MODELING AND SIMULATION OF COMPACT FLUORESCENT LAMP FOR THE ANALYSIS AND MITIGATION OF HARMONICS INJECTION INTO POWER DISTRIBUTION NETWORK

By

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AHMADU BELLO UNIVERSITY ZARIA

NIGERIA

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By

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DEPARTMENT OF ELECTRICAL ENGINEERING
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NIGERIA

JULY, 2017

Declaration

I, declare that the work in this dissertation entitled “modeling and simulation of compact fluorescent lamp for the analysis and mitigation of harmonics injection into power distribution network” has been performed by me in the Department of Electrical and Computer Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this Dissertation was previously presented for another degree or diploma at this or any Institution.

Bashir Musa UMAR _____ _____

Signature Date

Certification

This dissertation entitled “modeling and simulation of compact fluorescent lamp for the analysis and mitigation of harmonics injection into power distribution network” by Bashir Musa UMAR meets the regulations governing the award of Master’s Degree (M.Sc.) Electrical Power Systems Engineering of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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Dedication

This dissertation is dedicated to my late father, Malam Umaru. May Aljannatul Firdausi be his final abode. Aamin.

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Firstly, I would like to profoundly thank Almighty Allah for sparing my life, keeping me physically and emotionally stable, as well as for giving me this golden opportunity to undergo master degree program in Electrical Power Systems Engineering in this great University (The Ahmadu Bello University).

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Abstract

Modern electrical devices such as Compact Fluorescent Lamp (CFL), many of which are non-linear loads inject harmonics into the Power Distribution Network (PDN). For the devices to operate efficiently as well as reduce electricity consumption and environmental impacts without introducing undesirable side effects, such as harmonics into the distribution network, the devices performance need to be analyzed. CFL has highest penetration level of about 80% compared to other lighting devices. The current and voltage Total Harmonics Distortion (THDi and THDv) being emitted by CFL are within the range of 90% – 200% of the fundamental current and 20% - 40% of the fundamental voltage respectively. These harmonics cause power quality problems such as overheating of Distribution Transformer (DT) and low tension conductors, mal-operation of energy meter, deterioration of protective equipment. The combined effects of these small sources are as detrimental as one large source. Mitigation of these harmonics is even harder once injected into the network due to their distributed nature. Consequently, this research work modeled and simulated compact fluorescent lamp for the analysis of harmonics injections into power distribution network. A suitable method was also developed for mitigating the harmonics emissions before they are injected into the distribution network with the view to mitigating their effects. Linear Technology Spice (LTspice) software package was used to generate voltage and current waveforms. The acquired waveforms were used to simplify the Fast Fourier Transform (FFT) harmonics analysis generic algorithm, which was found to be simpler than the generic. Analysis of the CFL harmonics was carried out using the simplified algorithm; LTspice software as well as powergui analyzer software on MATLAB R2012a. The results obtained for THDi and THDv were in relation to the CFL fundamental current and voltage: 135.50% and 35.43%; 130.13% and 33.64%; as well as 130.08% and 36.55% with simplified FFT harmonics analysis algorithm, LTspice software, and Powergui harmonics analyzer respectively. The results were

observed to be in agreement with laboratory test bed results which were averagely 128.90% and 31.60% of the fundamental current and voltage for THDi and THDv respectively. These results were found to be violating the IEEE standard limits for harmonics. Analog passive series and shunt filter networks were also developed. CFL Simulink models with the series and shunt passive harmonics filters networks were developed. The FFT harmonics analyses results of the developed Simulink models were: 9.54% and 5.00% of the fundamental current and voltage for the THDi and THDv with the series filters; 3.65% and 0.05% of the fundamental current and voltage respectively were obtained with the shunt filters. It was observed that the levels of reductions of THDs of the CFL were in compliance with the IEEE 519-2014 standard harmonics limits.

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List of Abbreviations

Abbreviation	Definition
AC	Alternating Current
AF	Audio Frequency
CFL	Compact Fluorescent Lamp
CLP	Constant Load Power
CMR	Current Measurement Resistor
DC	Direct Current
DFT	Discreet Fourier Transform
DN	Distribution Network
DPF	Diversity Power Factor
DT	Distribution Transformer
EB	Electronic Ballast
EMTP	Electro Magnetic Transient Program
EPS	Electrical Power System
FFT	Fast Fourier Transform
FL	Fluorescent Lamp
GUI	Graphical User Interface
HD	Harmonic Distortion
IC	Integrated Circuit
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineering
IHDi	Individual Current Harmonic Distortion

IHDv	Individual Voltage Harmonic Distortion
IL	Incandescent Lamp
IPC	Industrial Power Corruptor
kHz	kilo Hertz
LTspice	Linear Technology Spice
MHz	Mega Hertz
MVA	Mega Volt Ampere
PCC	Point of Common Coupling
PCs	Personal Computers
PDN	Power Distribution Network
PF	Power Factor
PTC	Positive Temperature Coefficient
RF	Radio Frequency
SMPS	Switched-Mode Power Supply
Std	Standard
THD	Total Harmonic Distortion
THDi	Current Total Harmonics Distortion
THDv	Voltage Total Harmonics Distortion
TV	Television
UPS	Uninterrupted Power Supply
WT	Wavelet Transform

CHAPTER ONE

INTRODUCTION

1.1 Background

In recent time there has been considerable increase in the number of Compact Fluorescent Lamp CFL connected to electrical power distribution network. From the viewpoint of the electric utility industry, it is important to understand the impacts of such devices on distribution network.

Compact Fluorescent Lamp is an extension of Fluorescent Lamp (FL). CFL is designed to replace Incandescent Lamp (IL) and fit into most existing light fixtures especially those for the IL (Mansurali and Swamynathan, 2014). This is due to the following advantages of Compact fluorescent lamps (CFLs) over Incandescent Lamps (ILs) (Cunill-Solà and Salichs, 2007 and Singh and Katal, 2013):

i. CFLs are cost efficient.

ii. CFLs are energy efficient.

iii. CFL has longer lifespan (10,000hrs).

Due to the above listed advantages of CFL, the lamps are being promoted by governments and electricity supply utilities worldwide as part of energy conservation program (Jabbar *et al.,* 2008). CFLs are increasingly being used for residential and commercial applications, retrofitting a large number of IL and other lighting devices.

One major disadvantage of CFL is that it increases level of disturbances that might affect customer as well as utility equipment on the distribution system, (Pourarab *et al.,* 2011). This is due to the fact that it emits and injects harmonics into the power distribution network. Power System harmonic is a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the power system fundamental frequency (Feng *et al.,* 2013).

CFL operates through chemical reaction unlike IL that operates through heating (Singh and Katal, 2013). Every CFL uses Electronic Ballast (EB) circuit to generate a high frequency within the range of 10 kHz to 40 kHz which in turn enables the tube to emit visible light from its inner coating (Jabbar *et al.,* 2008). In other words, EB of the CFL uses rectifier to input power to an inverter which in turn supplies necessary AC power to the lamp, (Singh and Katal, 2013). The phenomena of ballast circuit are the major sources of harmonics in CFLs. It is responsible for rise in harmonics current injections into the electrical power distribution Network. A typical CFL consists of three main parts as in Plate 1.1. The screw base and housing which holds the unit firm in a lighting fixture, it also serves as neutral for the supply to the lamp as well as houses the electronic ballast circuit. The electronic ballast circuit which supply and maintain sufficient current in the lamp circuit. Finally, the lamp emits visible light.

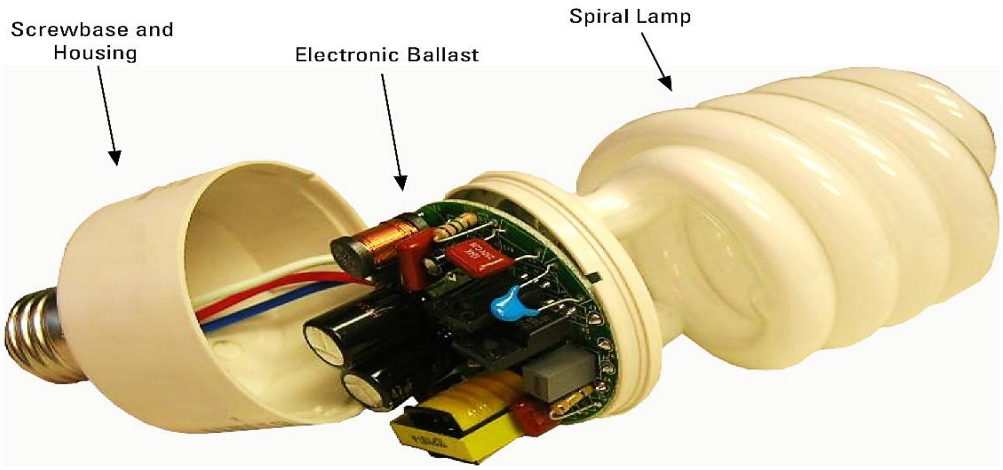


Plate 1.1: CFL Three Main Parts (Oramus *et al.,* 2013).

The operation of CFL is carried out in three main stages based on the works of Shafi *et al.,* (2007) and Moulahoum *et al., (*2013) as in Figure 1.1.

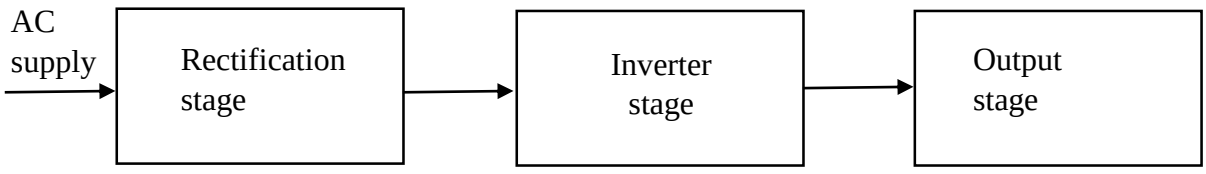


Figure 1.1: Block Diagram of CFL Operation Stages

The first stage is rectification stage. This stage consists of a full bridge diode rectifier circuit that converts AC to DC. A series resistor R_F which serves as current peak limiting component and a fuse for protection is connected at the input side to this stage. The DC obtained at the stage is filtered by a capacitor C_{Bus} to provide a smooth DC voltage for the resonant inverter in the second stage known as inverter stage. The lamp in the last stage (Output stage) is powered by the inverter. The resulting frequency at this stage which self-oscillates between 10 – 40 kHz is associated with high voltage which provides an invisible light that strike the coating in the inner side of the tube. The coating emits visible light for the normal operation of the lamp. The electronic configuration of the stages is in Figure 1.2 (Shafi *et al.,* 2007 and Moulahoum *et al.,* 2013). A Positive Temperature Coefficient (PTC) device (Thermistor) is connected by some manufacturers across the terminals of the lamp to prolong tube life span (Oramus *et al.,* 2013).

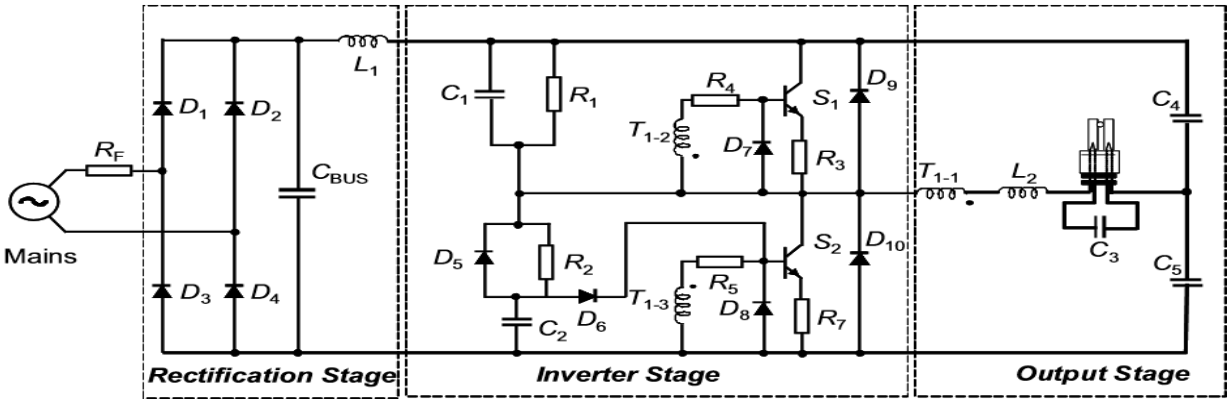


Figure 1.2: A Typical CFL Circuit (Shafi *et al.,* 2007 and Moulahoum *et al.,* 2013)

Compact fluorescent lamp generates harmonics during its operation. According to Nassif and Acharya, (2008) and Oramus *et al.,* (2013), the current and voltage total harmonics distortion of most commercially available CFL are within the range of 90 – 200% and 20 – 45% respectively with a corresponding power factor within the range 50 - 65%. However, the current and voltage THD limits of the CFLs with electronic ballasts according to Institute of Electrical and Electronics

Engineers (IEEE) Std. 519-2014 and International Electro technical Commission (IEC) are 20 % and 8% (Niitsoo, 2011). Harmonics are usually a superposition of signals which are multiples integer of power system fundamental frequency (50Hz or 60Hz as the case may be); they can be voltage or currents (Jabbar *et al.,* 2008, Elphick *et al.,* 2010 and Ndungu *et al.,* 2012,). The harmonics being generated by CFL are due to the conversion of the frequency from one low level to a much higher level (50 or 60 Hz to 80 kHz), (Jabbar *et al.,* 2008 and Teodosescu *et al.,* 2012). Therefore, proliferation of CFLs increases the harmonics level in power distribution system that could adversely affect the system as well as the consumers (Pourarab *et al.,* 2011).

