinear loads, that is, supplying domestic consumers in a rural setup, the current harmonic distortion limits are noted to be above the permissible current harmonic distortion limits stipulated in IEC 61000-3-2 standard.

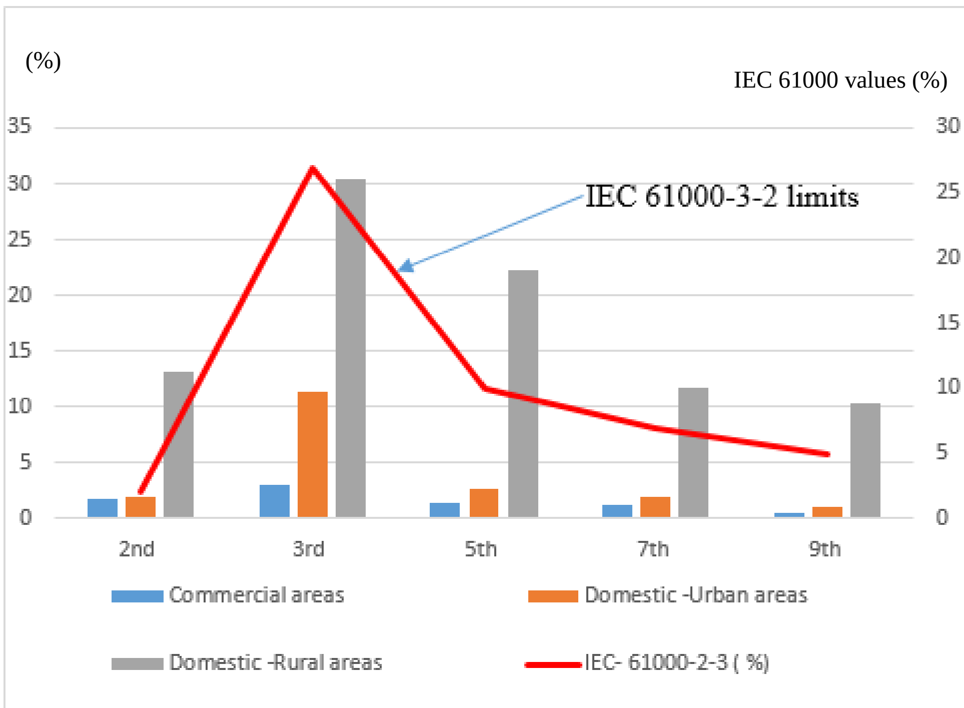


Figure 4.6: Harmonic distortions levels at LV side of transformers compared with IEC 61000-3-2 standard

For the harmonics limits to be well within acceptable limits defined in IEC 61000-3-2, there is needs to mitigate the harmonic distortions from the load source. Harmonics pollution are known to diminish the transformer windings insulation and transformer oil insulation properties. This work investigated the effect of harmonics on transformer oil insulation. Fast degradation of the transformer oil is mainly caused by ambient temperature that is above the expected limit within the transformer. It increases with

Watt-losses, that is, the higher the Watt-losses the higher the ambient temperature. To determine Watt-losses, computation of total stray losses was carried out. The results of Watt-losses obtained from the sampled transformers are shown and discussed hereafter.

(c) ***Computed total stray losses (Watt-losses) due to current harmonics measured at LV side of distribution transformers***

Table 4.6 shows computed Watt-losses using current harmonics orders measured at secondary side of the sampled distribution transformers as shown in Appendix 4.

Table: 4.6: Computed transformer Watt-losses from current harmonics orders of sampled distribution transformers

Nature of loads	**Individual current harmonic distortions**				P_{ec} **losses (W)**	P_{OSL} **losses (W)**	P_{TSL}**(W)**
	3rd	**5th**	**7th**	**9th**			
Domestic loads – Urban setup	16.42	4.59	4.76	2.3	28.07	18.2	46.27
Domestic loads – Rural setup	166.93	245.4	136.1	174	722.7	254.6	977.37

Where; P_{OSL} is the stray losses, P_{TSL} is the Total stray losses and, P_{ec} is the eddy current losses

Figure 4.7 shows the computed results of total stray losses. Based on the magnitude of the Wattage losses, it can be concluded that distribution transformers supplying domestic consumer loads in a rural setup dissipates more heat due to current harmonic distortions emanating from domestic appliances, as compared to distribution transformers supplying domestic consumer loads in an urban setup.

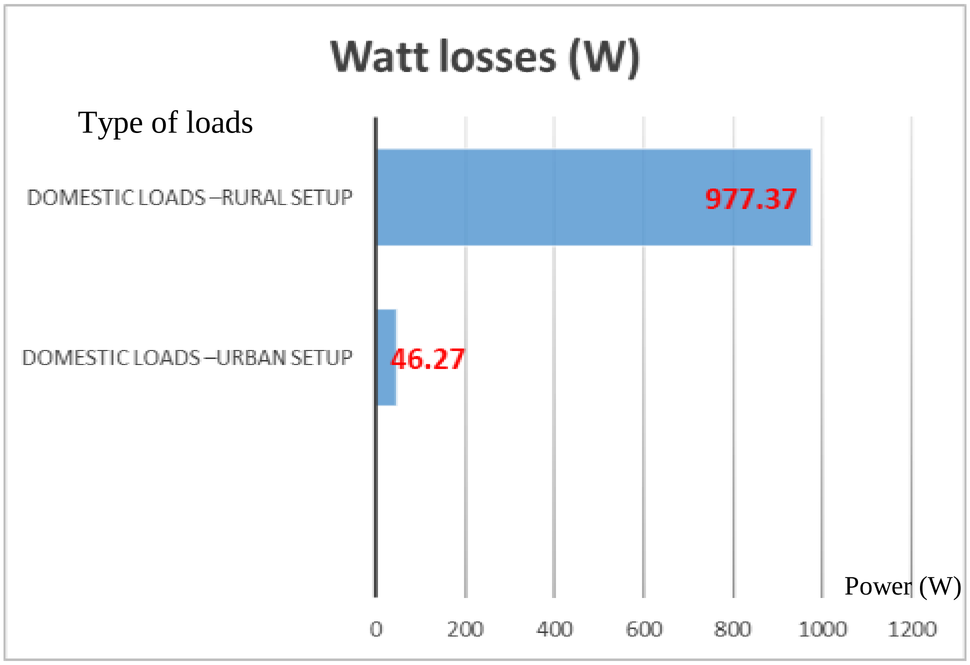


Figure 4.7: Computed total stray losses (P_{TSL} - losses) of sampled transformers

It can be concluded that distribution transformers supplying domestic power end users in rural setups dissipate more heat due to current harmonics streaming from nonlinear loads. Consequently, the high Watt-losses are expected to accelerate transformer oil deterioration resulting in early or premature transformer failure. The results obtained necessitated the measurement and analysis of the transformer oil characteristics. In this work, oil BDV, moisture content and oil color of sampled transformers were measured and determined. The selection criteria of the transformers whose oil has to be tested was guided by transformer dominant loads as well as the age of the transformer. The results obtained are shown and discussed in the next section.

4.3.2 Oil characteristics of sampled distribution transformer oil

The measured average BDV values, moisture content, and oil color obtained for each oil sample are shown in Table 4.7.

Table 4.7: Oil characteristics of the sampled transformers

Parameters under investigation	Nature of Distribution Transformer Loads			
	Loads at power substation	Loads at commercial setup	Loads at domestic- urban setup	Loads at domestic- rural setup
Oil Color	Brownish	Yellowish	Clear	Clear
BDV AVE (kV)	74	79.4	55.8	24.8
THD_i %	14.0	10.25	28.58	38.40
Moisture Content (ppm)	26.6	28.39	13.98	26.65

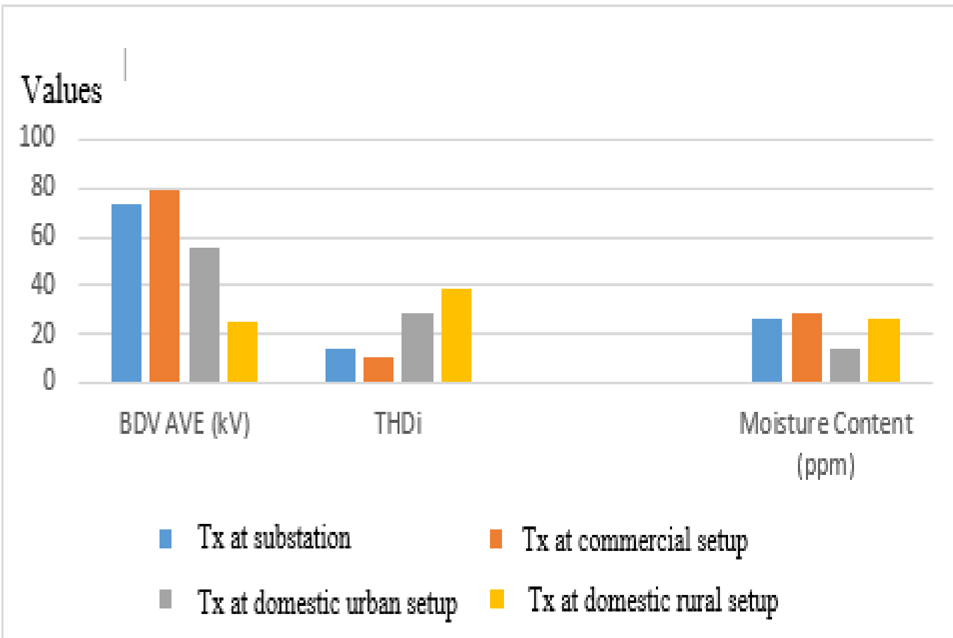


Figure 4.8: Oil BDV, THD_i and moisture content values for the sampled transformer oils

Figure 4.8 shows characteristics of transformer oil in terms of BDV values, moisture content values as well as color presented in Table 4.7. From Figure 4.8, it is seen that oil breakdown voltage (BDV) for the distribution transformer supplying loads in domestic rural setup is the lowest (24.8 kV). This observation correlates well with the expected, as the same sampled transformer was found to have highest current harmonic distortions (THD_i of 38.4%) as seen in subsection 4.3.1. The results obtained for a similar transformer supplying substation loads, which acted as control sample transformer, clearly asserts that the age of transformer has minimal influence on oil BDV value of a transformer. This points out clearly that there is a strong correlation of the harmonic level and the transformer oil deterioration, and further to the premature failure of the transformer. The recommended transformer oil BDV value should be greater than 30 kV to provide an adequate dielectric insulation of the transformer as per IEC 60354 (however, for new oil specifications the minimum oil BDV recommended is 50 kV. On the other hand, the recommended oil color is clear or yellowish. It can therefore be observed, that only the oil sampled at substation transformer was discolored beyond the recommended color. This can be attributed to the years the transformer has been in service, that is, more than 40 years (since 1978 to date).

The oil moisture content was also determined, where it was noted to be the highest for the transformer supplying commercial setup and lowest for the transformer supplying domestic urban setup. However, it is noted that the obtained moisture content levels for the sampled transformers were well within the limits of less than 35 ppm as per ASTM D6304 -20 standard. This implies that the sampled distribution transformers were well sealed, airtight and meet IP 54 requirements.

From the oil characteristics results obtained, it can be concluded that high current harmonics have adverse effects in the degradation of the dielectric strength of transformer oil. In other words, the deterioration of the oil characteristics (such as decrease in oil BDV) can be clearly be correlated to the presence of high magnitude of harmonics pollution. The low oil BDV results in premature failure of the transformers. Investigation and comparison of the number of failed transformers in one of the region of a power utility that constituted four counties was carried out. The results obtained are presented in the consequent section.

4.3.3 Results of the number of failed distribution transformers

The results of the number of failed distribution transformers data obtained from urban and rural setups in the sampled region are shown in Table 4.8.

Table 4.8: Number of failed distribution transformers in rural and urban setups

County	Installed Transformers		Failed Transformers		Urban setup installed Transformers	Rural setup installed Transformers
	Domestic users (Urban setup)	Domestic users (Rural setup)	Domestic users (Urban setup)	Domestic users (Rural setup)	Per 1000 failed	Per 1000 failed
A	9,944	7,001	80	136	8	19
B	113	46	7	8	62	174
C	59	51	3	2	51	39
D	91	53	6	4	66	75
Total	10,207	7,151	96	150	9	21

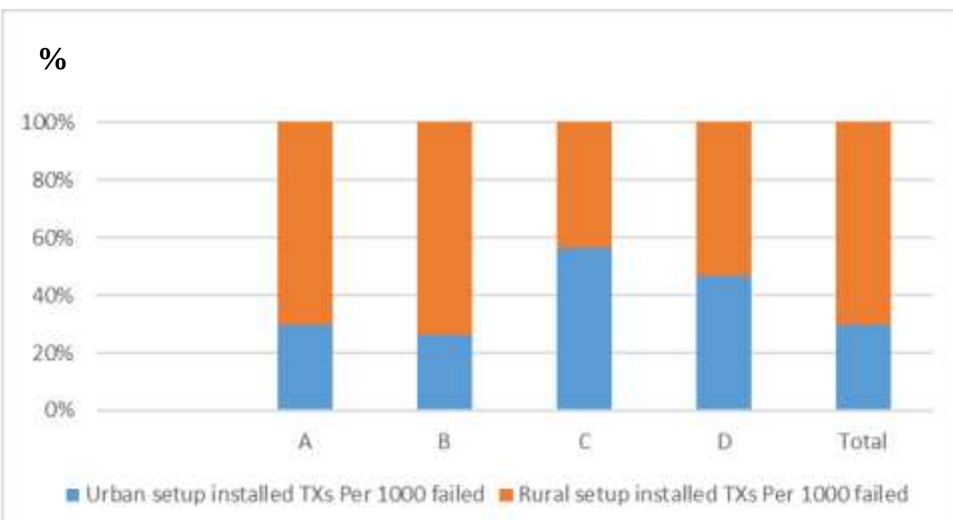


Figure 4.9: Percentage of failed distribution transformers in rural and urban setups

Where; A, B, C and D are counties that constitutes the region

Figure 4.9 shows the results of the number of failed distribution transformers in each of the four counties under study. From Figure 4.9, it is observed that the numbers of failed distribution transformers supplying domestic consumers in rural setups are higher than their counterpart in urban setups except in county C. This result was as expected because in county C the transformers are also serving several urban setups. This can mainly be attributed to high current harmonics in the distribution transformers supplying domestic power end users in rural setups, as is noted in earlier results (4.3.1). It can, therefore, be deduced that the distribution transformers supplying domestic consumers in the rural setups, which are characterized by few installed loads, causes high current harmonic distortions. The consequence of the high harmonics is fast deterioration of the dielectric strength of transformer oil, which is expected to results to early distribution transformer failure.

To reduce the failure rate due to high current harmonics in the distribution transformers especially in rural setups, this work proposed, modelled, and simulated a single-phase shunt AHF for use at point of common coupling of domestic power consumers. The proposed AHF was simulated using MATLAB-Simulink shown in Appendix 7. The results and discussion of the simulated AHF are illustrated in the next section.

4.4. Simulation Results for Designed Single Phase Shunt Active Harmonic Filter

The active harmonic filter is based on synchronous reference frame and also use of fuzzy logic controller for effective cancellation of the harmonic distortions emanating from single phase domestic nonlinear loads. It also ensures that the designed AHF is robust and efficient in both states of the power distribution system (steady and transient states).

4.4.1 Fictitious signals generation for synchronous reference frame

Figure 4.10 shows the simulation results of SRF, where two fictitious signals are generated by current source inverter (CSI) and the third signal is from a single-phase loads (whose harmonic distortions are to be filtered and cancelled). Two fictitious signals from CSI inverter are employed to realize three phase signals for Park transformation as earlier explained in the methodology. The third signal is the distorted signal that is generated by the single-phase nonlinear loads. It is notable that the proposed method achieved the desired results of generating the two fictitious signals for Park transformation as seen in the Figure 4.10.

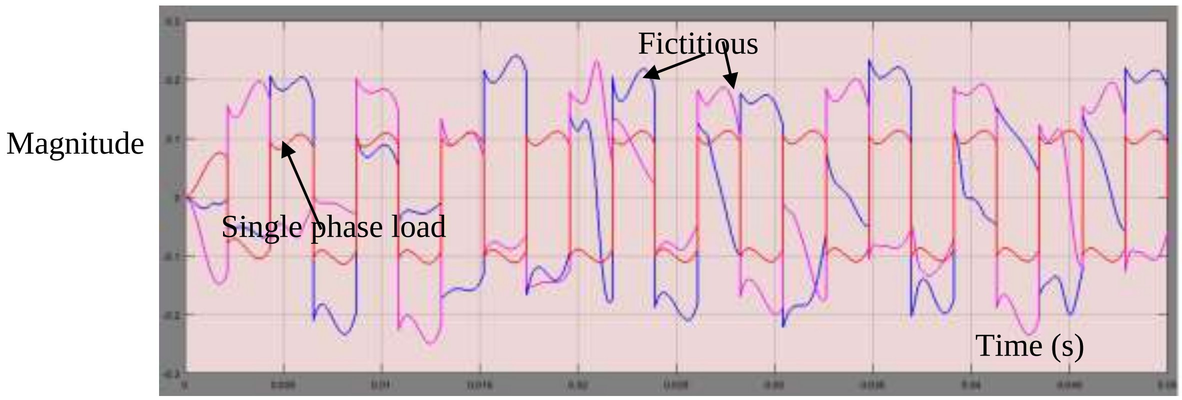


Figure 4.10: SRF simulation results for the input signals for Park transformation

4.4.2 Simulation results for Fuzzy Logic Controller

The FLC simulation results were expected to conform as per fuzzy logic control rules stipulated in Table 4.9.

Table 4.9: Fuzzy logic database control offline rules

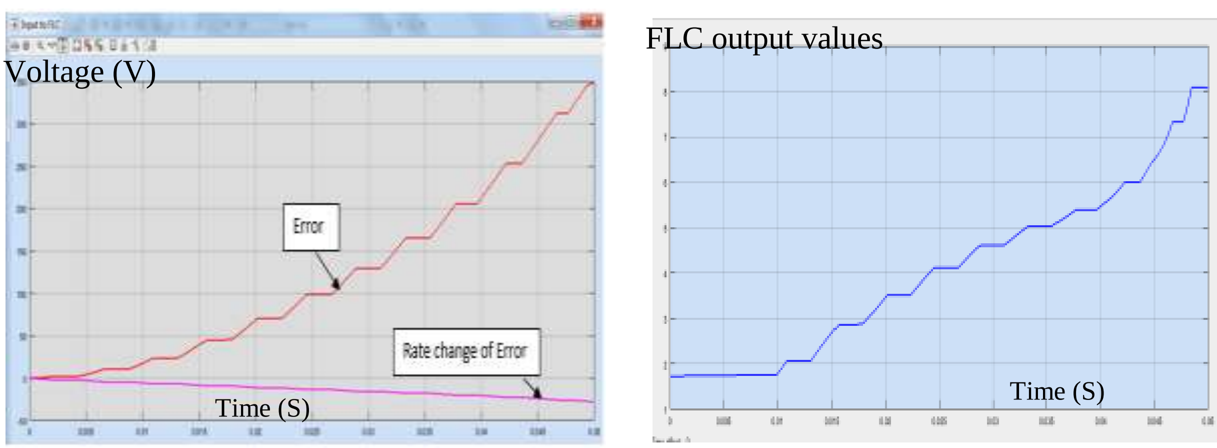
Error change \ Error	Negative	Zero	Positive
Positive	**Decrease**	Zero	Increase
Zero	Zero	Zero	Increase
Negative	Decrease	Zero	Increase

The subsequent section gives the outcomes and discussion of the simulation results of FLC.

(a) Fuzzy logic controller input and output signals

Figure 4.11 shows simulation results for fuzzy logic controller input and output signals. From Figure 4.11(a), error was 340 V (system voltage less DC-bus voltage) and rate of change of error of -45 V (derivative of DC-bus voltage) by end of simulation time of 0.05s. From Figure 4.11(a), the error is noted to rapidly increase positively, while the rate of the change of the error is found to decrease gradually. Consequently, the FLC output increases as per the FLC offline database control rules, that is, if the error is **Positive** and rate of change of error is **Negative**, the FLC output **Increases**. This is clearly seen in Figure 4.11(b). This implies, therefore, less losses that are associated with switching of gating devices. As a result, the DC- bus voltage across the capacitor is expected to be maintained fairly constant.

From the simulation results of FLC inputs and output, it can be concluded that the results are as expected. Thus, the proposed FLC is noted to perform as per fuzzy logic flow chart and as per offline fuzzy logic controller database control Table.



(a) (b)

Figure 4.11: FLC input and output signals; (a) Error and rate of change of error signals, and (b) Output of FLC

(b) Capacitor DC-bus voltage

The performance of the FLC is examined by its ability to maintain the capacitor DC- bus voltage fairly constant. Figure 4.12 shows the simulation result of the voltage across the DC-bus capacitor over the entire simulation period. It is clearly seen from Figure 4.12(a) that without FLC connected, at 0.02S simulation time, the capacitor voltage decreased to less than 1 V. However, with the connection of FLC, the voltage across the capacitor DC- bus is maintained fairly constant as seen in Figure 4.12(b).

It can be deduced that the proposed FLC maintained a constant DC-bus voltage across the capacitor of the VSI as desired.

After obtaining satisfactory results from modelled AHF, there is need to validate the model and also carry out performance evaluation of designed AHF. These are discussed hereunder.