Some of the effects caused by harmonics to the power system are (Fehér and Puklus, 2007):

A. Distorted line current

i. Reduced power factor means reduced available power, increased distribution losses (exacerbated by sky and proximity effects).

ii. The third harmonics means excessive current in neutral conductor (danger of fire).

iii. Overheating of transformers and generators (copper losses).

iv. Increased audio noise, increased telephone interference.

B. Distorted Line voltage (caused by distorted line current due to the presence of distribution impedance)

i. Overheating of transformers and generators (increased iron losses).

ii. Cogging (refusal to start smoothly) and crawling (very high slip) in induction motors; mechanical oscillations.

iii. Overheating of Power Factor correcting capacitors (premature failure).

iv. Dielectric stress in insulation systems.

v. Resonances (overvoltage insulation failure).

vi. Impaired performance of power-line communication systems.

In summary, harmonics if not mitigated affect power quality of the entire distribution system through (Rawa *et al.*, 2015):

i. Increase in voltage distortion.

ii. Equipment failure.

iii. System resonance.

iv. Increase system losses.

v. Decrease system efficiency.

Some researchers attempted to provide platform for the harmonics being generated by CFLs to be quantified for its mitigation before it is injected into the network (Molina et al., 2014). This is because, if the harmonics are not mitigated and once injected into Distribution Network (DN) is difficult to do so and this could seriously affect the performance of the Power Distribution Network (PDN) (Ingale, 2014).

Some previous works on modeling of the CFL for harmonic analysis used laboratory test bed to take measurements of the harmonic emissions of individual or grouped CFLs in order to provide platform to analyze harmonics. This method is associated with challenge of cut-off of harmonics being injected to the lamp by the distribution network through the AC current being drawn by it. This affects accuracy of the overall results. In order to clearly quantify the harmonics produced by CFLs precisely, a more appropriate procedure for modeling the lamp is required, (Rawa *et al.*, 2014).

Other researchers carried out harmonic analysis in frequency domain. In the method of harmonic analysis in frequency domain, the principle of superposition is applied to enable each harmonic to be considered separately. The differential equations obtained are usually converted to complex algebraic equations. These equations are then represented by complex phasor either in rectangular

or polar form. Even though this method was said to have advantage of computational efficiency, it is complex.

In view of the above, this research modeled and simulated compact fluorescent lamp for analysis of harmonics injection into power distribution network using software packages (LTSpice and MATLAB R2012a) and developed an appropriate method of the harmonics emission reduction with the view to mitigating their injection into the power distribution network.

1.2 Problem Statement

Harmonics distortion in power systems has been attracting significant attention of researchers recently. This is largely due to the mass use of nonlinear loads such as CFL which increases problem with the network voltage and current distortion (Molina and Sainz, 2014). CFL emits and injects harmonics into the Power Distribution Network (PDN) (Molina and Sainz, 2014). Power System (PS) harmonics are multiple integer of the fundamental power system frequency. The combined effects of the wide use of CFLs can be just as detrimental as one large harmonics source (Yong *et al.,* 2010). Moreover, mitigation of harmonic distortions caused by nonlinear load such as the CFL is very difficult once they are injected into power distribution network (Watson *et al.,* 2007). Therefore, this research modeled and simulated compact fluorescent lamp for the analysis and mitigation of harmonics emissions before they are injected into power distribution network.

1.3 Justification of the Research

The research is carried out with the view to reducing CFL current and voltage harmonics injections into power distribution network to conform to the IEEE-519 2014 standard limits. This effort will improve power quality of the network by reducing losses, overheating of equipment, avoiding system resonance etc. It will also improve the power quality of the lamp and this will help

consumers making some savings for not replacing the lamp at a shorter life span as mentioned by the manufacturers.

1.4 Aim and Objectives

The aim of the research is modeling and simulation of compact fluorescent lamp for the analysis and mitigation of harmonics injection into power distribution network.

The objectives of the research are to:

i. develop CFL model and determine its current and voltage total harmonics distortions being injected into power distribution network.

ii. develop analog passive harmonics filter network for the CFL harmonics injections mitigation.

iii. validate results obtained through comparison with measured values from experimental fixed-bed.

CHAPTER TWO

LITERATURE REVIEW

2.1 Review of Fundamental Concepts

Some fundamental concepts related to this research work are reviewed. Some of the concepts discussed here are power system harmonics, power factor, support model equations relevant to the research and other aspects of significance to the research.

2.1.1 Power system

Electric power system is a network of electrical components installed to supply, transfer, and use electric power. Also, it is known as the grid (Weedy et al., 2012). A grid consists of three main sections: the generators that supply the power; the transmission system that carries the power from the generating centers to the load centers; and the distribution system that feeds the power to nearby homes and industries. Smaller power systems are also available in some industries, hospitals, commercial buildings and homes. The majority of these systems rely upon three-phase AC power (Kersting, 2012). A typical power system diagram is given in Figure 2.1 (Weedy *et al.*, 2012)

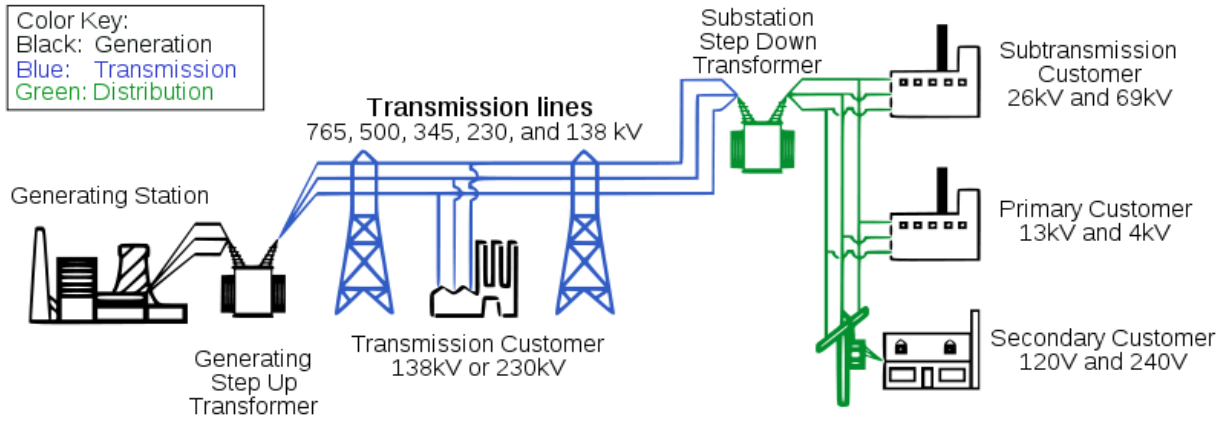


Figure 2.1: Electric Power System Diagram (Weedy *et al.*, 2012)

Each section of the power system consists of many components interconnected to give the desired output. A problem associated with any of the sections means no supply to the consumer.

2.1.2 Harmonics in power system

One of the major power quality concerns is harmonic (Singh *et al.*, 2014). The main objective of electricity utility is to deliver sinusoidal voltage at fairly constant magnitude throughout the power system. However, there are loads on the system that produce harmonics currents, this result in distorted current and voltage waveforms that adversely impact the system performance, (Singh *et al.*, 2014).

Harmonics are considered by-products of modern electronic devices such as Personal Computers (PCs), laser printer, Television (TV) sets, battery chargers, Un-interrupted Power Supply (UPS) units, CFLs etc. These loads that are being powered by Switched-Mode Power Supply (SMPS) unit are referred to as nonlinear loads. They create harmonics by drawing current in abrupt short pulses. Any DN feeding nonlinear loads will contain some degree of harmonic frequencies (Sekaran & Anbalagan, 2008 andPourarab *et al.*, 2011). Due to the rapidly increasing number of nonlinear loads in DN, the harmonic distortions ofcurrent and voltage increase (Singh and Singh, 2010). As the number of harmonics-producing loads at the consumer end increases over the years, it has become increasingly necessary to address their effects on the DN (Tripathy *et al.*, 2010). The existence of harmonics that caused waveform distortion of the signal in electrical power system (EPS) is common, and its effect is harmless as long as it is maintained at the acceptable level of 8% for THDv and 3% for Individual Harmonic Distortion in voltage (IHDv) considering system with voltage level up to 69kV as recommended by IEEE Std. 519-2014 (Farooq *et al.*, 2013). The limit for THDi is 20% and limits for Individual Harmonic Distortion in current (IHDi) is given in Table 2.1 (Farooq *et al.*, 2013).

Table 2.1: IEEE Individual Harmonic Distortions in Current Limits (IEEE 519-2014).

Harmonic Order	***h*<11**	**11≤*h*<17**	**17≤*h*<23**	**23≤*h*<35**	***h*≥35**
% IHD_i	4.0	2.0	1.5	0.6	0.5

With rapid advancement of power electronics and electrical devices, the power system harmonics have attracts more attention of researchers. Power quality of DN is severely affected due to the flow of these generated harmonics. Harmonic currents generated by nonlinear loads can cause problems in the power system (Efe, 2015). Feng *et al.*, (2013) attributed excessive heat in electrical appliances which is responsible for the reduction in the life span of the distribution transformer; increase in power consumption; reduction of system efficiency; lowering of the system power factor which increases monthly utility bills to harmonics in some countries. Harmonic Distortion (HD) is the degree to which a waveform deviates from its pure sinusoidal waveform as a result of the summation of all harmonic elements (Efe, 2015). While Total Harmonic Distortion (THD) is the summation of all harmonic components of the voltage or current waveform compared with the fundamental component of current or voltage. The Total Harmonic Distortion in Voltage (THDv) and Current (THDi) can be calculated using the following equation (Venkatesh *et al.*, 2008 and Efe, 2015).

$$THDv = \frac{\sqrt{\sum_2^\infty V_n^2}}{V_1} \tag{2.1}$$

$$THDi = \frac{\sqrt{\sum_2^\infty I_n^2}}{I_1} \tag{2.2}$$

Furthermore, the THD is related to Power Factor (PF) in a nonlinear load as in the following equation (Nassif and Acharya, 2008).

$$PF = \frac{DPF}{\sqrt{1+THD^2}} \quad (2.3)$$

When the phase shift between the voltage and the fundamental component of the current is zero, the purity (the 50/60Hz power factor) also known as Distortion Power Factor (DPF) is unity and therefore equation (2.3) becomes (Venkatesh *et al.*, 2008):

$$PF = \frac{1}{\sqrt{1+THD^2}} \quad (2.4)$$

where,

V, V_1 and V_n: total, fundamental and harmonic voltages, V.

I, I_1 and I_n: total, fundamental and harmonic currents, A.

2.1.3 Power factor

Power Factor (PF) is defined as a measure of how effectively electricity is being used (Ise *et al.*, 2000). In other words, Power factor also known as Cos θ is defined as the ratio of the average power converted by the load (i.e. ratio of the active power which is the real power of the fundamental frequency P_1) to the maximum average power that may be converted to the apparent power of the fundamental frequency, S_1) considering the same Root Mean Square (RMS) values of voltage and current as given in the following equation (Niitsoo, 2011 and Dolara & Leva, 2012).

$$PF = Cos\ \theta = \frac{P_1}{S_1} \quad (2.5)$$

where,

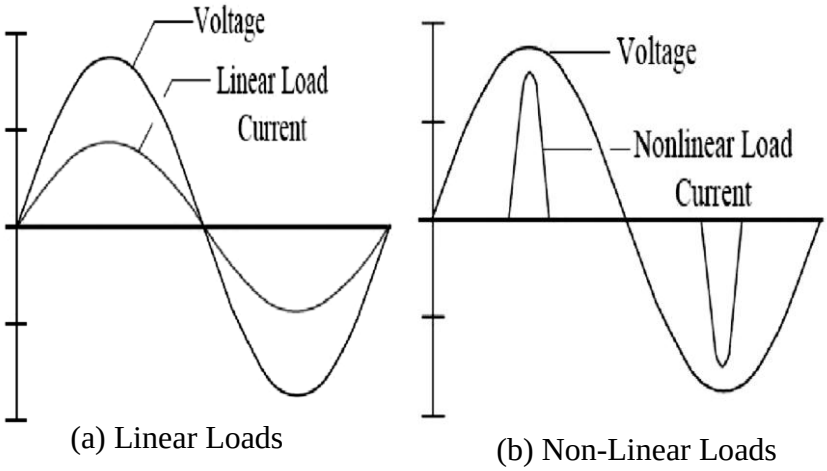
P_1 is the real power, W.