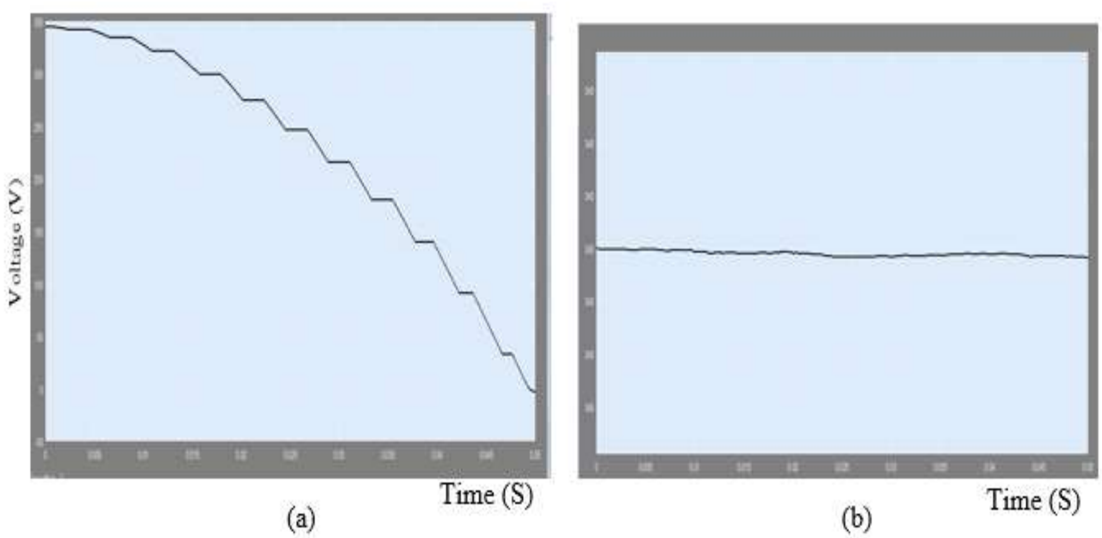


Figure 4.12: Capacitor DC-voltage: (a) without FLC connected, (b) with FLC connected

4.5 Validation and Performance Evaluation of the Designed Active Harmonic Filter

Validation of proposed AHF was meant to confirm whether the simulation results obtained from the designed AHF model conforms to the field data measured, that is, multiple loads with similar electrical characteristics magnify the current harmonics, and on the other hand dissimilar electrical characteristics nonlinear loads attenuate the harmonic distortions. This was realized by simulating individual and multiple loads. Further, validation was also done by analyzing the waveforms generated by various loads with and without designed AHF connected. Lastly, there was need to carryout performance evaluation of the proposed AHF. Simulation results obtained from the modelled AHF is evaluated by comparative analysis with IEEE 519-1992 standard as well as a comparative analysis with a similar previous designed single phase active harmonic filter.

4.5.1 Validation of harmonic distortions for individual and multiple (combined) loads

Table 4.10 shows the simulation results obtained for individual and multiple loads.

Table 4.10: Harmonics results for individual and multiple loads

Type of loads	THD_i (%)	Harmonic distortions order (A)			
		3rd	5th	7th	9th
A	89	7.8	1.4	0.48	0.33
A *3 (combining three similar loads)	57	12	2.1	0.73	0.54
B	35	-	-	-	-
Line Inductor with A	19	4.4	0.8	0.16	0.27
Combination of A and B	8.4	4.4	0.87	0.09	0.36
C	2	0.65	0.11	0.21	0.18

Where load type **A** is the nonlinear load (with natural commutation devices (diodes)), load type **B** is the nonlinear load (with forced-commutation devices (IGBT)) and load type **C** is the linear load (resistive).

Simulation results of THD_i and current harmonic for different single phase loads are presented hereunder.

(a) ***THD_i simulation results for different single phase loads***

Figure 4.13(a) shows THD_i results for various single phase loads presented in Table 4.9. From the Figure, it is observed that a linear load (type **C** load) generates least current harmonic distortions, while nonlinear load with natural commutation devices (type **A** load) generates highest current harmonic distortions. This is because nonlinear loads draw current in pulse form, while linear loads draw a sinusoidal current. Further, nonlinear loads with forced-commutation devices (type **B** load) are noted to have lower current total harmonic distortions as compared to natural commutation. This simulation outcome is as expected since forced –commutation devices are known to generate fewer harmonic distortions than the natural commutation devices. Furthermore, the modern electronic equipment has low harmonic levels due to the fact that the front-end rectifier employs forced-commutation (pulse width modulated) devices such as IGBTs, MOSFET, GTO and IEGT (Injected-Enhanced Gate Transistor) rather than natural commutated devices, that is, diodes or thyristors for AC-DC power conversion.

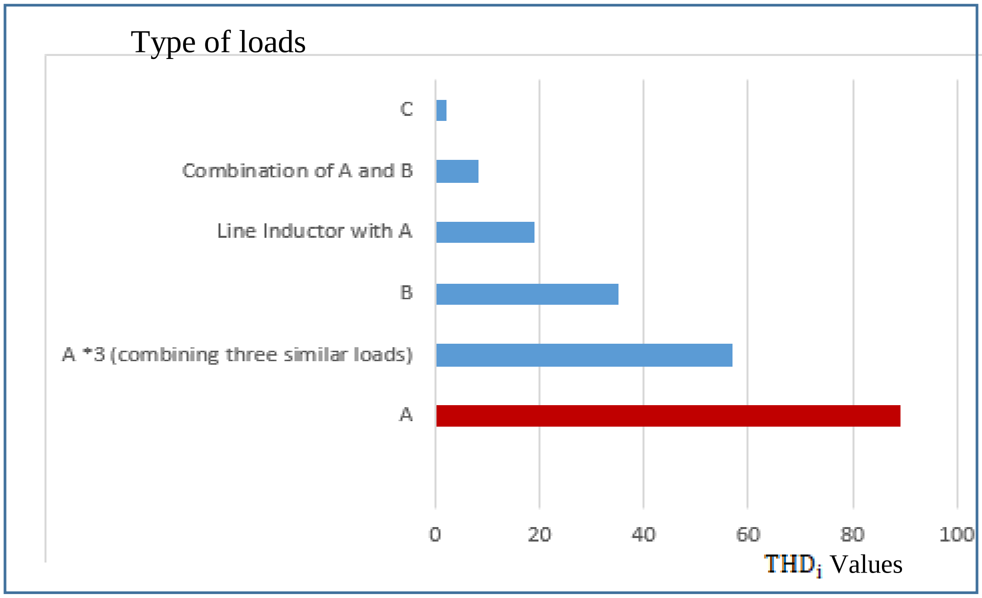


Figure 4.13(a): Simulation results for different loads

(b) Current harmonic results for different loads

Figure 4.13(b) shows the THD_i results of combining nonlinear loads that have similar and dissimilar electrical characteristic, that is, combination of load A (similar loads) and combination of loads A and B (dissimilar loads). From the Figure, current harmonics for individual harmonic order are noted to increase when three (3) similar nonlinear loads are combined. It is observed that, the current harmonics for each harmonic order reduce substantially when dissimilar loads are combined (type **A** and **B** loads) as well as when a line inductor is added. The simulation results for dissimilar nonlinear loads compared well with the field data measurement shown in Figure 4.2(b). This is considered to be due to the harmonic pollution damping effect as nonlinear loads with dissimilar electrical characteristic are noted to attenuate harmonic distortions. On the other hand, line inductor acts like a low pass filter hence it blocks flow of high harmonic frequencies.

The simulation results from the model and the field results obtained from domestic appliances are seen to compare.

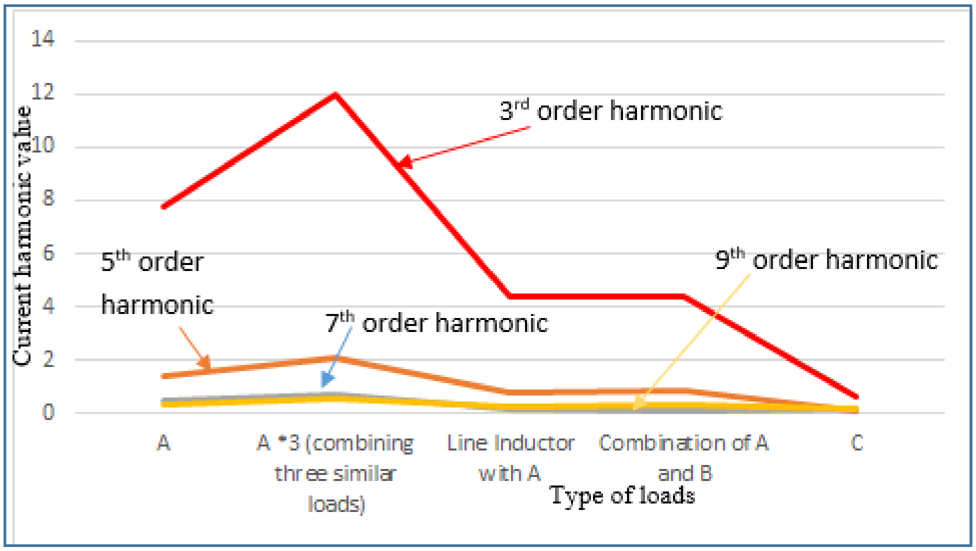


Figure 4.13(b): Magnitude of current harmonic distortions for different loads

4.5.2 Validation of the model by analyzing generated waveforms with and without AHF connected

It is well known that harmonic distortions is a complex waveform made up of a series of sinusoidal waves whose frequencies are integral multiples of frequency of the fundamental wave (50 Hz or 60 Hz). The odd harmonic orders, where triple-n (homopolar) harmonics are the dominants for single phase nonlinear loads, result in a symmetric distorted waveform which contains both fundamental (50 Hz) and harmonics frequencies. This subsection presents the performance of the designed AHF for various nonlinear loads.

a) Nonlinear inductive load (lagging Pf)

Figure 4.14 shows the current harmonic waveforms for nonlinear load of 150 Var with lagging power factor (inductive load). Example of such inductive loads include; radio, microwave and fridge.