S_1 is the apparent power, VA.

Factors that cause low power factor are excess reactive current and harmonics current. Sources of reactive power are capacitive and inductive loads. Capacitive load produces an electric field thereby generating reactive power. However, inductive load produces magnetic field therefore absorbs reactive power (Ndungu *et al.,* 2012). CFL produces electric field consequently, generates reactive power. In this case power factor is leading power factor and high odd harmonics pollution resulted, (Ndungu *et al.,* 2012).

2.1.4 Production of harmonics

There are two types of load in electrical power system, linear and nonlinear loads (Shmilovitz *et al.,* 2007). A linear load is any electrical device that draws current from the source which is directly proportional to the applied voltage, provided the current drawn is of sinusoidal or undistorted type. Examples of linear loads are: resistance heaters; ILs etc. The current and voltage waveforms of linear loads are as in Figure 2.2a. A nonlinear load is a type of electrical load which draws current from the source that is different in shape with the applied voltage. The current waveform of nonlinear load differs from that of the applied voltage as in Figure 2.2b (Feng *et al.,* 2013).



(a) Linear Loads (b) Non-Linear Loads

Figure 2.2: Current and Voltage Waveforms (Ingale, 2014)

If a signal is periodic with frequency f, the only frequencies compose of the signal are integer multiples of f, i.e., f, 2f, 3f, 4f, etc. These frequencies are called harmonics. The first harmonic is f, the second harmonic is 2f, the third harmonic is 3f, and so forth. The first harmonic (i.e., f) is also called the fundamental frequency (Ndungu *et al.,* 2012). Operation of nonlinear electric loads in electric power system is responsible for emission of harmonic current and voltage into the system. Harmonic frequencies in the power grid are frequent cause of power quality problems. Harmonics in power systems result in increased heating in the equipment and conductors, misfiring in variable speed drives, and torque pulsations in motors. Analysis and reduction of harmonics are considered desirable (Wen *et al.,* 2011 and Ingale, 2014).

Symmetrical wave is the waveform in which its positive portion of the wave is the same as the negative portion of the wave. On the other hand, unsymmetrical wave contains a DC component or offsets or the load is designed such that the positive portion of the wave is different from the negative portion. An example of unsymmetrical wave is a half wave rectifier (Feng *et al.,* 2013). Most power system equipment nowadays are symmetrical. However, there are exceptions in the way that normally-symmetrical loads may also produce even harmonics due to component mismatches or failures (Feng *et al.,* 2013).

2.1.5 Types of harmonics

There are two types of Harmonics. These are odd and even harmonics. Odd harmonics distortion is dominant in supply voltage and load current (Bollen *et al.,* 2006). Third harmonic component is responsible for change in the crest factor (Cristaldi *et al.,* 2002). The effect of the distortion is the same for both the positive and negative halves of the sine wave. The positive cycle is the same as the negative cycle of the voltage wave as long as only odd harmonics are presents in the voltage. Even harmonics are normally small. They are being generated by some large converters, transformer energizing (temporary increase), but modern rule on harmonic distortion state that

equipment should not generate any even harmonics. In fact, a measurement of supply voltage shows that the amount of even harmonic is indeed very small (Ingale, 2014). Even harmonic distortion results in changing positive and negative half cycles of the signal to as-symmetrical. They only occur in the presence of a DC component. The signal is not symmetrical with respect to zero axis if there are significant amount of even order harmonics (Cristaldi *et al.,* 2006). Symmetrical waves contain only odd harmonics whereas un-symmetrical waves contain both even and odd harmonics (Feng *et al.,* 2013). The two most commonly used indices for measuring the harmonic content of the waveform are the total harmonic distortion of current and voltage (THDi and THDv) (Ingale, 2014).

2.1.6 Concept of wave distortion

It is essential to analyze the distorted waveform by harmonics analysis in order to understand the distortion phenomena and provide appropriate method for its emission mitigation. Harmonic analysis enables the expression of the distorted waveform as a sum of DC component, fundamental sine wave of the distorted waveform and series of pure sine waves. Sine waves have different magnitudes, and their frequencies are integer multiple of the fundamental distorted waveform and this is Fourier series representation. A distorted waveform can be studied using Fourier's series through the following equations (Feng *et al.,* 2013).

$$F(t) = a_0 + \sum a_n\, Cos(n\omega t) + b_n\, Sin(n\omega t) \tag{2.6}$$

$$a_0 = \frac{1}{T}\int_0^T f(t)d(t) \tag{2.7}$$

$$a_n = \frac{2}{T}\int_0^T f(t)Cos(n\omega t)d(t) \tag{2.8}$$

$$b_n = \frac{2}{T}\int_0^T f(t)Sin(n\omega t)d(t) \tag{2.9}$$

where,

$n = 1, 2, 3 \ldots$

f(t) is the function in time domain.

ω is the fundamental frequency.

a_n and b_n are Fourier cosine and sine coefficients respectively.

When the positive and negative half cycles of a waveform have the same shapes with respect to the vertical axis and the average value of its period is equal to zero, the Fourier series contains odd harmonic components only (Collin et al., 2014).

Single phase nonlinear loads are prevalent in modern applications. Harmonics are caused by and are the byproducts of modern personal electronic equipment as mentioned earlier. It can be seen that even though different equipment will show their different harmonics profiles, but the same equipment from different manufacturers will show more or less the same characteristic harmonics pattern, (Rawa and Thomas, 2015).

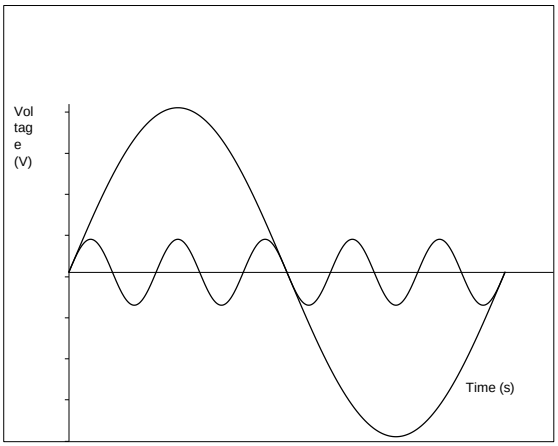


Figure 2.3: Fundamental Waveform and its Harmonic Component (Franco *et al.*, 2015)

The concept of waveform distortion is demonstrated in Figure 2.3. The waveform of larger amplitude and lower frequency is the fundamental waveform and the distorted waveform is the one with smaller amplitude and higher frequency (Franco *et al.*, 2015). The resulting signal of the

sum of the two waveforms is as depicted in Figure 2.4. The waveform is not a perfect sinusoidal (Franco *et al.*, 2015).

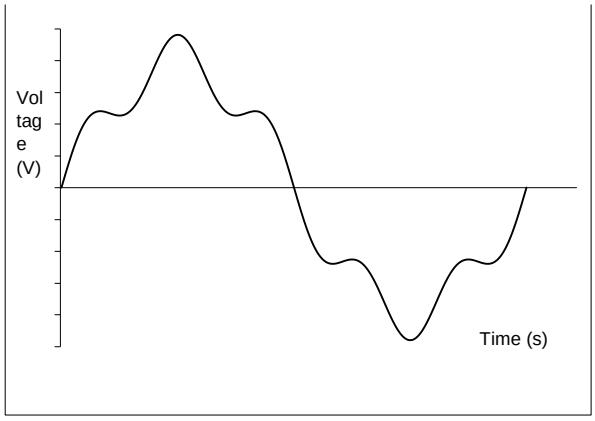


Figure 2.4 Waveform of a Voltage Signal Distorted by Harmonic Component (Franco *et al.*, 2015)

2.1.7 Methods of harmonics analysis

Harmonics analysis is carried out using any of the following four methods (Singh et al., 2014).

i. Wavelets Transform (WT).

ii. Instantaneous reactive power (P - Q) theory.

iii. Fast Fourier Transform (FFT).

iv. Filter.

2.1.7.1 Wavelets transform

Wavelet is a mathematical (tool) function used to divide a given function or continuous-time signal into different scale components (Akansu *et al.*, 2010 and Kaiser, 2010). It is of two types: discrete and continuous wavelet transforms. A discrete wavelet transform is one for which the wavelets are discretely sampled while continuous wavelet transform is a convolution of the input data sequence

with a set of functions generated by the mother wavelet. Wavelet function is mathematically expressed as in the following equation (Chui, 2014):

$$\varphi(t) = \frac{\sin(2\pi t) - \mathrm{Sin}(\pi t)}{\pi t} \quad (2.10)$$

Wavelet transform is applied in a signal for data compression or signal coding (Akansu *et al.,* 2010). Data compression in signal processing also known as source coding or bit-rate reduction is a process of encoding signal using a fewer bits than the original representation (Kaiser, 2010 and Chui, 2014).

Wavelets are localized in both time and frequency domains. However, it is associated with the following disadvantages (Singh *et al.,* 2014, Ingale, 2014 and Gupta *et al.,* 2015)

i. Frequency/time resolution trade-off.

ii. Sometimes the original signal must be sampled logarithmically in time, which is only useful for certain types of signals.

iii. It is computationally complex.

2.1.7.2 Instantaneous reactive power theory

The instantaneous reactive power (p-q) theory is based on set of instantaneous powers defined in time domain and uses the Park transform (Czarnecki, 2006). This method is used only in three-phase circuits. In p-q theory method, instantaneous currents and voltages are converted to instantaneous space vectors. These space vectors are easily converted into the α – β orthogonal coordinates. The instantaneous three phase currents and voltages as well as instantaneous real and imaginary powers are calculated using the following equations (Afonso *et al.,* 2003 and Herrera & Salmeron, 2007).

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (2.11)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2.12)$$

$$P_o = V_o I_o \quad (2.13)$$

$$p = V_\alpha I_\alpha + V_\beta I_\beta \quad (2.14)$$

$$q = V_\alpha I_\beta + V_\beta I_\alpha \quad (2.15)$$

where

$V_{\alpha,}$ V_β and $I_{\alpha,}$ I_β are instantaneous real and imaginary components of voltage and current respectively.

P_o is the instantaneous zero-sequence real power

p and q are the real and imaginary instantaneous powers

This method is based in the time domain; it is valid for both steady-state and transient operation, (Herrera & Salmeron, 2007). P-Q theory based method has simple circuit and is good when practically implemented but yield significant error during voltage variation and is restricted to three phase balanced load (Czarnecki, 2006).

2.1.7.3 Fast Fourier transform

A fast Fourier transform (FFT) is an optimized computational algorithm to implement the Discreet Fourier Transform (DFT) of an N samples. It computes the DFT of a sequence, or its inverse (Khalil and Ibrahem, 2013 and Sowjanya & Kumari, 2013). FFT computes the DFT of an N-element vector in N $\log_2$ N operations in contrast to the N^2 operations required for computing the DFT. (Franchetti *et al.,* 2009). FFT converts a signal from its original domain (often time or space) to a representation in the frequency domain and vice versa (Wörner, S., 2001 and Khalil and Ibrahem, 2013).

Fast Fourier transform is used to calculate the harmonic distortion and to separate even, and odd harmonics (Ingale, 2014). FFT plays significant roles in analysis, design, and implementation of discrete Fourier transform (Gupta *et al.,* 2015). FFT may be associated with some problems such as leakage, picket fence and aliasing effects. However, FFT possesses high computational efficiency and is simple to implement (Franchetti *et al.,* 2009). FFT calculation is based on the DFT equation (Khalil and Ibrahem, 2013):

$$F(n) = \sum_{k=0}^{N} X(k) W_N^n \tag{2.16}$$

where,

n = 0, 1, 2 … N-1

N: number of samples.

X (k): input signal.

W_N^n is the Twiddle factor and is given in the following equation.

$$W_N^n = e^{-\frac{j2k\pi n}{N}} \tag{2.17}$$

Equation (2.16) can be broken up into two summations of half the size of the original. The summations are 'Even terms' E and 'Odd terms' O as given in the following equation (Khalil and Ibrahem, 2013).

$$F(n) \quad = \sum_{k=0}^{\frac{N}{2}-1} X(2k)\, e^{\frac{-j2\pi kn}{\frac{N}{2}}} + W_N^n \sum_{k=0}^{\frac{N}{2}-1} X(2k+1)\, e^{\frac{-j2\pi kn}{\frac{N}{2}}} \qquad (2.18)$$

The first term of equation (2.18) is the even and the second term is the odd.

FFT may look complex but easier and more accurate to use when compared with other methods (Ingale, 2014).

The flowchart of FFT generic algorithm is as depicted in Figure 2.5 (Khalil and Ibrahem, 2013). The algorithm is found to be with some complex commands which need additional effort to interpret and it is seen to be very lengthy. These and some other reasons make it desirable to have a simplified algorithm for the CFL FFT harmonic analysis.