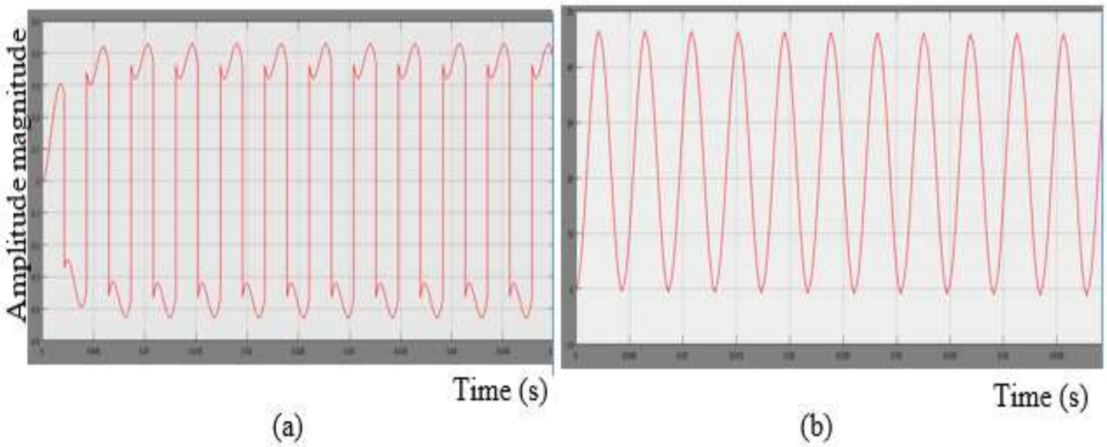


Figure 4.14: Inductive nonlinear load waveform; (a) Without AHF, and (b) With AHF

As observed in Figures 4.14(a), an inductive nonlinear load with a lagging power factor is seen to be a symmetrical non-sinusoidal (distorted) current waveform which shows that the load current comprises both the fundamental and harmonic signals. However, when single phase AHF is introduced, the current waveform is seen to be sinusoidal (only fundamental signal present) as depicted in Figure 4.14(b), but with a phase shift. This, therefore, implies that the harmonic signals are eliminated/cancelled as expected after introduction of a shunt AHF.

b) Nonlinear load with leading power factor

Figure 4.15 shows the current harmonic waveforms for a nonlinear load of 150 Var with a leading power factor (a capacitive load). As observed in Figures 4.15(a), a capacitive nonlinear load with a leading power factor is seen to be a symmetrical non-sinusoidal (distorted) waveform, which implies the waveform contains both fundamental and harmonic frequencies. Again, when single phase AHF is introduced, the current waveform becomes sinusoidal (as seen in Figure 4.15(b)), but with a phase shift. It can be concluded that the generated waveform for capacitive nonlinear loads was as expected. Further, connection of AHF resulted in a sinusoidal waveform which again shows that the harmonics were mitigated.

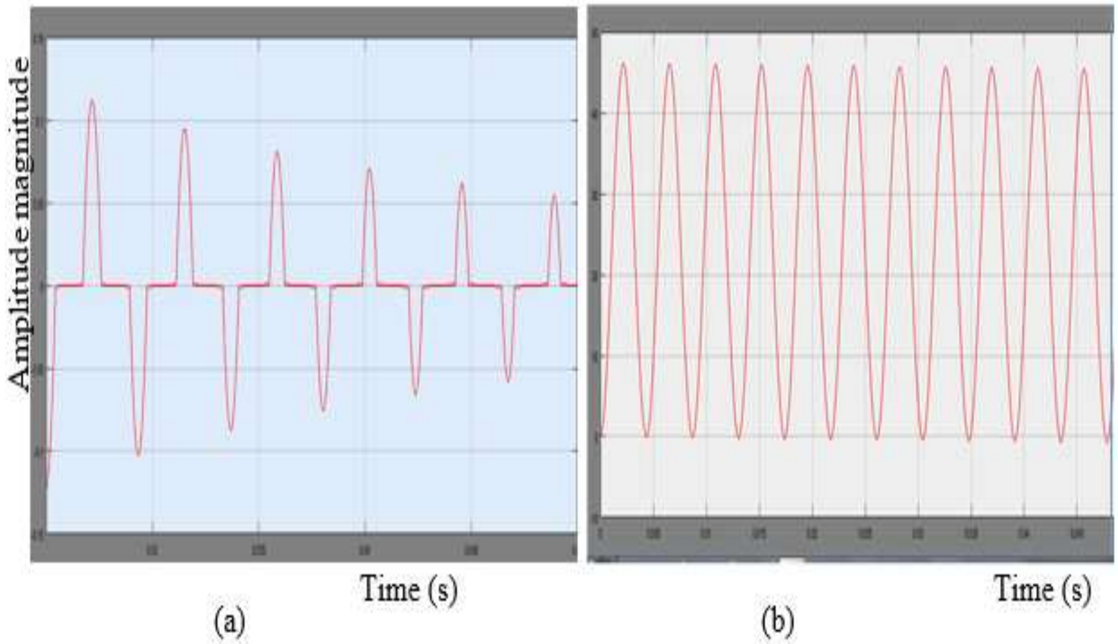


Figure 4.15: Capacitive nonlinear load waveform; (a) Without AHF, and (b) With AHF

(c) Nonlinear load with power factor near unity

Figure 4.16 shows the current waveforms of nonlinear load with high power factor (pf near unity). An example of such a load is water dispenser. As observed in Figures 4.16(a), a nonlinear load with almost a unity power factor is also seen to be a symmetrical non-sinusoidal waveform. However, when AHF is introduced, the current waveform is also seen to be sinusoidal as depicted in Figure 4.16 (b), but with a phase shift, which implies that the harmonics present are eliminated as expected. This shows successful cancellation of harmonic distortions by the proposed AHF.

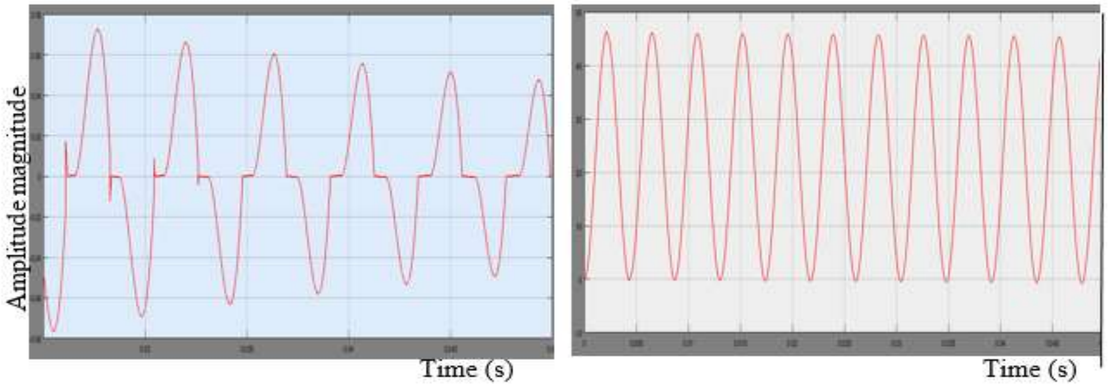


Figure 4.16: Nonlinear load with high pf waveforms (a) Without AHF, and (b) With AHF

(d) Resistive load

Figure 4.17 shows the simulated waveform for a resistive load. It can be clearly seen that the waveform generated is sinusoidal (non-distorted) signal. As expected, after connecting the AHF, the waveform remained a sinusoidal waveform.

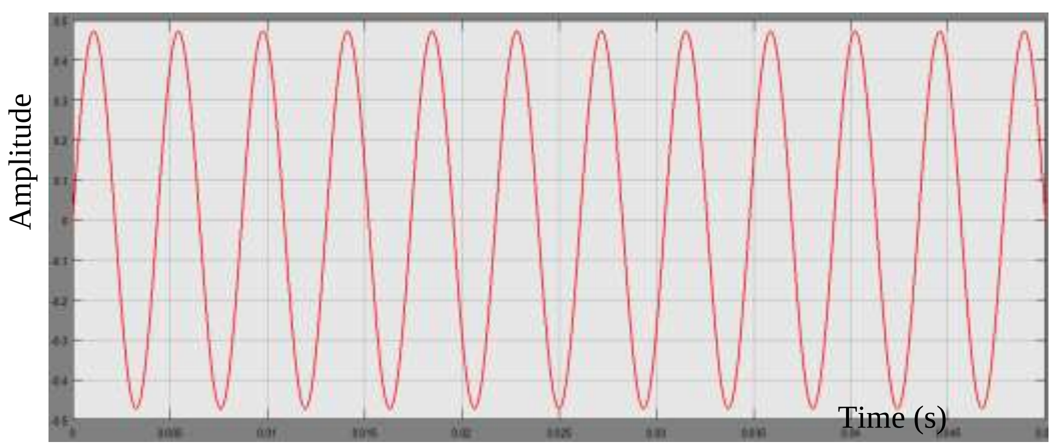


Figure 4.17: Linear load at unity power factor (resistive load) waveform both with and without AHF connected

From the above discussion, it can be concluded that the proposed and designed AHF performed as expected.

4.5.3 Performance evaluation of designed active harmonic filter

Performance evaluation for the proposed harmonic active filter was carried out by a comparative analysis performed by comparing results obtained with IEEE 519 and a similar filter designed for a single-phase distribution network. The subsequent section provides the results obtained.

(a) Results obtained compared with IEEE 519 standard recommendations

The performance evaluation of designed AHF was carried out by comparing the individual current harmonics order (3^{rd}, 5^{th}, 7^{th} and 9^{th}) with and without AHF. Table 4.11 shows individual harmonic orders (3^{rd}, 5^{th}, 7^{th} and 9^{th}) with and without AHF connected. The IEEE 519-1992 recommended the THD_i% limits to be below 4% (refer Appendix 2, Table 1c: IEEE 519:1992, THD_i% recommended limits ≤69 kV)) at point of common coupling of power consumers supplied by a voltage below 69 kV.

Table 4.11: Results of individual current harmonic distortions orders for different type of loads

		Current harmonic order levels (A)			
Type of load	**THDi%**	**3^{rd} Harmonic**	**5^{th} Harmonic**	**7^{th} Harmonic**	**9^{th} Harmonic**
Resistive load (500 Watt)					
Without AHF	1.435	0.105	0.35	0.05	0.025
With AHF	0.195	0.037	0.18	0.034	0.02
Capacitive load (500 Watt, 150 Var)					
Without AHF	10.95	0.69	2.28	0.43	0.28
With AHF	0.18	0.037	0.18	0.034	0.020
Inductive load (500 Watt, 150 Var)					
Without AHF	7.83	0.11	0.35	0.047	0.019
With AHF	0.19	0.037	0.18	0.034	0.02
Load (500 Watt, 150 Var- capacitive, 150 Var Inductive)					
Without AHF	11.94	0.799	3.354	0.594	0.342
With AHF	0.19	0.037	0.18	0.034	0.020

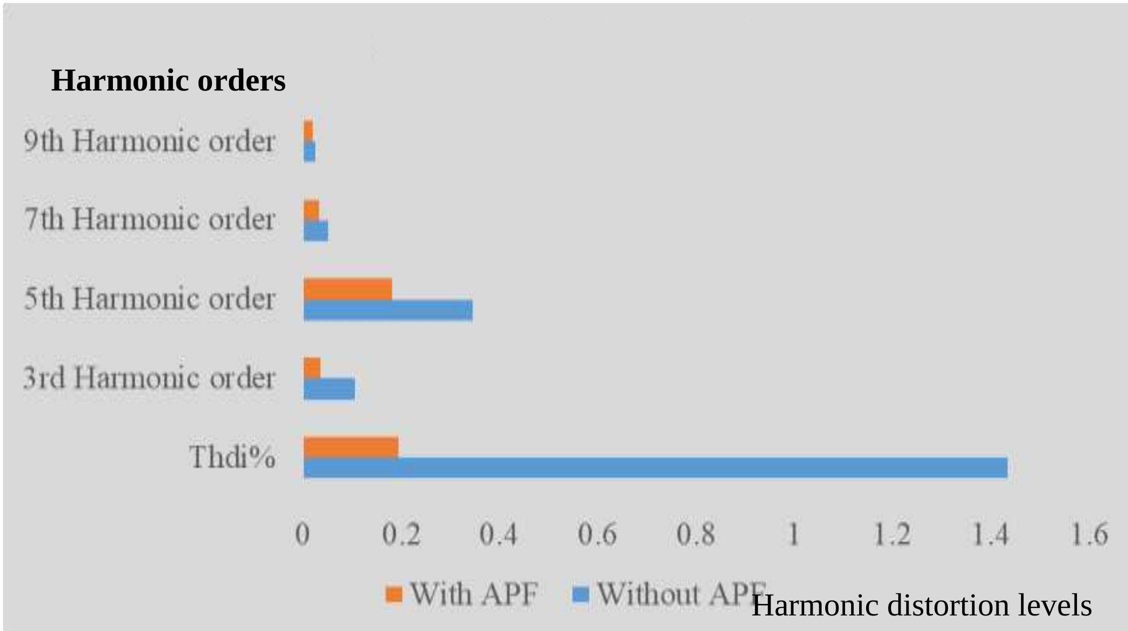


Figure 4.18(a): THD_i and individual harmonic order level for a resistive linear load

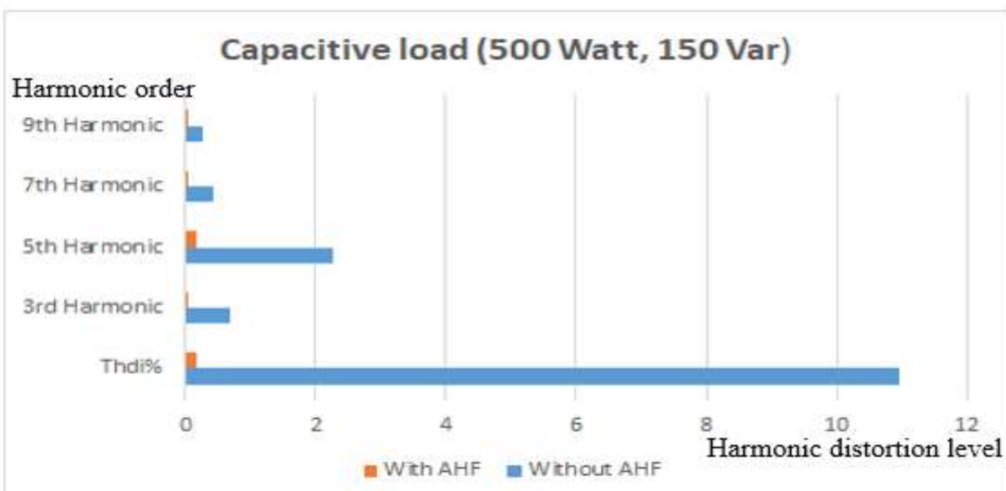


Figure 4.18(b): THD_i% and individual harmonic order level for a capacitive nonlinear load

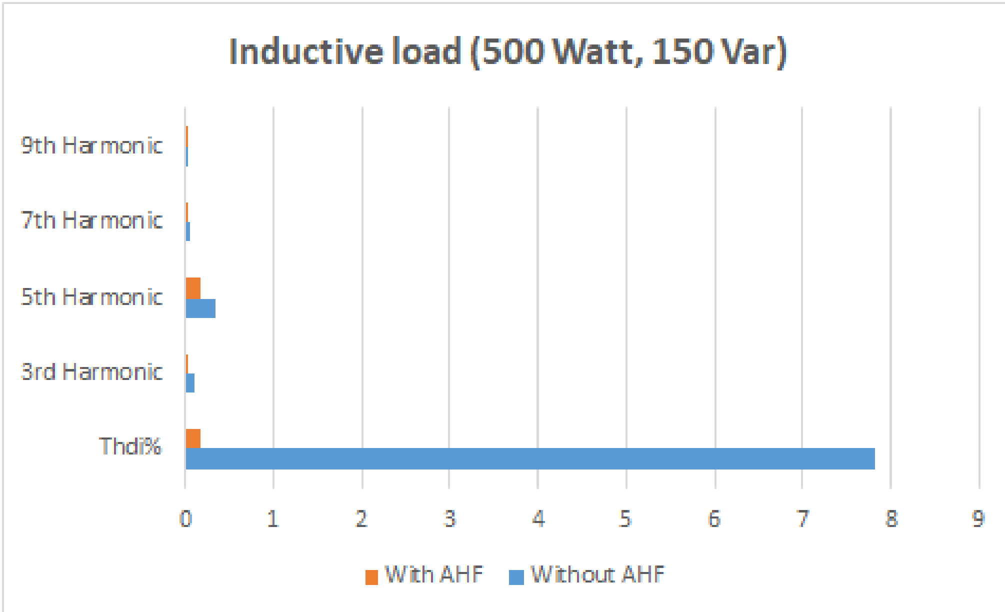


Figure 4.18(c): *THD_i*% and individual harmonic order level for an inductive nonlinear load

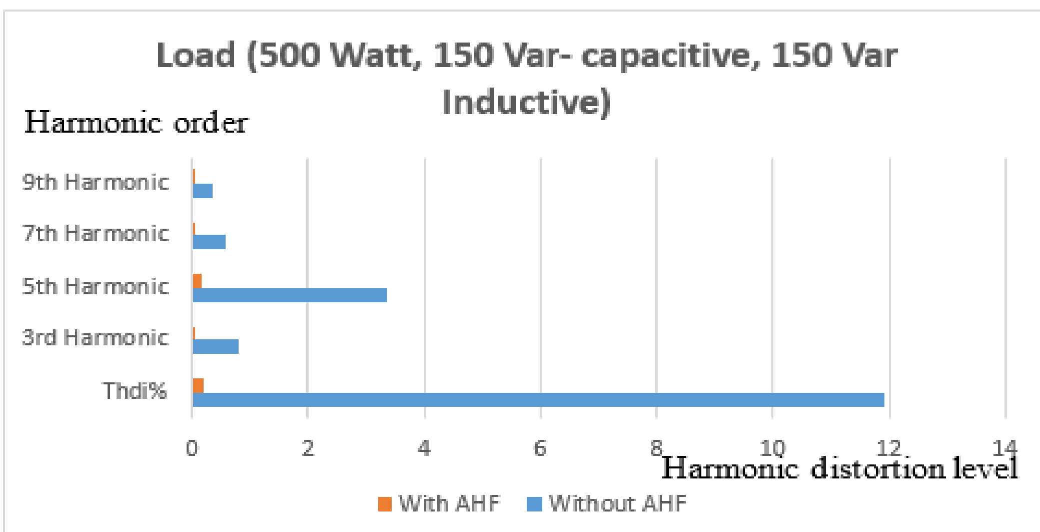


Figure 4.18(d): *THD_i*%and individual harmonic order level for a combined load

Figures 4.18(a)–4.18(d) show results for different load current harmonic orders levels and THD_i% presented in Table 4.11.

From Figures 4.18(a)–4.18(d), the following are noted;

i. The THD_i% and individual harmonic orders levels without AHF are seen to be high. However, when active harmonic filter is introduced, harmonic distortions levels are noted to reduce significantly. This shows that the AHF reduced or mitigated the harmonics generated by nonlinear loads.
ii. The 5th harmonic distortion order is found to be the dominant harmonic order. This is due to the type of the nonlinear load used for simulation (PWM of 6 pulses). For 6 pulses PWM, the dominant harmonic orders are given by (6±1), hence the reason why the 5th harmonic is the most dominant order. As expected, the 9th harmonic order level was the lowest level amongst the harmonics order under investigation.
iii. The THD_i% is lowest when inductive or capacitive appliances are combined and vice versa when capacitive and inductive loads are combined.
iv. The results obtained compared well with results analyzed for multiple (combined) nonlinear loads.

From the above simulation results, it can be deduced that the designed harmonic active filter achieved the following outcomes;

i. Cancelled the entire harmonic spectrum including the dominant harmonic order (5th harmonic) frequency
ii. Reduced THD_i to < 1% in all the loads under consideration conformed to the acceptable threshold limits recommended in IEEE 519-1992, a power quality standard. The results obtained was compared with IEEE 519-1992 because it is standard adopted by many power utility companies and industries.

(b) *Results compared with a similar previous designed AHF*

Further evaluation is carried out by a comparative analysis performed by comparing the designed AHF with another similar simulated AHF. The THD_i results obtained from proposed single phase shunt AHF compared with a similar simulated AHF (Musa, et al., 2017), are represented in Table 4.12. From the Table, the designed AHF is found to give lowest THD_i after compensation compared to a previous similar simulated AHF.

From the simulation results obtained, it can be concluded that the proposed mitigation method gives the expected simulation results. It is, however, also expected that the mitigation method can work practically when applied in power utility system.

Table 4.12: Comparative simulation results for the designed AHF and a similar AHF

THD_i value	**Proposed AHF**	**Previous AHF (Musa, et al., 2017)**
Before compensation	11.94%	25.60%
After compensation	0.19%	0.92%

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research entailed investigation, analysis and mitigation of the effects of harmonics from domestic single phase nonlinear loads on power distribution network.

The following conclusions were derived from this research;

(i) Domestic single phase nonlinear loads generate high current harmonic distortions that stream back to the low voltage side of the distribution transformers.

(ii) Combing nonlinear loads that have similar electrical characteristics increases the level of harmonics, while combing nonlinear loads that have dissimilar electrical characteristics reduces the harmonics level. It is important to note that since it is not possible to dictate or control the consumer behavior in electrical appliance usage, cancellation of harmonics by combination of loads with dissimilar electrical characteristics will always remain a mirage and, therefore, harmonics level are expected to increase more and more with emerging of modern harmonics generating loads.

(iii) From tests and analysis of the transformer oil properties and measurement of harmonic levels, it is concluded that the early failure of the transformers in distribution network correlate well with the presence of high harmonics in the network and therefore, there is need to devise means of harmonic reduction or cancellation at point of harmonics generation in order to protect the distribution transformers.

(iv) Though only in simulation environment, the effectiveness of the designed and modelled active harmonic filter in harmonics reduction was tested and ascertained.

5.2 Recommendations

Based on the results obtained from this study, the following recommendations are made:

i. To reduce early failure of distribution transformers, especially in rural setups, this study recommends frequent replenishment of transformer oils.
ii. Further, it is recommended that domestic consumers, where possible, be connecting multiple appliances rather than individual appliances.

For future work, this study suggests the following:

i. There is need to investigate the effect of the introduction of feed-in tariff that involves net-billing on distributed generations (such as solar and wind distributed generations), on the levels of the current harmonic distortions on the distribution network.
ii. There is need to do further analysis on distribution transformer oil (dielectric dissipation factor, oxidation stability, and dissolved gas analysis) to fully establish the effects of harmonics on the transformers.
iii. A practical development and testing of a prototype single phase active harmonic filter for mitigation of current harmonics needs to be done and tested on the utility point of common coupling of a domestic consumer.