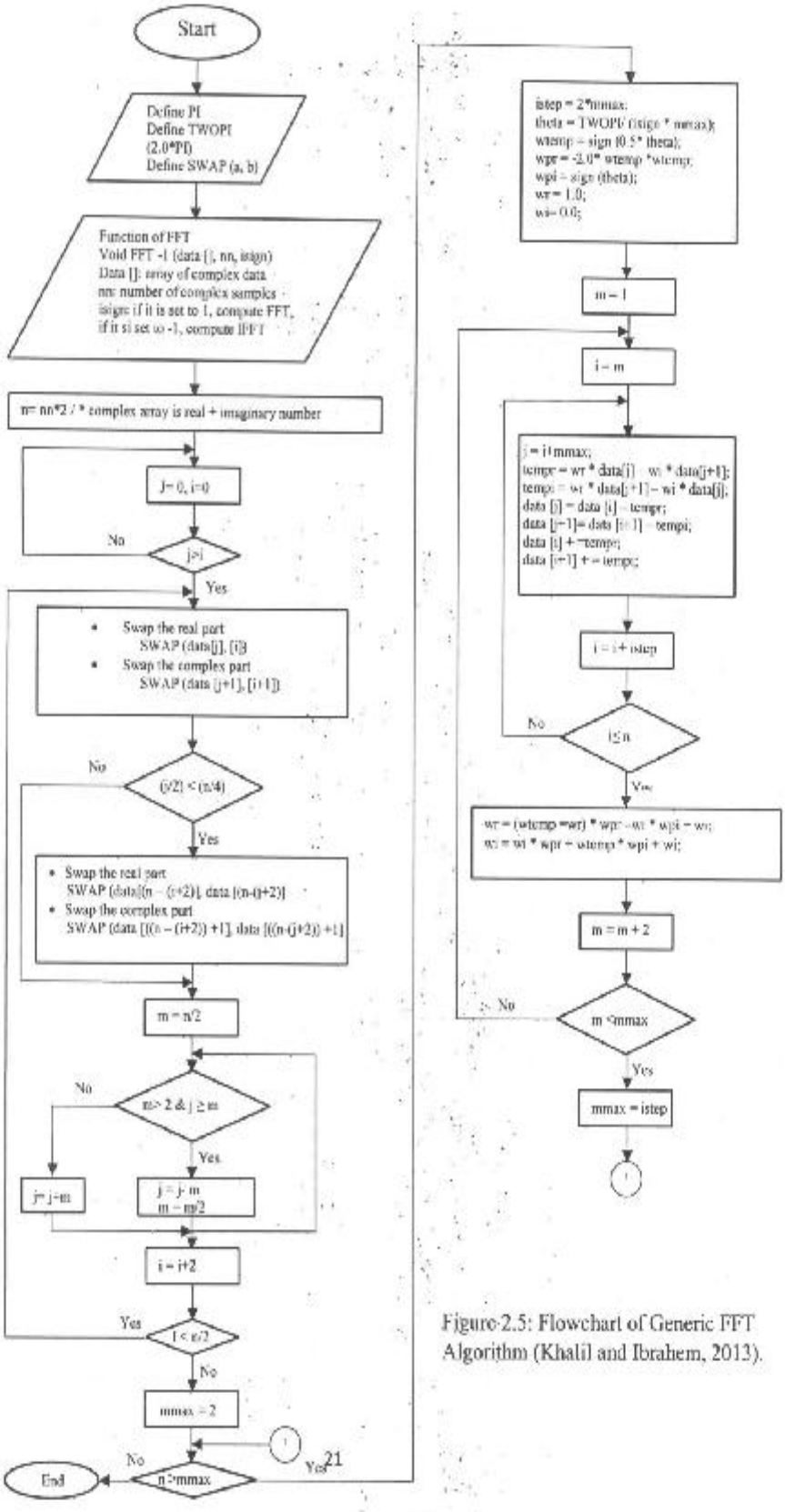


Figure-2.5: Flowchart of Generic FFT Algorithm (Khalil and Ibrahem, 2013).

2. 1. 7. 4 Filter method

Filter may be electrical, hydraulic, acoustical, etc. but the most commonly used is electrical type (Gufta, 2011). An Electric filter is a device that prevents some kinds of light, sound, electronic noises, etc., from passing through. In other words, filter is a network designed to attenuate certain frequencies but pass others without attenuation (Rabiner *et al.*, 2013 and Keerthi et al., 2016). This means that, filter separates some frequencies from others within a mixed-frequency signals. A filter circuit possesses at least a pass band which is a band of frequencies in which the output is approximately equal to the input which means attenuation equals zero and an attenuation band in which output is zero i.e attenuation is infinite (Gufta, 2011). Electric filters are practically used in all circuits which requires separation of signals according to their frequencies (Gufta, 2011).

a. Forms of filters

Filter networks are divided into two major forms (Gufta, 2011):

i. Active filter network which contains transistors and/or operational amplifiers in combination with R, L and C elements to obtain desired filtering.

ii. Passive filter network - this category of filter consists of series-Parallel combination of R, L and C elements.

b. Basic types of filter

Four broad types of filter which are widely used are as follows, (Lacanette, 1991 and Gufta, 2011):

i. Low-Pass filter – This type of filter allows only low frequencies to pass through, but attenuates (to a lesser or greater extent) all higher frequencies. The maximum frequency it allows to pass through is called cut-off or break frequency 'f_c';

ii. High - Pass Filter which allows signals with higher frequencies to pass from input to output while rejecting lower frequencies. The minimum frequency it allows to pass is also called

cut-off frequency 'f_c';

iii. Band Stop, wave traps, notch, band elimination, band-separation or band rejection Filter – This type of filter is a resonant circuit that rejects a certain band of frequencies while passing all frequencies below and above the rejected band;

iv. Band Pass or Pass Band Filter is a type of filter which is also a resonant circuit which is tuned to pass a certain band or range of frequencies while rejecting all frequencies below and above this set range.

Depending on the type of components, technique used in the design of filter and frequencies being considered in the filtering, a filter may generally be classified as (Gupta, 2011):

i. Analog or Digital filters – Depending on the type of technique used in the process of analog signals, the filter may be analog or digital. A filter designed to process analog signal using analog technique such filter is called analog while a filter designed to process analog signal using digital technique is called digital filter;

ii. Audio – Frequency (AF) or Radio Frequency (RF) – Filters may be classified to AF or RF according to the frequency range.

c. Topology of filters

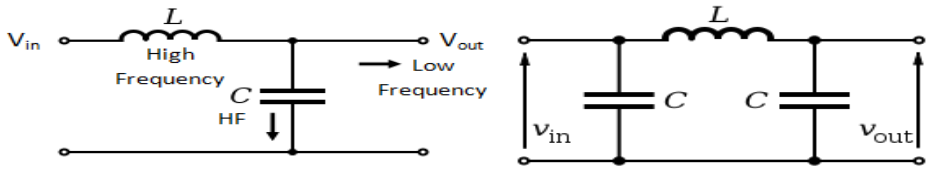
There are three topology based on which a filter can be designed (Theraja, 2012):

i. Inverted – L Type in which inductive reactance of the choke, L (X) blocks higher frequencies and Capacitor 'C' shorts them to ground. Hence only low frequencies below f_c (for which X is very low) are passed without significant attenuation.

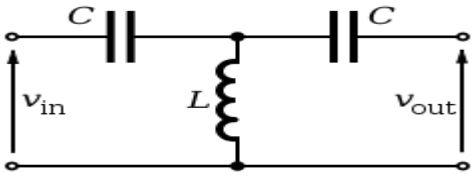
ii. π (Pi)– Type – This type of filter consists of an additional shunt capacitor 'C' which further improves the filtering action by grounding higher frequencies.

iii. T – Type - In this type of filter design, a second capacitor ‘C’ is connected on the output side which improves the filtering action.

The three topologies for designing an analog passive filters are as indicated on Figure 2.6



(a) Inverted – L Filter. (b) π - Filter



(c) T- Filter

Figure 2.6: Topology of Filter Circuit

The absolute value of capacitance, inductance and the series resistance of the nth order filter were calculated using the following equations respectively (Keerthi *et al.*, 2016).

$$C_n = \frac{Q_c}{m\omega {V_s}^2} \tag{2.19}$$

$$L_n = \frac{1}{n^2\omega^2\, C_n} \tag{2.20}$$

$$R_n = \frac{n\omega L_n}{Q_n} \tag{2.21}$$

where,

m is the number of branches in the passive filter for all the phases.

V_s is per-phase fundamental voltage across the filter.

ω is the fundamental frequency of the supply.

Q_n is the quality factor of the inductor of the nth order filter, which is normally considered as $10 < Q < 100$.

Analog filter is used for analysis of level of harmonics in a distribution network. Analog filter method is simple and cheap to implement (Ingale, 2014).

2.1.8 Methods of harmonics injection mitigation

In order to mitigate harmonics emission and injections into PDN, some researchers as well as some manufacturers considered introducing some filters into the circuit of CFL putting into consideration: Cost, size and weight of the CFL. However, this is not enough as the total harmonic distortions of CFL do not comply with the provision of IEEE Std. 519 2014 in most cases.

In terms of input system, CFLs are categorized into five categories, (Teodosescu *et al.,* 2012 and Oramus *et al.,* 2013):

2.1.8.1 Category I

In this category, the CFLs ballast circuits do not include filtering circuit, it consists of only basic input system, and so the total harmonic distortions are on the high side. Input system of these CFLs is as in Figure 2.7. This category of CFLs generates high harmonic current levels within the range of 90 and 200%, and is therefore, associated with poor power quality issues.

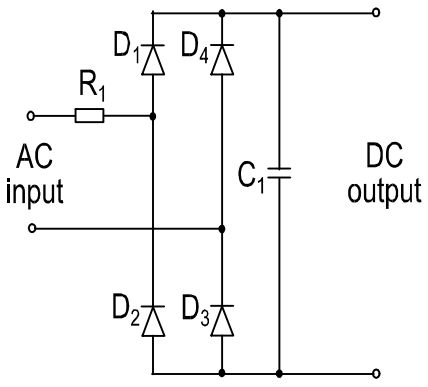


Figure 2.7: CFL Basic Input System (Oramus *et al.,* 2013 and Teodosescu *et al.,* 2012)

2.1.8.2 Category II

Here the design of the electronic ballast circuit consists of a passive filtering circuit at the input. This circuit uses a combination of inductor/capacitor (L_1/C_1) in inverted L- topology with a desired resonance frequency for the rectifier circuit as in Figure 2.8. The resonance frequency is usually three times of the line frequency. This technique of filtering is simple and therefore, easily implementable. However, there is need to improve on this method in order to reduce the THD to values within acceptable limits as recommended by the IEEE 519-2014.

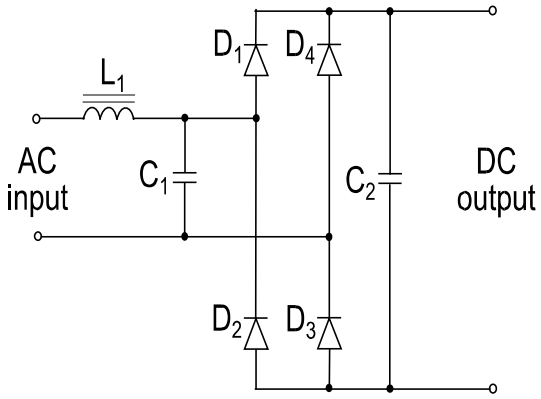


Figure 2.8: CFL Input System with Passive Filtering Circuit, (Oramus *et al.*, 2013 and Teodosescu *et al.*, 2012)

2.1.8.3 Category III

To better reduce CFL harmonics, the CFL circuit is altered to improve its current waveform. In the valley-Fill circuit, Figure 2.9, the filtering capacitor is splited into two small values C_1 and C_2 and are charged and discharged in alternate manner using the three diodes D_5, D_6 and D_7. The main drawback associated with this category is appearance of large voltage ripple on DC. This may reduce the CFL's life span.

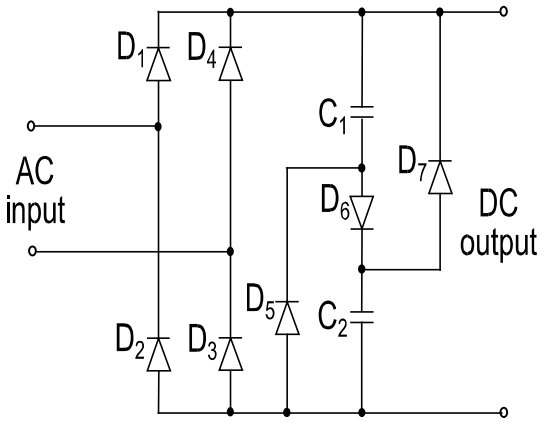


Figure 2.9: CFL Input System with Passive Filtering Circuit, (Oramus *et al.*, 2013 and Teodosescu *et al.*, 2012)

2.1.8.4 Category IV

In order to reduce the effect of Valley-Fill filtering method introduced in Category III, the circuit is improved by two identical capacitors C_1 and C_2 as in Figure 2.10. These two capacitors enhance the current waveform near cross-over point. Resistor R1 is connected to limit the charging current crests at the voltage peak.

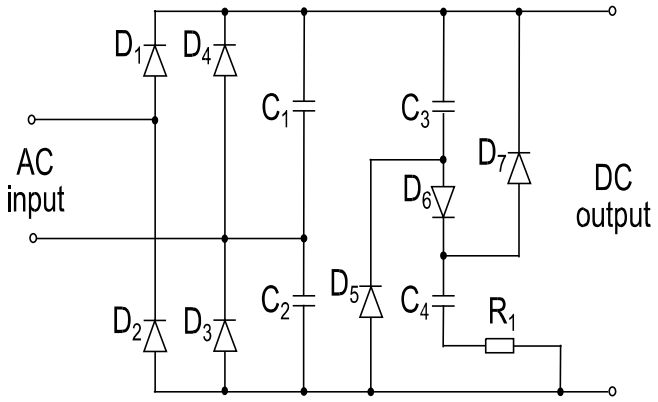


Figure 2.10: Improved Valley-Fill Filtering Circuit, (Oramus *et al.*, 2013 and Teodosescu *et al.*, 2012)

2.1.8.5 Category V

CFLs in this category consist of active filter circuit. In this method, the PF is controlled by a high frequency switch operated by means of Integrated Circuit (IC) chip as in Figure 2.11. This method of harmonic reduction is complicated and expensive compared with the passive filter method.

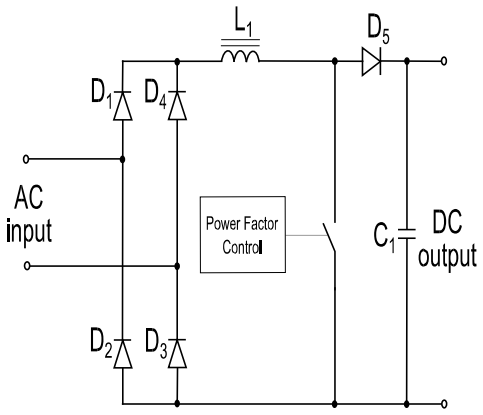


Figure 2.11: CFL Input System with Active Filtering Circuit, (Oramus *et al.*, 2013 and Teodosescu *et al.*, 2012)

Due to cost efficiency as well as size and weight considerations while constructing CFLs, some manufacturers construct CFLs without filters or with a filter that does not reduce the harmonics levels as expected to conform with the IEEE 519 2014 requirements on harmonics . These make many of the CFLs being imported in Nigeria substandard (Igwilo *et al.*, 2013). This action is one of the actions that have been contributing towards energy crises in Nigeria.

2.2 Review of Similar Works

In this section researches related to this work are reviewed. This is with the view to knowing the extent of research in the area, technique used and shortcomings.

Pileggi *et al.*, (1993) carried out a research on "the effect of modern compact fluorescent lights on voltage distortion". The study was one of the pioneers in the research area. It considered and measured harmonic contribution of CFLs of low input power of 9W to 33W which were used in a

residential area of 3,000 households. The work established that the CFL being used in the residential area would create a total load of 300kW to 500kW. In the study, the researchers used computer simulation of three real life 13.8kV feeders supplying consumers with nonlinear loads which included CFL with electronic ballasts. The computer simulations were supported by laboratory experimental measurements and in-the-home installation/monitoring of CFLs. The results obtained were used to develop load models. The research revealed that the input current to the CFL has unusually high total harmonic distortion, which was within the range of 116% to 142%.The research concluded that for safe operation of a 15kV feeder with a maximum 10MVA load capacity the total load of CFLs should not exceed 100kW. But this may cause unacceptable voltage distortion at some points along the feeder. Further, the research did not consider time duration factor of peak voltage distortion. 5% voltage distortion for a few minutes in a day may be tolerable and will have negligible impact on the distribution system, but the same distortion if it takes hours may cause damage to the system.

Mohamed *et al.,* (2010) conducted a study on "Harmonics from Compact Fluorescent Lamps" The research investigated the amount of harmonic generation from CFLs. This was achieved through laboratory test bed using Industrial Power Corruptor (IPC). The result of the study proved that CFLs produce harmonics as a result of their operation and increase the value of current THD along this type of electrical load. However, the results obtained are largely dependent on the value of the Current Measurement Resistor (CMR). Consequently, the integrity of the result may be affected when a large current greater than the limiting current of the CMR is drawn by the lamp.

Yong *et al.*, (2010) carried out a research on "A Frequency-Domain Harmonic Model for Compact Fluorescent Lamps". The research developed and verified three analytical CFL harmonic models. The developed models were frequency-domain harmonic models. A model was first developed which can accurately present the CFL harmonic-producing characteristics, but is complicated to

use. This model is suitable for assessing the collective impact in terms of harmonic injection into the distribution network of a large number of CFLs. This is because the model included the impact of supply-voltage harmonics on the harmonic currents produced by the CFLs. The model was subsequently simplified and two variants were proposed. They investigated the attenuation characteristics of CFLs using the model. This method is complex and is associated with too many assumptions as such the result will be largely affected due to large error involved.

Teodosescu *et al.,* (2012) conducted a research on "Study of the improvement of a CFL's power factor by using a valley fill filter" The research analyzed a method of improving a compact fluorescent lamp's power factor through the use of two passive valley filter. Circuit diagram of 18W Philips ecotone was put on Orcad program and simulated through computer. According to the researcher, the current total harmonic distortion was found to be 77% and was reduced to 66% and 29%. However, none of the results complied with the IEEE standard limit of 20%.

Mohamed *et al.,* (2012) did a study on **"**An Analysis of Harmonic Emission from Compact Fluorescent Lamps" The study analyzed harmonics generated from CFLs and compared them with those obtained from ILs. The research used laboratory tests on various CFLs and ILs in order to tap the load current behavior under different conditions. And it performed frequency domain based analysis. The study concluded that harmonic levels of dimmable and non-dimmable CFLs were experimentally evaluated and compared. The performances of dimmable CFLs and incandescent lamps at various brightness were also investigated. The results showed that the dimmable CFLs produced more harmonics compared to incandescent lamps and non-dimmable CFLs. Due to the fact that the AC current harmonic generation by the network conductors had to be isolated from that of the one generated by the load and coupled with the fact that the method is too mathematical, a software package based simulation may revealed more accurate.

Dolara and Leva, (2012) conducted a research on "Power quality and harmonic analysis of end user devices". The research used 300 MHz, four channels digital oscilloscope for the measurement of the voltage and current waveforms. The research investigated the effect of CFLs on power system in relation to harmonic distortions and low power factor inherently associated with CFLs. The study established that the lamps generate substantial harmonic distortions and leading power factor. However, it proposed that combination of IL and CFLs in one circuit would improve power quality of the distribution network. This method of harmonic analysis does not take into consideration idea of energy saving as using ILs to reduce the harmonics will result in energy wastage.

Oramus *et al.,* (2013) carried out a research on "Modeling of specific harmonics source in EMTP/ATP–case study of Compact Fluorescent Lamp". The research focused on CFL as widely used nonlinear load. Additionally, typical electric diagram of CFL registered current waveform and its analysis for single CFL, as well as numerical model of CFL in Electromagnetic Transient Program (EMTP) was presented. The Model of CFL developed in the study using EMTP simulation software may be useful for simulations related to analysis of influence of large number of CFLs installed into power network on power quality factors in low-voltage electrical distribution networks. However, this method is complex and this may have effect on the obtained result. To improve on it, an electronic model will be required to carry out the analysis.

Rawa *et al.,* (2014) conducted a research on "Experimental Measurements and Computer Simulations of FL and CFL for Harmonic Studies". The research developed a model which quantified the harmonics produced by FLs and CFLs. MATLAB Simulink was used to model and simulate the full models of FLs and CFLs to give close results to the experimental values. A Constant Load Power (CLP) model was also modeled and its results were compared with the full models of FLs and CFLs. According to the researchers, it is faster and easier to simulate the CFL

model using CLP model than the full model. However, using the developed CLP model, any variation in voltage may affect harmonics generated by the CFLs. Therefore, the CFLs must be supplied using programmable AC source chroma^{TM} that helps in isolating the test rig and filtering out harmonics and fluctuation from the main power supply. The model does not have universal application.

Molina and Sainz, (2014) presented a research on "Model of Electronic Ballast Compact Fluorescent Lamps" The research developed a CFL model based on the CFL equivalent circuit. The CFLs model was used for calculating their harmonic current injections into the distribution network, as well as a simple estimation algorithm for determining the model parameters from experimental measurements. The research proposed a simple method based on CFL supply voltage and ac current measurements to estimate the electrical parameters of the proposed CFL equivalent circuit. Both the proposed model and estimation algorithm were validated with laboratory tests. Significance of the model developed was limited to prediction of harmonic current emission by CFLs with large ac resistances and small dc capacitors. However, a model is required that can predict the emissions by any CFL into the distribution network.

Molina and Sainz, (2015) conducted a research on "Compact Fluorescent Lamp Modeling for Large-Scale Harmonic Penetration Studies". This research presented and discussed several approximate CFL models based on the harmonic-coupled admittance matrix model which reduces computational effort associated with other CFLs Models while maintaining reasonable accuracy. The computation time requirement and accuracy of the models were analyzed by simulation and laboratory measurements. The performance of the models was validated with CFL laboratory measurements. However, these models still require great computational effort in predicting harmonic current emission into the network for large-scale CFLs penetration studies which may greatly affect the predicted result.

In many of the literature reviewed, harmonics were the utmost concern in terms of power quality of the distribution network while using CFLs. However, results of previous works in analysis of harmonics were characterized with the following shortcomings.

i. Do not provide optimal harmonics injection mitigation.

ii. Do not have universal application.

iii. Complexity.

iv. Required large computational efforts.

In view of the above challenges, this research modeled and simulated compact fluorescent lamp for analysis of harmonics injection into power distribution network. LTspice software was used to develop CFL equivalent circuit which was used to develop CFL MATLAB Simulink model. FFT harmonics analysis of the CFL equivalent circuit was also carried out with the LTspice. Also, the research developed appropriate filters network MATLAB Simulink models for mitigating effects of CFL harmonics on power distribution network. Appropriate analog series and shunt passive filter networks were developed with the view to mitigating harmonics emission by CFLs.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Introduction

Details of the materials and methods used to model, simulate and analyze the compact fluorescent lamp harmonics emissions as well as methods of its injection mitigation are presented

3.2 Materials

The materials employed for the actualization of this research work are as follows:

3.2.1 Personal computer

LTspice CFL Simulations, FFT current and voltage harmonics analyses as well as display of the 3θ power and harmonics analyzer results were carried out using HP Notebook computer with the following specifications.

i. Intel(R) Atom (TM) CPU D2500.
ii. 1.86 GHz processor.
iii. 2.00GB installed memory (RAM).
iv. 32-bit Operating System (OS).

3.2.2. Compact fluorescent lamp

The ircuit diagram of real CFL 15 W half spiral, white in color, pin type CFL was used for the research work. The CFL was numbered MD HS-15W B22 (220-240V 50/60Hz 0.15A) which was a product of YESIMODI, a company in China. The CFL was made in China. Lifespan of the lamp was put at 8,000 hrs for 4 hrs operation per day by the manufacturer.

3.2.3 Power and harmonics analyzer

Three phase (3Ø) Power and Harmonics analyzer, PQ3350 made in Taiwan by EXTECH Instruments was used in the laboratory experimental test bed. This was in order to obtain the CFL current and voltage total harmonic distortions for the purpose of validation of the results obtained via FFT harmonics analysis method carried out under virtual platform using MATLAB R2012a on personal computer.

3.2.4 Current probe

Current probe, CAT III 600V, PQ3120 was used as one of the components of the laboratory experimental test bed to help determine the current total harmonics distortion using the 3θ power and harmonics analyzer. CAT III 600V was also made by EXTECH Instruments in Taiwan.

3.3 Method

The outlined objectives were achieved in line with the following procedures.

3.3.1 Acquisition of compact fluorescent lamp circuit diagram

The circuit diagram of the CFL described in 3.2.2 was acquired from the YESIMODI Company that produces electrical appliance in China. Commercially available real lamp of the acquired circuit was purchased for use on the experimental laboratory test bed.

3.3.2. Linear technology spice software

Linear Technology Spice software IV was downloaded from http://ltspice-iv.en.lo4d.com/ . The software was downloaded on 1st August, 2016. The CFL circuit diagram in Figure3.1 was replicated on the LTspice in order to obtain current and voltage waveforms of the signal to be used for the FFT analysis on MATLAB. The replicated circuit diagram is as shown in Figure 3.1.