REFERENCES

Roger, S. (2002). '*Electrical Power Systems Quality*, (2nd ed.) New Delhi, India,

IEEE Std. (1995). Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems. IEEE Industry Applications Society.

Ceramia., P. (2008). Modeling of domestic nonlinear loads for harmonic analysis," *Journal of Energy Technologies & Policy*, *6*(3}, 1-5,.

Iagar, A (2014). The influence of home nonlinear electrical operating modes on power quality," *Journal of Energy Technologies & Policy*, *13*

Purushothama, R. (2012). Modeling and harmonic analysis of domestic/ industrial loads," *International Journal of Emerging Technology and Advanced Engineering*, 2, 485-491.

Farooq, H., Zhou, C., Allan, M., Farrag, M. E., Khan, R. A., & Junaid, M. (2011). Investigating the power quality of an electrical distribution system stressed by non-linear domestic appliances. *Renewable Energy and Power Quality Journal*, *1*(9).

Shah, H. (2012), 'Harmonics: A Power quality problem. *International Journal of Emerging Technology and Advanced Engineering*, *4*(7)

Mazumdar, J. (2006). *System and method for determining harmonic contributions from nonlinear loads in power systems* (Doctoral dissertation, Georgia Institute of Technology).

Venkatesh, C., Kumar, D. S., Sarma, D. S., & Sydulu, M. (2008, December). Modelling of nonlinear loads and estimation of harmonics in industrial distribution system. *In Fifteenth National Power Systems Conference (NPSC)*, IIT Bombay (pp. 592-597).

Mehta, V.K. (2011). *Principles of Power System*. (4th ed.)

Schipman, K., & Delincé, F. (2010). The importance of good power quality. *ABB Power Qual. Prod., Charleroi, Belgium, ABB Review.*

Gunda, S. K., Sudheer, A. D., & Sarma, D. S.(2012). Harmonic Analysis of Personal Computer System using Kalman Filtering Algorithm and Experimental Verification.

Khatavkar, V. (2009).'*Study of harmonics in industrial: A Power Quality Aspect,*

Dugan, R. C., McGranaghan, M. F., & Beaty, H. W. (1996). Electrical power systems quality. *New York*.

Chan, M. Y., Lee, K. K., & Fung, M. W. (2007). A case study survey of harmonic currents generated from a computer centre in an office building. *Architectural Science Review*, *50*(3), 274-280.

Godbole, P. (2014). Effect of harmonics on active power flow and apparent power in the power system. *IOSR Journal of Electronics and Communication Engineering (IOSR-JECE),* 39-43.

Dolara, A., & Leva, S. (2012). Power quality and harmonic analysis of end user devices. *Energies, 5*(12), 5453-546

Said, D. M., Ahmad, N., & Zin, A. A. M. (2003, December). Power supply quality improvement: harmonic measurement and simulation. In *Proceedings. National Power Engineering Conference, 2003. PECon 2003.* (pp. 352-358). IEEE.6.

Ndung'u, C., Nderu, J & Ngoo, L (2011). *Impact of compact fluorescent lighting bulbs on power quality*. Kenya Society of Electrical Electronic Engineers.

Ndung'u, C., Nderu, J., & Ngoo, G. (2014, December). Mitigation of Harmonic Distortions and Low Power Factor Using Active Power Filter for Low Voltage

Power Supplies. In *Proceedings of Sustainable Research and Innovation Conference* (pp. 275-279).

Ranade, T (2010). *An overview of harmonics modeling and simulation*. New Mexico State University

Bayliss, C. R., Bayliss, C., & Hardy, B. (2012). *Transmission and distribution electrical engineering*. Elsevier.

Jan, S. T., Afzal, R., & Khan, A. Z. (2015, February). Transformer failures, causes & impact. In *International conference data mining, civil and mechanical engineering* (pp. 49-52).

Ndungu, C., Nderu, J., Ngoo, L., & Hinga, P. (2017). A study of the root causes of high failure rate of distribution transformer-A case study. *International Journal Engineering and Science*, *2*, 14-18.

Rajurkar, S. S., Nandapurkar, J. G., & Kulkarni, A. R. (2010, December). Analysis of power transformer failure in transmission utilities. In *16th National Power Systems Conference* (pp. 180-185).

Kazem, H. A. (2013). Harmonic mitigation techniques applied to power distribution networks. *Advances in power electronics*, *2013*.

Singh, S. N. (2008). *Electric power generation: transmission and distribution*. PHI Learning Pvt. Ltd...

Ndung'u, C., Nderu, J. & Ngoo, L (2013). *Mitigating of harmonic distortions and low power factor in unbalanced three-phase system using fuzzy logic controller*. M.Sc. Thesis, Dept. of Electrical and Electronic Eng., JKUAT, Kenya, 2013.

Singh, R., Zadgaonker, A. S., & Singh, A. (2014). Impact Of Harmonics On Distribution Transformer Supplying A Technical Institution–A Case Study. *Journal of research in electrical and electronic engineering*.

Shepherd, J., Morton, V & Spence, L. F (2009). *Higher Electrical Engineering*. 2nd ed.,.

A Standard Guide for Investigating Failure, Deformation And Analysis For Power Transformer And Shunt Reactors, IEEE C57.125.

Uzair, M. A. R., Mohiuddin, M., & Shujauddin, M. K. (2013). Failure analysis of power transformers. *International Journal of Emerging Technology and Advanced Engineering*, *3*(9), 162-171.

Ghadai, J., & Das, C. (2014). Failure of transformers due to Harmonic loads. *International Journal of Electrical, Electronic and mechanical controls*, *3*(3).

Sinha, M. N., Patel, P., Doshi, P. S. M., & Bhalodiya, N. (2015). Case Studies Of The Transformers Failure Analyses. *Electrical India*.

Bartley, W. H. (2011). *Failure analysis of transformer*. The Hartford Steam Boiler Inspection and insurance Co., unpublished

Singh, R., Zadgaonker, A. S., & Amarjit, S. (2014). Premature failure of distribution transformer-a case study. *International Journal of Science & Research, 5*, 18-23.

Kumar, A., Singh, S. K., & Husain, Z. (2013). Root Cause Analysis Of Transformer Failure Scenario At Power Substation. *Advances in environmental and agriculture science*.

Zynal, H. I., & Ala'a, A. (2012). The effect of harmonic distortion on a three phase transformer losses. *ratio*, *6*, 7.

Gupta, A., & Singh, R. (2011). Evaluation of distribution transformer losses under harmonic loads using analytical and simulation methods. *International Journal on Emerging Technologies*, *2*(2), 90-95.

Mohd Nor, N., Abdullah, M. F., & Arumugam, U. (2011). A Brief Review on Advances of Harmonic State Estimation Techniques in Power Systems. *International Journal of Information and Electronics Engineering*, 1(3), 217-222

Rajesh, T., Aravindhan, S., Sowmiya, M., Thenmozhi, S., & Scholar, U. (2016). Design of shunt active filter for reduction of harmonics. *International Journal of Engineering Science*, *6*(4), 3317-3321.

Azevedo, H. J., Ferreira, J. M., Martins, A. P., & Carvalho, A. S. (2003). Direct current control of an active power filter for harmonic elimination, power factor correction and load unbalancing compensation. *Proceedings of the EPE 2003*.

Boonrvang, W. & Punyapat, C., (n,d). *Single phase to three sinusoidal waveform converter for driving three phase induction motor based on SPWM inverter*.. unpublished paper.

Sobly, S., Sayed, K. F., Abdalla, Y. S., & Hafez, W. A. (2008). Shunt Active Filter For Harmonic Mitigation Of A Resistance Spot Welding Machine. *Journal of Electrical Engineering*, *3*(2).

Lucian, A., & Steffan, H (n.d). *Evaluation of harmonic detection methods for active power filter applications*. unpublished.

Sneha, J., & Sreehari, S., (2015). Synchronous reference frame based control method for UPQC. *International Research Journal of Engineering and Technology* (IRJET), *02*(04)

Kesler, M., & Ozdemir, E. (2010). Synchronous-reference-frame-based control method for UPQC under unbalanced and distorted load conditions. *IEEE transactions on industrial electronics*, *58*(9), 3967-3975.

Monfared, Mohammad, Saeed Golestan, & Josep M. Guerrero (2013). A new synchronous reference frame-based method for single-phase shunt active power filters. *Journal of power Electronics 13*(4), 692-700.

Mazumdar, J., Harley, R. G., & Venayagamoorthy, G. K. (2006, November). Synchronous reference frame based active filter current reference generation using neural networks. In *IECON 2006-32nd Annual Conference on IEEE Industrial Electronics* (pp. 4404-4409). IEEE.

Balasubramaniam, P. M. & Prabha, S.U.(2013). A practical approach to harmonic compensation in electrical power systems- using shunt active power filter," *Australian Journal of Basic and applied Sciences,* 7(10), 576-585

Dey, P., & Mekhilef, S. (2014, May). Synchronous reference frame based control technique for shunt hybrid active power filter under non-ideal voltage. In *2014 IEEE Innovative Smart Grid Technologies-Asia (ISGT ASIA)* (pp. 481-486). IEEE.

Chebabhi, A., Fellah, M. K., Benkhoris, M. F., & Kessal, A. (2016). Artificial neural network based synchronous reference frame theory in the DQ0 axes for reference harmonic currents generation of a four leg shunt active power filter.

Rao, N. S., & Jayatheertha, H. J. (2012). Modeling and simulation of various SRF methods for shunt active power filter and application to BLDC drive. *International Journal of Advanced Engineering Research and Studies*, *1*(4), 18-22.

Anooja, C. L., & Leena, N. (2013). Single phase shunt active filter with fuzzy controller for harmonic mitigation. *International Journal of Scientific & Engineering Research*, *4*(9), 445-451.

Davudi, M., Torabzad, S.,, & Ojaghi, B., (2011). Analysis of harmonics and harmonic mitigation method in distribution systems. *Australian Journal of Basic and Applied Science*, *5*(11), 996-1005

Srinath, S., Prabakaran, S Mohan, K. & Selvan, M.P., (2010) Implementation of single phase shunt active harmonic filter for low voltage distribution system," Presented at the *16th National power systems conference*, pp. 295-300, Dec. 2010.

Mazumdar, J. (2006). *System and method for determining harmonic contributions from nonlinear loads in power systems* (Doctoral dissertation, Georgia Institute of Technology).

Musa, S., Radzi, M. A. M., Hizam, H., Wahab, N. I. A., Hoon, Y., & Zainuri, M. A. A. M. (2017). Modified synchronous reference frame based shunt active power filter with fuzzy logic control pulse width modulation inverter. *Energies*, *10*(6), 758.

Msigwa, C. J., Kundy, B. J., & Mwinyiwiwa, B. M. (2009). Control algorithm for shunt active power filter using synchronous reference frame theory. *World Academy of Science, Engineering and Technology*, *58*.

Kumar, C. S., & Gopalakrishnan, D. V. (2013). Investigation of harmonic detection techniques for shunt active power filter. *Journal of Electronics & Communication Engineering*, 68-73.