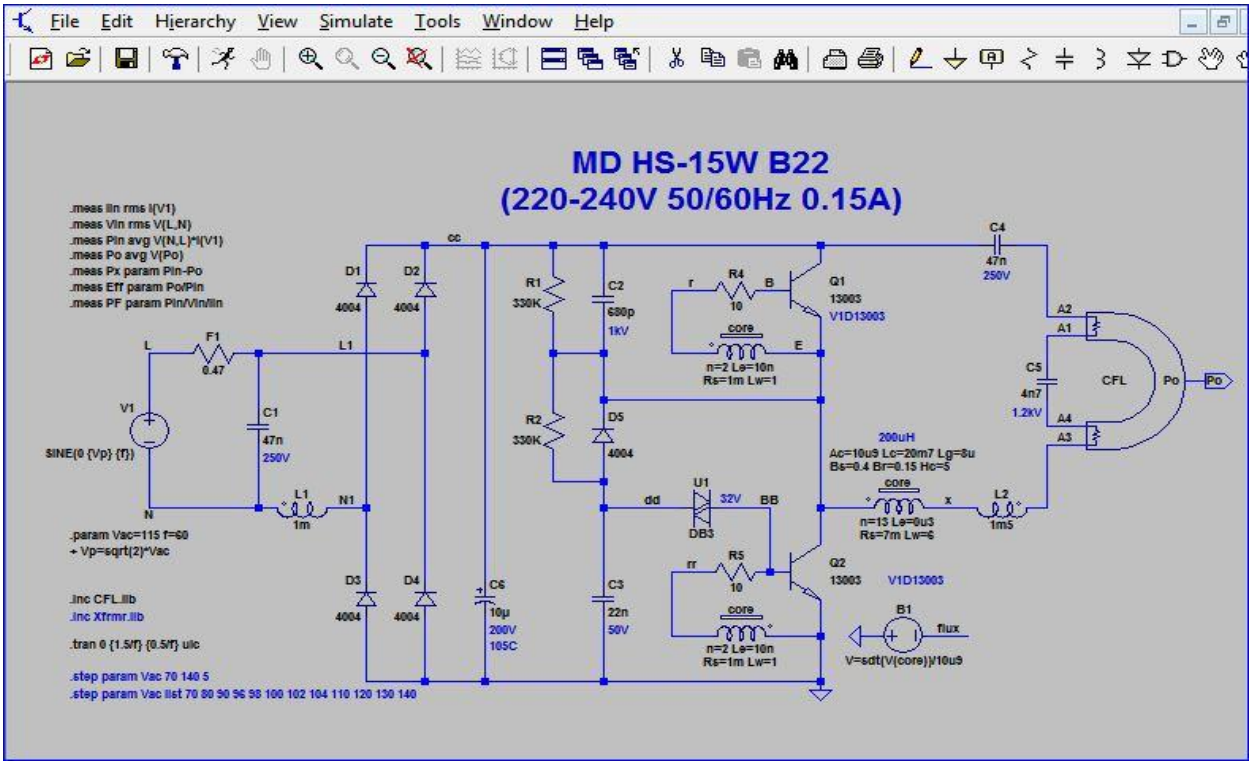


Figure 3.1: Replicated CFL Circuit diagram

Values of each of the elements/components of the CFL circuit diagram are in Appendix A. The required voltage of the circuit was injected into the circuit model and subsequent simulation of the circuit after replication on LTspice was ran. With the help of digital visual probe, current and voltage waveforms were obtained with the probe placed at point A_1 (same as A_2, A_3 and A_4) as contained in Figure 3.1. The Simulation time was 25ms at simulation speed of between 22 and 37 µs/s.

3.3.3 Current and voltage waveforms characterization

The output current and voltage waveforms at points A_1 and U4: F on Figure 3.1 were respectively obtained.

3. 3. 3. 1 CFL voltage waveform

The voltage waveform of the signal of the replicated CFL circuit on LTspice is given in Figure 3.2.

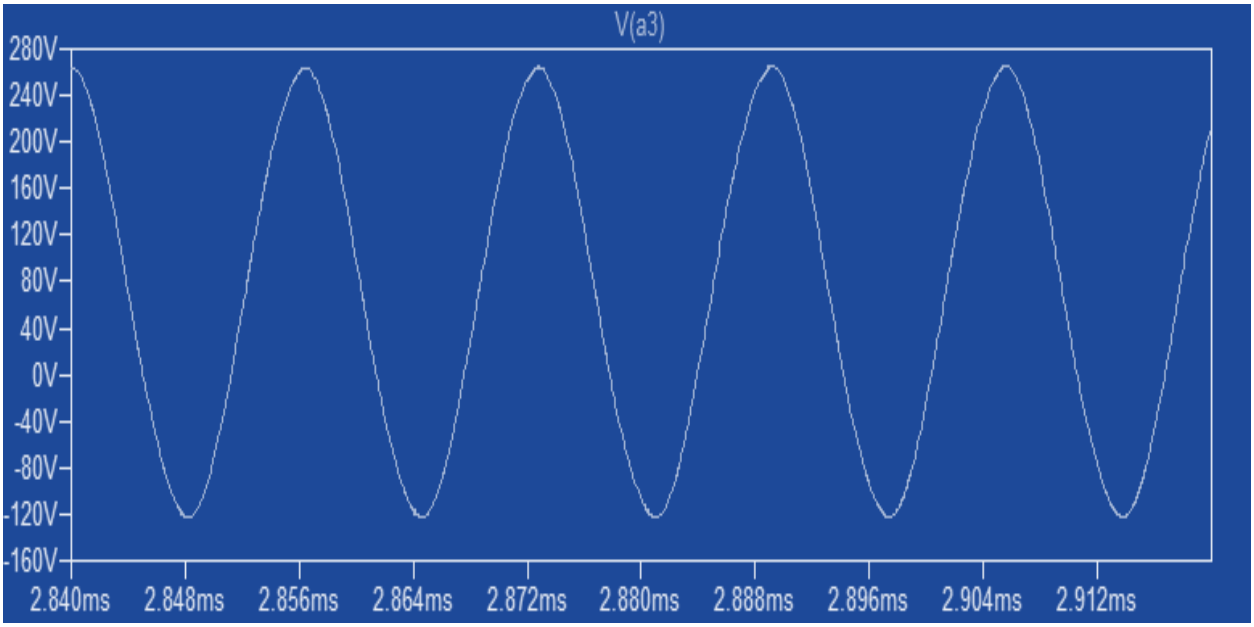


Figure3. 2: CFL Voltage Waveform

The waveform is a cosine function with a period 'T' of 0.032ms. In the waveform the sine component of the signal is zero. Therefore, Fourier series representation for the voltage signal in equation (2.9) becomes:

$$v(t) = \sum_{n=1}^{\infty} a_n \cos(n\omega_0 t) \tag{3.1}$$

and

$$\omega_0 = 2\pi f_0 \tag{3.2}$$

where,

n = 1, 2, 3…

f_0 = fundamental frequency in Hz.

a_n = Fourier cosine coefficient

The voltage signal is represented as follows:

$$v_{(t)} = a_1 Cos2\pi f_0 t + a_2 Cos4\pi f_0 t + a_3 Cos6\pi f_0 t + a_4 Cos8\pi f_0 t +$$

$$a_5 Cos10\pi f_0 t + a_6 Cos12\pi f_0 t + a_7 Cos14\pi f_0 t + \ldots \quad (3.3)$$

3. 3. 3. 2.CFL current waveform

The CFL current waveform without developed filter on LTspice software is as shown in Figure 3.3.

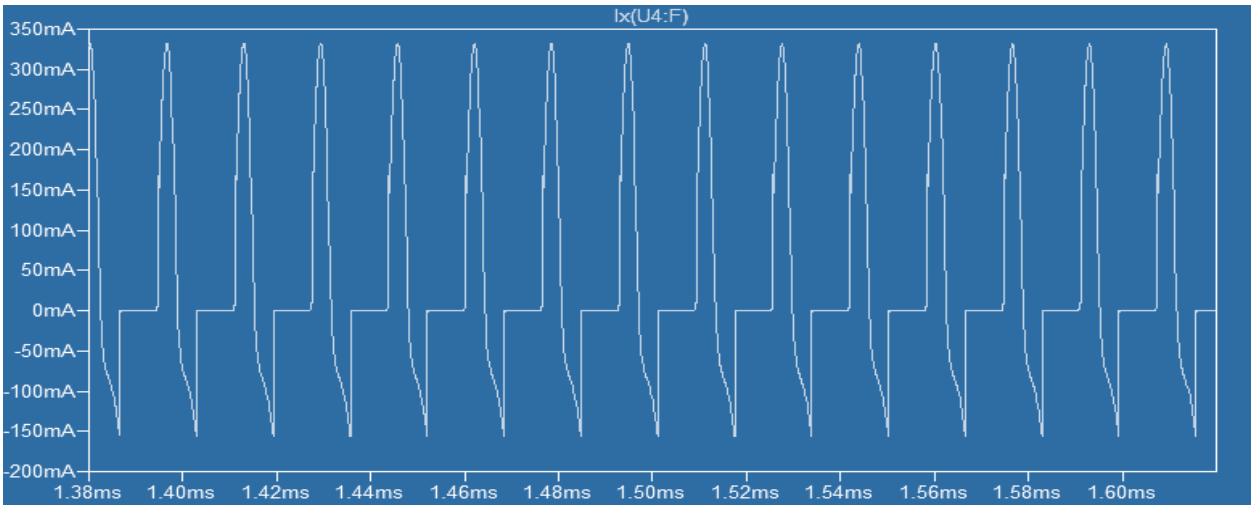


Figure 3.3: CFL Current Waveform

Here, also the current waveform shown in Figure3.3 is none smooth cosine waveform. Furthermore, unlike the voltage waveform, the current waveform contains DC component. Presence of harmonic is clear on the waveform due to its non-smoothness. The period 'T' of the cosine function was 0.018ms. The function of the current signal of the waveform was deduced from Figure 3.3 and is in the following equation.

$$i(t) = \begin{cases} -6150t + 84.865; 1.38ms \leq t \leq 1.388ms \\ 0; 1.388ms \leq t \leq 1.396ms \\ 17000t + 238.39; 1.396 \leq t \leq 1.398ms \end{cases} \quad (3.4)$$

The Fourier series of signal representation in equation (2.9) for the current signal was reduced to:

$$i(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega_0 t) \quad (3.5)$$

where, a_0 = DC component of the current signal.

In order to obtain the current signal mathematical expression based on the waveform in

Figure: 3. 3, equations (2.9) and (2.10) were used. Therefore, a_0 was calculated as 188.2mA approximately and a_n was calculated as follows:

$$|a_n| = \frac{0.11}{n^2\pi^2} \quad (3.6)$$

For n = odd numbers.

The detailed calculation is in Appendix B.

Therefore, by substituting equation (3.6) and value of a_0 in equation (3.4) i(t) was calculated as follows:

$$i(t) = 0.1882 + \frac{0.11}{\pi^2} \sum_{n=odd}^{\infty} \left[\frac{\cos(2n\pi f_0 t}{n^2}\right] \quad (3.7)$$

The mathematical expression of the current signal is as as shown in equation (3.6). Details of the calculation procedure for a_0, a_n and i (t) are in Appendix B.

3. 3. 4 Fast Fourier transform harmonics analysis

In order to carry out FFT analysis, FFT algorithm line code was written on the voltage and current signal waveforms using equations (3.3) and (3.7) respectively. To carryout FFT analysis using MATLAB, the sampling frequency (f_s) of 1500Hz was used with the fundamental frequency of

50Hz. The choice of the sampling frequency was to enable the FFT harmonics analysis accommodates as many harmonics as possible for the computation of current and voltage total harmonic distortions. Short line code of the simplified FFT algorithm is as shown in Appendix C. Flowchart of the simplified FFT algorithm is in Figure 3.4.

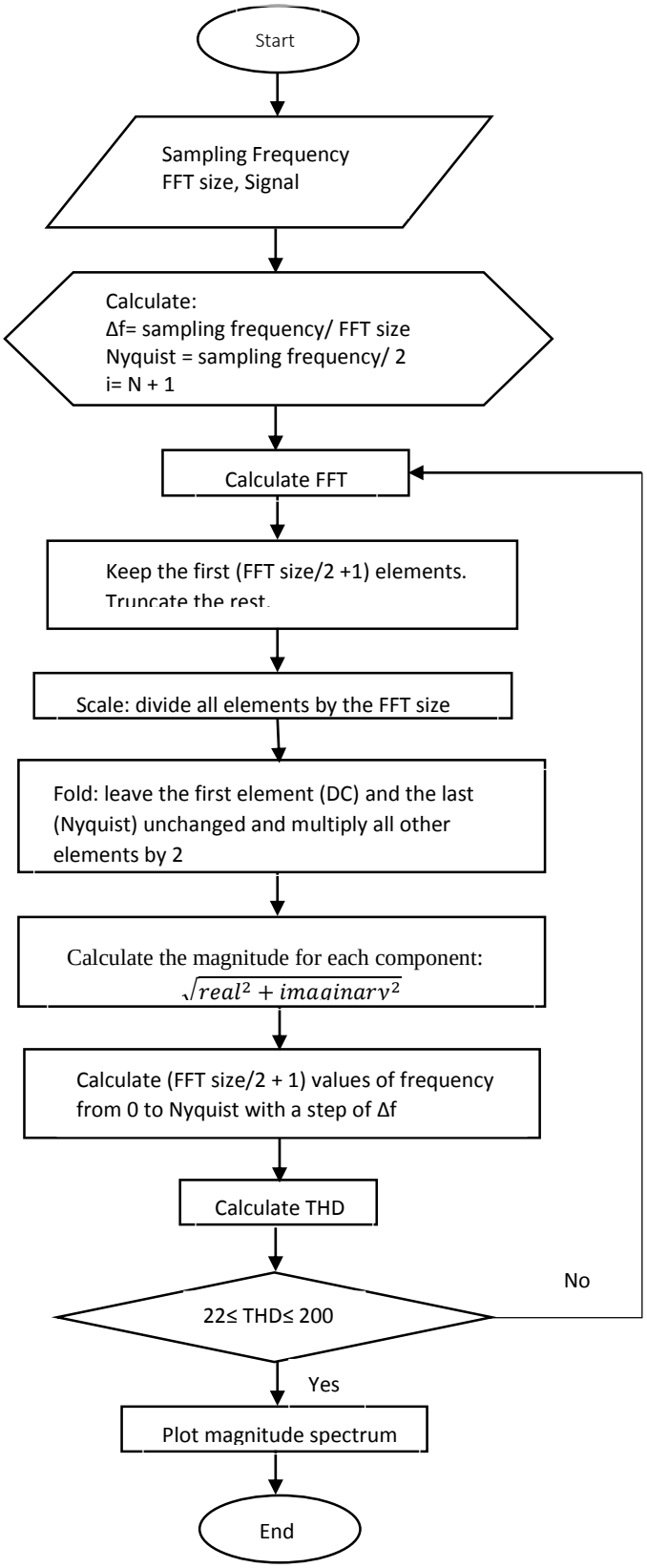


Figure 3.4: Flowchart of Simplified FFT Algorithm

At the end of the analysis, the current and voltage total harmonic distortions were automatically computed online based on equations (2.1) and (2.2) and the results were recorded.

3.3.5 Development and implementation of harmonics passive filters

After obtaining the current and voltage total harmonic distortions of the CFL, analog series and shunt passive filters were developed.

Graphical user interface was used to develop visual series and shunt filters using MATLAB software called powergui analyzer, which were implemented in the MATLAB for FFT analysis. In order to further simplify the procedure for the implementation and further FFT harmonics analysis of the CFL, its circuit diagram was represented by its equivalent. The equivalent circuit diagram of the CFL was developed and replicated on LTspice software as in Figure 3.5.

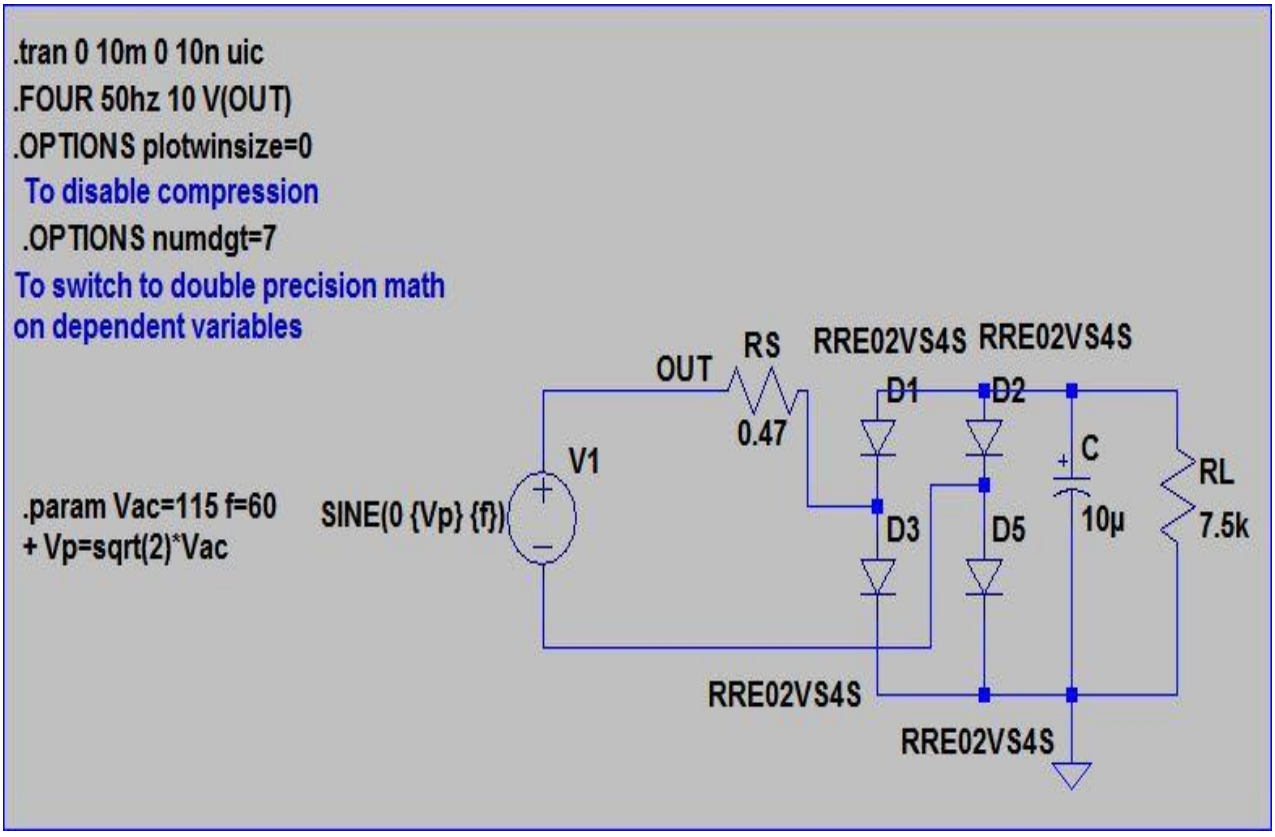


Figure 3.5: CFL Equivalent Circuit

The equivalent circuit was to further simplify the development of MATLAB Simulink models of the CFL. To develop the CFL equivalent circuit, the inverter and output stages of the CFL earlier mentioned in Chapter one were replaced by an equivalent resistance R_L. This was because the inverter functions within the range of frequency of 10 to 40 kHz as such acts as a constant load across the capacitance C (Molina and Sainz, 2014 and Yong *et al.*, 2010).The three parameters considered for the development of the CFL equivalent circuit were Rs, C and RL. Rs and C were given in the obtained CFL circuit diagram as in Chapter one which were represented as F1 and C6 on the diagram respectively. If they were not given, they can be calculated using the following equations respectively (Collin *et al.*, 2014).

$$Rs = 2.868 + 0.6851P_{CFL} \tag{3.8}$$

$$C = 0.24X10^{-6}P_{CFL} \tag{3.9}$$

Where,P_{CFL} is the CFL rated power in Watts (W) which was 15W in the research.

Equation (3.8) if solved, it gives maximum value of Rs (ohms) and equation (3.9) gives minimum value of the DC link capacitance (DC bus bar) 'C' in Farad.

Also, the DC equivalent resistance RL was calculated using the following equation (Yong *et al.*, 2010 and Molina and Sainz, 2014)

$$RL = \frac{KV}{I} \tag{3.10}$$

where,

K is a constant and equals: 1.676 p.u; 3.927 p.u. for rated voltage of 120V and 240V respectively (Molina and Sainz, 2014),

V was approximated to rated voltage of the CFL, and 'I' was calculated using the following equation (Molina and Sainz, 2014).

$$I = 0.85I_1 \tag{3.11}$$

where,

I_1 was the rated current of the CFL which was given as 0.15A.

RL was calculated to be approximately 7.5k. The equivalent circuit was replicated on the LTspice software. FFT harmonics analysis of the CFL was carried out on the LTspice on the PC. The current and voltage total harmonic distortions obtained using the LTspice software were compared with those obtained using the FFT simplified algorithm reported earlier. Values of the parameters used for the equivalent circuit on LTspice are as in Appendix E.

Simulink model of CFL equivalent circuit was developed in MATLAB as in Figure 3.6.

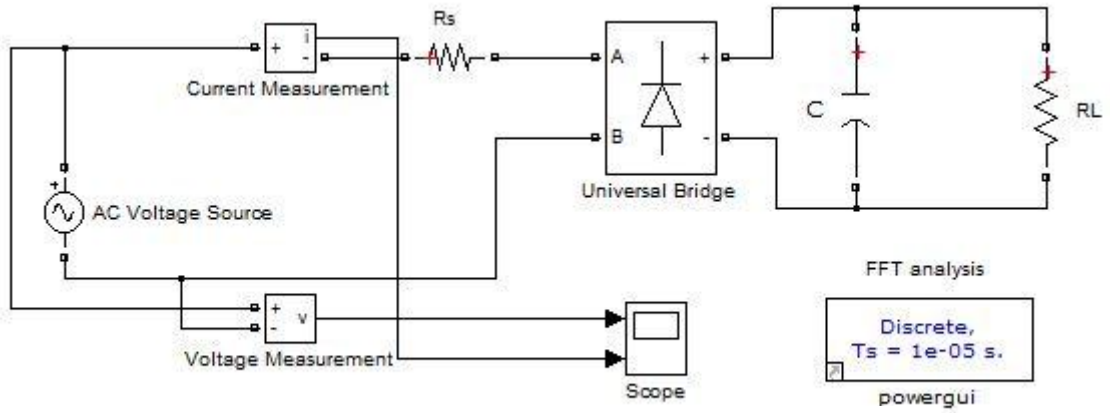


Figure 3.6: CFL Simulink Model

FFT harmonics analysis was carried out on the circuit in Figure 3.6 in MATLAB. The results for THDi and THDv obtained were compared with those obtained with the FFT simplified algorithm and LTspice this was to observe if there is agreement between the results.

Experimental fixed-bed was used to measure the CFL supply voltage, its corresponding current as well as power factor which were obtained as 215.75V, 0.145A and 0.55.

Using the following equations the apparent (S), real (P) and reactive (Qc) powers of the CFL were respectively calculated as follows:

Using

$$S = VI \quad (3.12)$$

$$S = 215.75 \text{ x } 0.145 = 31.28VA$$

$$P = S\cos\theta \quad (3.13)$$

$$P = 31.28 \text{ x } 0.55 = 17.20W$$

$$Q_c = \sqrt{S^2 - P^2} \quad (3.14)$$

$$Q_c = \sqrt{31.28^2 - 17.20^2} \quad = 26.13VAR$$

. Also, the Capacitance of the Capacitor (C_n) used to develop the filters was calculated using equation (2.19). Thus,

$$C_n = \frac{26.13}{2X2X3.142X50X215.75^2} = 0.8\mu F$$

As,

$$\omega = 2\pi f \quad (3.15)$$

$$\omega = 2X3.142X50 = 314.2$$

To develop the filter networks, the Inductance (Ln) and Resistance (Rn) for each of the harmonics orders up to 11^{th} were calculated using equations (2.20) and (2.21) as follows:

For 3^{rd}, 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonics orders, n = 3, 5, 7, 9 and 11.

Therefore,

$$L_3 = \frac{1}{3^2 X 314.2^2\ 0.8\ X\ 10^{-3}} = 1.4H$$

$$R_3 = \frac{3X314.2X\ 1.4}{100} = 13\Omega$$

$$L_5 = \frac{1}{5^2 X 314.2^2\ 0.8\ X\ 10^{-3}} = 0.5H$$

$$R_5 = \frac{5X314.2X\ 0.5}{100} = 7\Omega$$

$$L_7 = \frac{1}{7^2 X 314.2^2\ 0.8\ X\ 10^{-3}} = 0.2H$$

$$R_7 = \frac{7X314.2X\ 0.2}{100} = 4\Omega$$

$$L_9 = \frac{1}{9^2 X 314.2^2\ 0.8\ X\ 10^{-3}} = 0.1H$$

$$R_3 = \frac{3X314.2X\ 0.1}{100} = 2\Omega$$

$$L_{11} = \frac{1}{11^2 X 314.2^2\ 0.8\ X\ 10^{-3}} = 0.1H$$

$$R_{11} = \frac{11X314.2X\ 0.1}{100} = 11\Omega$$

Based on the calculated values of the inductance and Resistance of each of the harmonics order, series and shunt passive filter networks were developed and implemented in the CFL circuit on MATLAB. The Simulink Models of the CFL circuit with the developed series and shunt passive harmonics filters were developed in MATLAB as in Figure 3.7 and Figure 3.8 respectively.