Kasimvadi A., & Rao, J. S. (2012). Modeling and simulation of SRF and P-Q based control DSTATCOM," *International Journal Of Engineering Research And Development*, 1(10), 65-71.

Sunitha, M., & Kartheek, B. N. (2013). Elimination of harmonics using active power filter based on DQ reference frame theory. *International Journal of Engineering Trends and Technology*, *4*(4), 781.

Ghulbet, S. M., Hinga, P. K., & Nderu, J. N. (2017). An Investigation on Harmonic Problems for N-1 Contingency in Industrial Distribution and Its Mitigation Using Fuzzy Controlled Hybrid Filter. *International Journal of Applied Engineering Research*, *12*(20), 10284-10297.

Kerrouche, S., & Krim, F. (2009). Three-phase active power filter based on fuzzy logic controller. *International Journal of Sciences and Techniques of Automatic control & computer engineering IJ-STA*, *3*(1), 942-955.

Michael, S. (2007). *The influence of nonlinear loads on the power quality of the new Zealand low voltage electrical residential power distribution network*," Hong Kong Polytechnic University- China

Malengret, M., & Gaunt, C. T. (2020). Active currents, power factor, and apparent power for practical power delivery systems. *IEEE Access*, *8*, 133095-133113.

Parthasaradhy, P., Padhan, D. G., & Chinmaya, K. A. (2014). Regulation of the DC bus voltage of a three phase active power filter by PI and fuzzy logic controller. *The International Journal Of Engineering And Science (IJES)*, 78-84.

Nos, O. V., & Shalygin, K. A. (2013, July). DC-bus voltage control strategy of active power filter. In *2013 14th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices* (pp. 345-348). IEEE.

Cherian, E., Bindu, G. R., & Nair, P. C. (2016). Pollution impact of residential loads on distribution system and prospects of DC distribution. *Engineering Science and Technology, an International Journal*, *19*(4), 1655-1660.

APPENDICES

Appendix I: Author's Publications

C. Ndungu, J. Nderu, L. Ngoo and P. Hinga, "Mitigation of current harmonic distortions streaming from domestic nonlinear loads using single phase active harmonic filter", *Journal of Applied Science, Engineering and Technology for Development (JASETD)*, Vol. 3 Issue 1 May, 2018 pp 82-89.

C. Ndungu, J. Nderu, L. Ngoo and P. Hinga, "Effect of harmonic distortions emanating from domestic loads on low voltage installations", *Africa journal of Technical Vocational and Training*, ISSN: 2518-2722 On –line, May 2018.

C. Ndungu, J. Nderu, L. Ngoo and P. Hinga, "Impact of current harmonics emanating from single phase loads on low voltage network and distribution transformers- case study", *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, Vol. 4, Issue 3, March 2017.

C. Ndungu, J. Nderu, L. Ngoo and P. Hinga, "A study of the root causes of high failure rate of distribution transformers- A case study", *International Journal of Engineering and Science (IJES)*, Vol. 5, Issue 9, pg 64-66, 2016.

Appendix II: Power Quality International Standards

(i) Standard IEC 60364: Electrical installation of buildings part 5-52.

(ii) Standard EN 50160: Voltage characteristic of electricity supplied by public distribution system.

(iii) Standard IEC 61000: Electromagnetic Compatibility part 3-2 for device with current rating of 16A and below while part 3-4 for device with current rating of above 16A. IEC 61000 3-2 classify the equipment into;

- Class A- Balanced three-phase equipment and all other equipment not belonging to classes B, C and D.
- Class B- PorTable tools.
- Class C – Lighting equipment including dimming devices.
- Class D – Equipment having an input current with a special waveform shape and an active input power of less than 600 W. Examples of these loads are TVs, printers, and personnel computer power supplies except phase–angle controlled motor driven equipment. The special waveform is as defined by an envelope shown in Figure 2a). The equipment is deemed to be class D if the input current wave shape of each half period is within the envelope for at least 95% of duration.

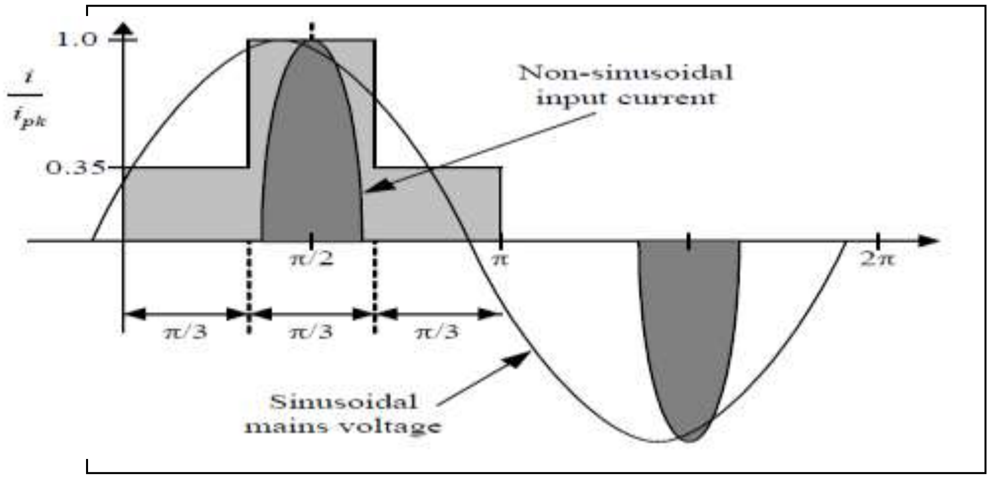


Figure 2a: Special waveforms for class D equipment

Standard IEC 61000 specified the harmonic level as shown in Table 2a.

(iv) Standard GS/4-1: Managing harmonics- ENA Engineering Recommendation.

Standard IEC 61000-3-2: Defines compatibility levels for low frequency in public low voltage power supply. The THDv of the supply voltage upto 40th harmonic order to be less than 8%. Permissible harmonic current of nonlinear appliance is as provided in Table 1a.

Table 2a: Permissible harmonic current of nonlinear domestic equipment

Harmonic order (*h*)	Max. permissible harmonic current %
2	2
3	30*P.F
5	10
7	7
9	5
11-39	3

(vi) IEEE 519-1992, 'Recommended Practices and Requirements for Harmonic Control in Electrical Power System'.

Tables 2b and 2c show the recommended THD_v and THD_i as defined by IEEE 519-1992.

Table 2b: IEEE 519 THDv recommended limit

Bus voltage at PCC	Individual Harmonic Voltage Distortion %	Total Voltage Distortion – THD %
less than 69 kV	3	5
less than 169 kV	1.5	2.5
Voltage > 161 kV	1	1.5

Table 2c: IEEE 519 THD_i recommended limit for $V_n \leq$ 69 kV

Vn ≤ 69 kV						
$^{Isc}/_{I_l}$	h < 11	11< h< 17	17 < h < 23	23 < h < 35	>35	TDD
< 20	4	2	1.5	0.6	0.3	5
20 – 50	7	3.5	2.5	1	0.5	8
50 – 100	10	4.5	4	1.5	0.7	12
100 – 1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

Appendix III: Calculation of short circuit current for domestic consumer at PCC

With reference to Table 2b and 2c (recommendation of IEEE 519-1992) the following is derived:

The ratio $\mathrm{I_{sc}}/\mathrm{I_l}$ at domestic PCC is obtained using equation (3a):

$$I_{sc} = \frac{Transformer\ kVA * 100}{Sqrt\ 3 * sec\ kV * \%z\ transformer} \qquad (3a)$$

Where transformer $kVA = 100$, sec $kV = 0.415$, $\%z$ transformer $= 3.5\%$

$I_{sc} = 4000$ A, $I_l = 2\ A$ (most of the domestic high rated loads are usually 500 W).

Substituting the values $Isc/I_l = 2{,}000$.

Appendix IV: Calculation of watt-loss in both rural and urban transformers

The following formulas were employed:

From literature, transformer losses consist of no-load (core losses) and load losses as given in equation (4a).

$$P_T = P_{LL} + P_{NL} \quad (4a)$$

Where P_{LL} = load losses, P_{NL} = No-load.

Load losses consist of P_{dc} losses (I^2R_{dc}) and stray losses, which are as a result of electromagnetic fields within windings, core clamps and tank walls. Stray losses are composition of winding eddy current losses (caused by eddy current and circulating current) and structural part. No load loss is insignificant on distribution transformer hence can be assumed. The load losses therefore can be expressed as in equation (4b).

$$P_{LL} = P_{dc} + P_{EC} + P_{OSL} = P_{dc} + P_{TSL} \quad (4b)$$

Where P_{TSL}- Total stray losses ($P_{EC} + P_{OSL}$), P_{EC} –Eddy current losses and P_{OSL} – other stray losses.

Eddy current losses include skin and proximity effects. Losses due to skin effect are directly proportional to square of the both the eddy current and frequency ($I^2 f^2$) based on equation (4c):

$$P_{EC} = P_{EC-0} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 h^2 \qquad (4c)$$

Where P_{EC-0} -Winding eddy-current loss at the measured current and power frequency, h_{max} – is the highest significant harmonic order, I_h – is RMS current at harmonic of order h and I is the RMS load current.

An internally induced voltage that causes eddy current to flow in the ferromagnetic materials such as core, clamps and structural parts causes other stray losses in transformers. The eddy losses increase at a rate proportional to I^2 and not proportional to f^2. The harmonic loss factor for stray losses that relate to transformer connections, structural parts is expressed as in equation (4d):

$$P_{OSL} = P_{OSL-R} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I}\right)^2 h^{0.8} \qquad (4d)$$

Proximity effect is due to the current carrying conductor inducing current in a neighbouring conductor. In distribution transformer, high-tension (HT) windings produce a flux density that cuts the LV windings inducing an emf that produces circulating or eddy current.

Because of complexity to calculate the eddy current losses directly, for dry -type transformer, eddy current losses are estimated as in equation (4e):

$$P_{EC} = 0.67 * P_{TSL} \qquad (4e)$$

The current harmonic obtained are as shown in Table 3a.

Table 4a: Individual current harmonic distortions

Nature of loads transformer supplies	Rating of transformer (kVA)	THDv (%)	Current (A)	3rd Harmonic Value (%)	Current (A)	5th Harmonic Value (%)	Current (A)	7th Harmonic Value (%)	Current (A)	9th Harmonic Value (%)	Current (A)
Domestic –Urban dwellers	100	4.8	0.46	44.4	2.08	17.89	0.66	10.1	0.48	8.3	0.26
Domestic –Rural dwellers	100	3.01	0.38	22.21	4.7	13.3	1.4	4.64	0.7	3.02	0.6

Appendix V: Clarke and Park Transformation

Clarke and Park transformation express voltage and current in terms of space vectors. The space vectors are presented in stationary reference frame. Clarke transformation transform a, b, c to real and imaginary current or voltage. The real part of the space vector is equal to instantaneous value of the direct- axis current component i_α and imaginary part is equal to quadrature-axis component i_β. The Park transformation realize Clarke transformation currents from the stationary to the rotating reference frame as shown in Figure 5a). The current vector in the stationary reference frame can be expressed as in equation (5a):

$$i = i_\alpha + i_\beta \qquad (5a)$$

In symmetrical three phase system, the direct and quadrature axis current i_α and i_β are fictitious quadrature (two phase) current component which are related to the actual three phase current as in equations (5b and 5c):

$$i_\alpha = k\left(i_a - \frac{1}{2}i_b - \frac{1}{2}i_c\right) \qquad (5b)$$

$$i_\alpha = k\frac{\sqrt{3}}{2}(i_b - i_c) \qquad (5c)$$

Current space vector equations to rotate at speed $\omega_{G,}$ current space vector can be written as in equation (5d):

$$i_G = ie^{-j\theta_G} = (i_x + i_y) \qquad (5d)$$

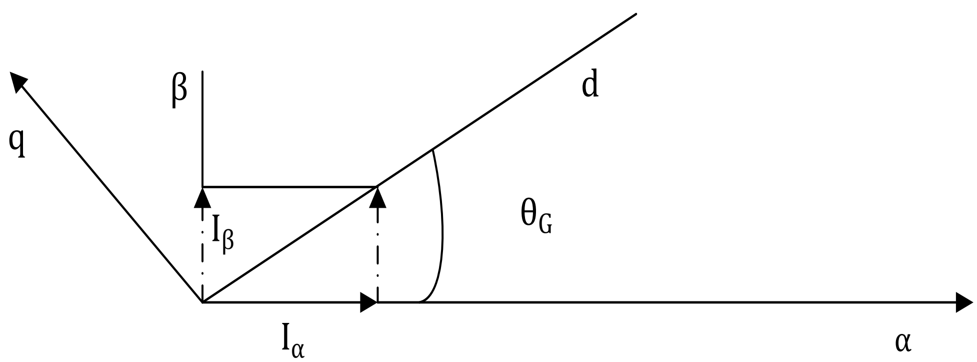


Figure 5a: d-q rotating frame

In (α, β) plane, the relation is as in equation (4a), which is repeated for convenience in equation (5e):

$$i = i_\alpha + i_\beta \qquad (5e)$$

In (d, q) plane, the relation is as in equation (5f),

$$i = i_d + i_q \qquad (5f)$$

The angle between (α, β) and (d, q) is θ_G so that equations (5g) and (5h) apply:

$$\sin\theta_G = \frac{i_\beta}{i_d} \qquad (5g)$$

$$\cos\theta_G = \frac{i_\alpha}{i_d} \qquad (5h)$$

Appendix VI: Transformer Harmonic Raw Data.

Table 6a presents the Harmonic data obtained from a transformer supplying urban setup.

Table 6a: Harmonic data obtained from a transformer supplying urban setup.

Date	Time	I1 h3 (A)	I1 h5 (A)	I1 h7 (A)	I1 h9 (A)
01.01.2016	0:05:00	2.52	2.38	1.26	0.150
01.01.2016	0:10:00	2.52	2.34	1.21	0.147
01.01.2016	0:15:00	2.49	2.44	1.23	0.177
01.01.2016	0:20:00	2.66	2.44	1.22	0.177
01.01.2016	0:25:00	2.58	2.49	1.21	0.150
01.01.2016	0:30:00	2.54	2.52	1.21	0.150
01.01.2016	0:35:00	2.54	2.46	1.21	0.177
01.01.2016	0:40:00	2.57	2.41	1.26	0.180
01.01.2016	0:45:00	2.52	2.42	1.26	0.177
01.01.2016	0:50:00	2.57	2.44	1.28	0.177
01.01.2016	0:55:00	2.47	2.52	1.26	0.147
01.01.2016	1:00:00	2.49	2.39	1.25	0.180
01.01.2016	1:05:00	2.54	2.39	1.23	0.180
01.01.2016	1:10:00	2.57	2.44	1.23	0.180
01.01.2016	1:15:00	2.62	2.50	1.23	0.150
01.01.2016	1:20:00	2.61	2.47	1.28	0.177
01.01.2016	1:25:00	2.67	2.47	1.26	0.180
01.01.2016	1:30:00	2.62	2.44	1.26	0.177
01.01.2016	1:35:00	2.55	2.45	1.23	0.177
01.01.2016	1:40:00	2.56	2.44	1.30	0.180
01.01.2016	1:45:00	2.57	2.44	1.23	0.150
01.01.2016	1:50:00	2.49	2.50	1.26	0.177
01.01.2016	1:55:00	2.51	2.47	1.22	0.177
01.01.2016	2:00:00	2.48	2.39	1.26	0.177
01.01.2016	2:05:00	2.57	2.41	1.22	0.177
01.01.2016	2:10:00	2.52	2.44	1.25	0.177
01.01.2016	2:15:00	2.52	2.44	1.22	0.177
01.01.2016	2:20:00	2.64	2.50	1.22	0.177

Table 6b: Harmonic data for transformer supplying rural setup

Date	Time	I1 h3 (A)	I1 h5 (A)	I1 h7 (A)	I1 h9 (A)
03.09.2016	9:25:00	7.53	1.45	3.83	1.22
03.09.2016	9:30:03	6.10	3.20	3.69	1.22
03.09.2016	9:35:13	9.17	1.93	3.63	1.34
03.09.2016	9:41:50	5.90	1.29	3.37	1.03
03.09.2016	9:48:56	5.80	1.49	3.80	1.23
03.09.2016	9:53:56	5.42	3.00	3.57	0.72
03.09.2016	10:42:38	8.05	3.12	3.70	0.97
03.09.2016	10:47:38	7.43	2.08	3.95	1.19
03.09.2016	10:56:16	5.78	1.95	4.16	1.01
03.09.2016	11:01:16	20.02	4.37	11.74	1.61
03.09.2016	11:06:16	8.14	2.59	3.65	1.25
03.09.2016	11:11:16	6.88	3.78	4.72	1.02
03.09.2016	11:16:16	6.17	2.60	3.66	1.11
03.09.2016	11:21:16	6.50	3.81	4.79	0.80
03.09.2016	11:26:16	6.43	3.12	3.66	1.24
03.09.2016	11:31:16	6.57	2.46	3.92	1.07
03.09.2016	11:41:17	6.49	2.31	3.68	1.63
03.09.2016	11:46:17	7.36	2.86	4.50	0.97
03.09.2016	11:51:17	7.64	2.54	3.56	1.15
03.09.2016	11:56:17	5.21	3.24	3.92	1.13
03.09.2016	12:01:17	7.50	5.43	6.20	0.94
03.09.2016	12:06:17	7.81	3.50	5.14	1.47
03.09.2016	12:11:17	4.88	2.52	3.81	1.00
03.09.2016	12:16:17	11.75	4.84	3.79	1.13
03.09.2016	12:21:17	6.39	3.56	3.80	1.18
03.09.2016	12:26:17	6.44	2.57	3.77	1.00
03.09.2016	12:31:17	6.81	2.53	4.01	1.26

Figure 7a shows the MATLAB-Simulink diagram of the designed single phase active harmonic filter using synchronous frequency frame extraction method.

Appendix VIa: MATLAB -Simulink diagram of the designed single phase active harmonic filter

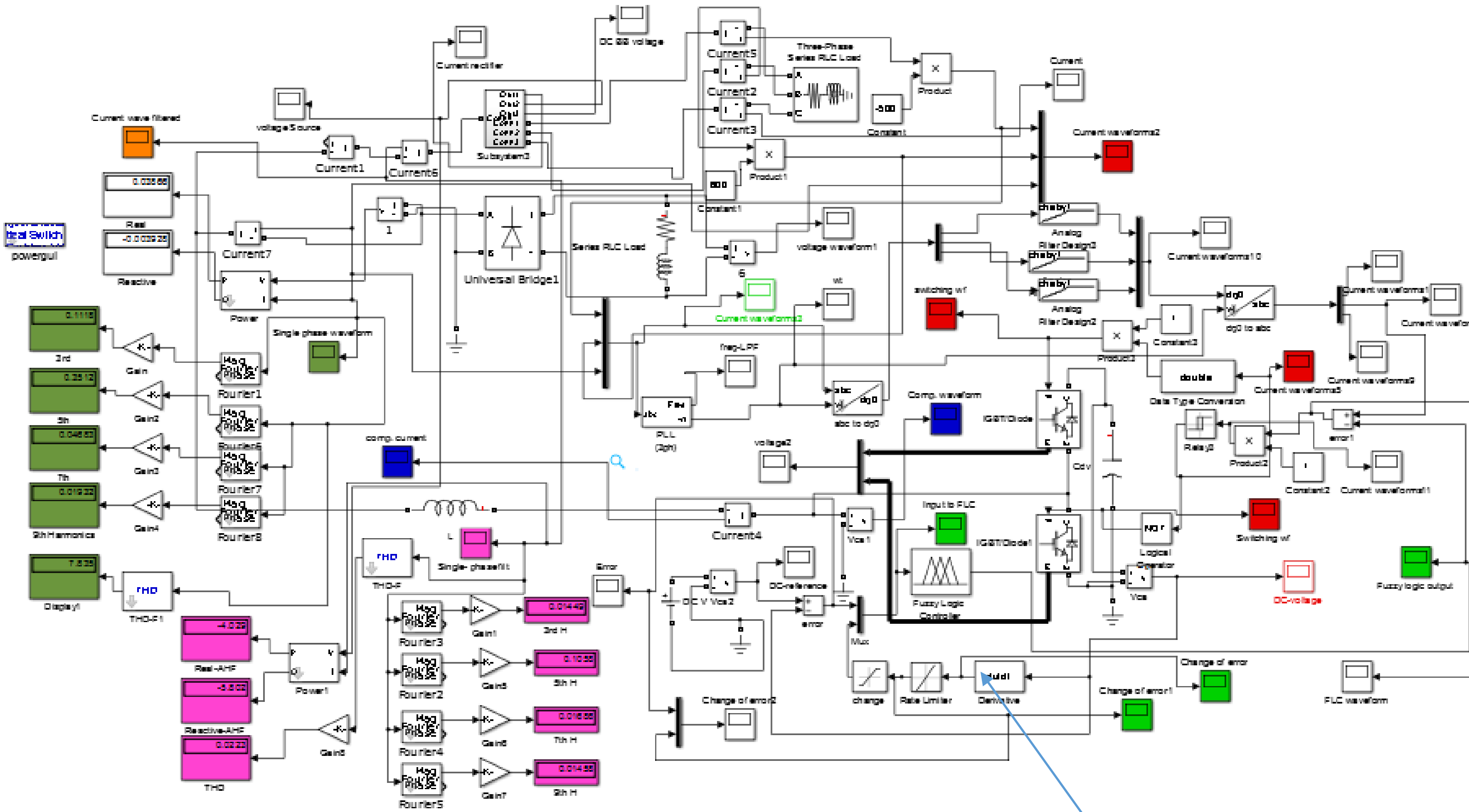


Figure 7a): The designed single-phase active harmonic filter using synchronous frequency frame extraction method. Fuzzy Logic controller