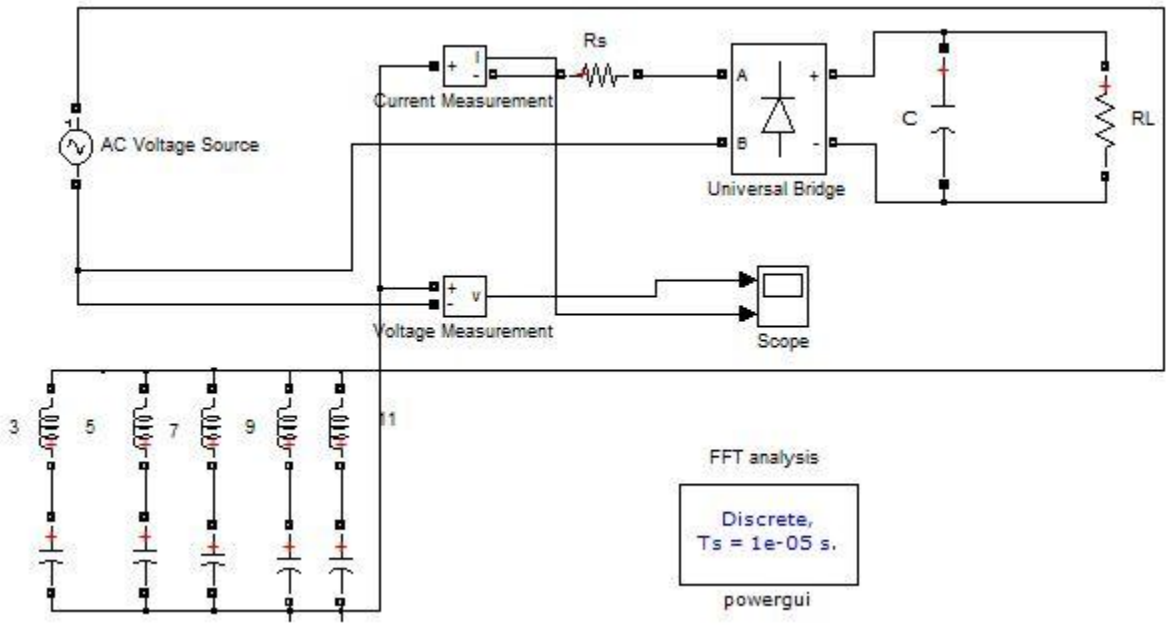


Figure 3.7: CFL with Developed Series Passive Filter Simulink Model

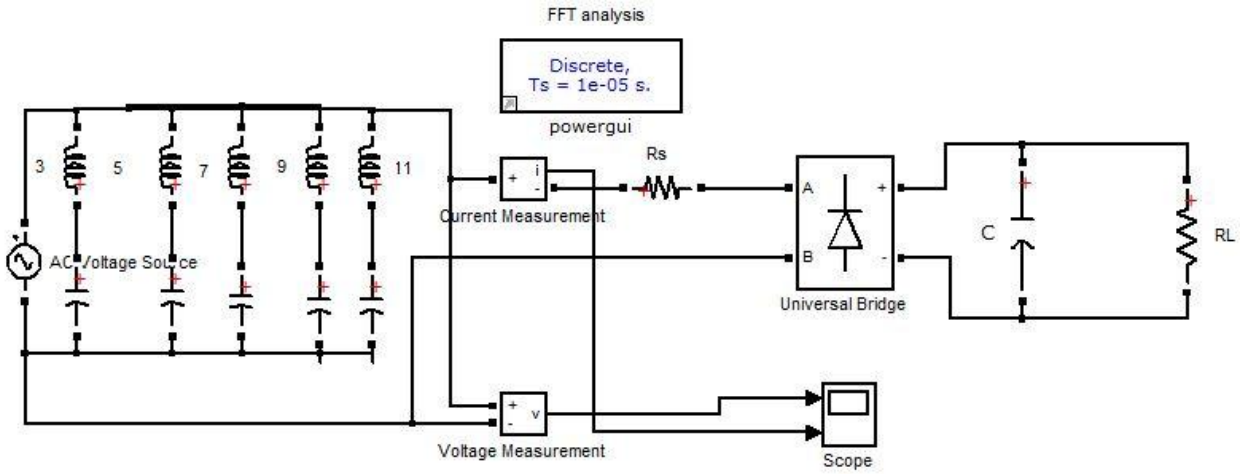


Figure 3.8: CFL with Developed shunt Passive Filter Simulink Model

Fast Fourier transform analyses of the developed CFL Simulink models were carried out in MATLAB by Graphical User Interface (GUI). The results of FFT analyses of current and voltage total harmonics distortion of the CFL with the series and shunt filter were recorded.

3.3.6 Experimental Fixed-bed harmonics measurements

The experimental fixed-bed was set up as in Plate II. This was with the view to obtaining the real CFL current and voltage total harmonics distortions which were compared with the results obtained with the simplified FFT algorithm, LTspice and the CFL Simulink model.

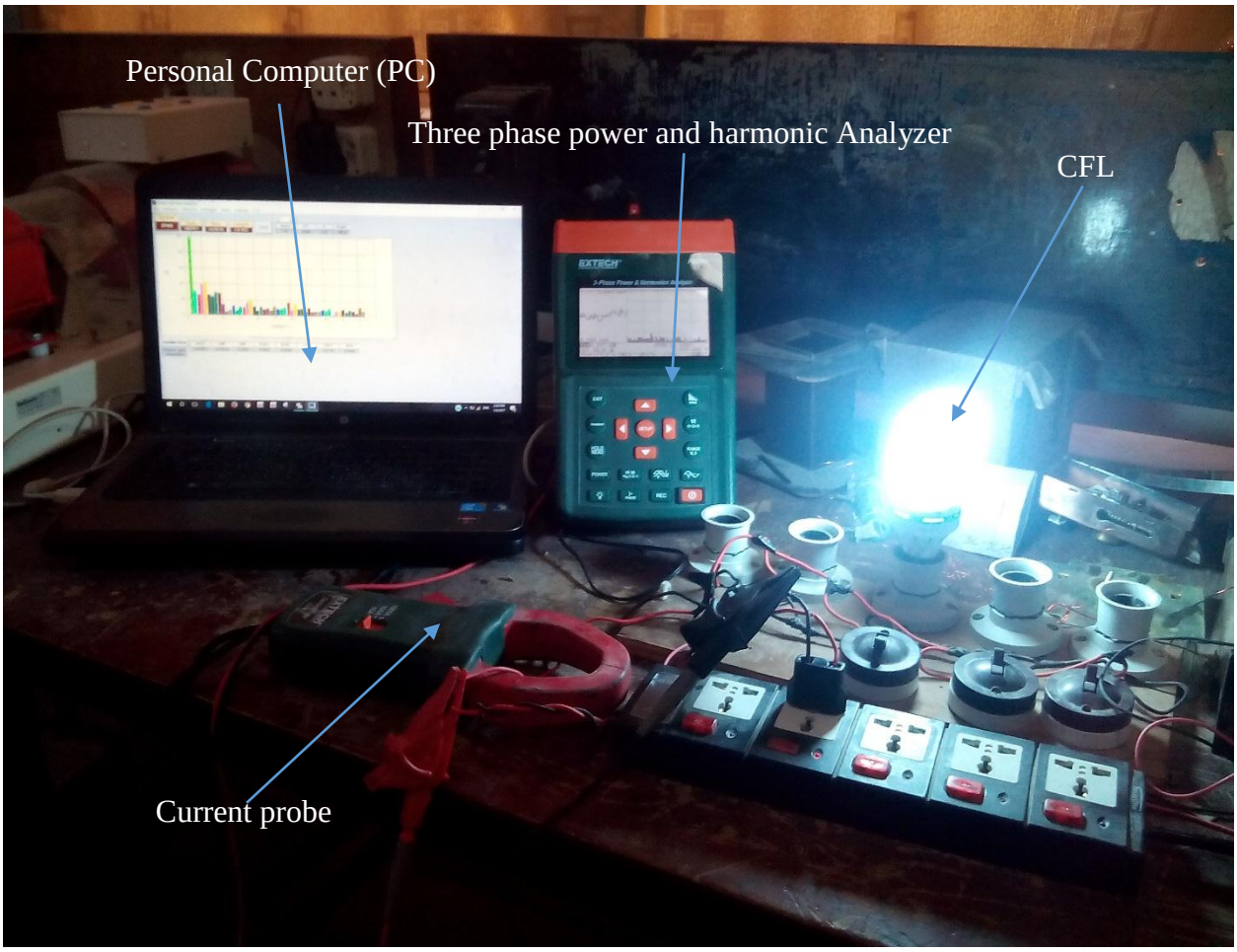


Plate 3.1: Experimental Fixed-bed Set-up

The current and voltage total harmonics distortions obtained with the experimental fixed-bed as in Plate I were found to be not in compliance with the IEEE 519-2014 harmonics standard limits. The average current and voltage total harmonic distortions obtained were recorded.

The results of FFT harmonics analysis with the simplified algorithm, LTspice and powergui analyzer were compared with those obtained with experimental fixed-bed for validation.

3.4 Conclusion

Materials used for the research were presented. Also, current and voltage mathematical expressions used to write the development of the MATLAB codes for the CFL FFT analysis were presented. Methods used for the development of CFL models on LTspice and Simulink as well as harmonics analyses were presented in this Chapter. Presented in this Chapter also, was the method through which validation of results obtained was achieved.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses FFT harmonic analyses results obtained before and after implementation of the developed harmonics filter networks. Simplified FFT algorithm, LTspice, powergui software in MATLAB as well as experimental Fixed-bed was used for the harmonics analyses.

4. 2 Simplified FFT Algorithm CFL Harmonic Analysis Results

Current and voltage total harmonic distortions after carrying out the harmonics analysis with the simplified FFT algorithm on MATLAB were 135.50% and 35.43% respectively.

The THDi and THDv obtained were far greater than the IEEE 519-2014 harmonics standard limits of 20% and 8% respectively.

The results of the spectrum analysis for current and voltage are as shown in Figures 4.1 and 4.2 respectively.

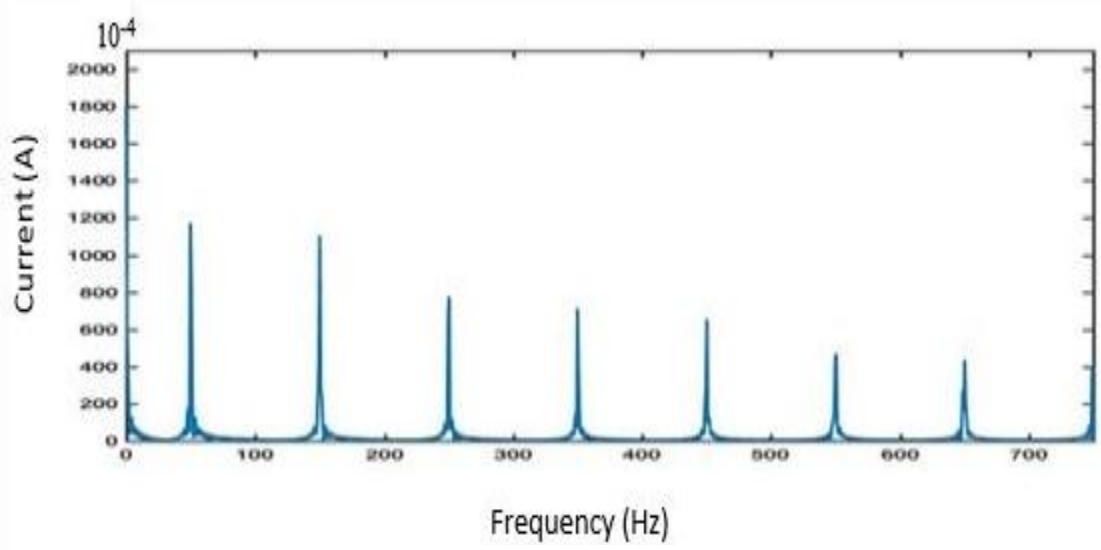


Figure 4.1: CFL Current Amplitude Spectrum

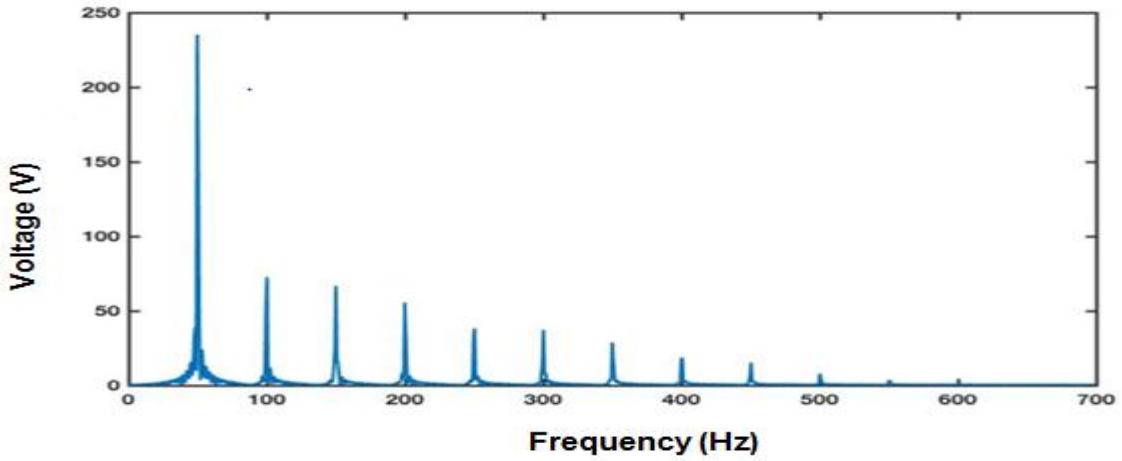


Figure 4.2: CFL Voltage FFT Amplitude Spectrum

The 1st, 3rd, 5th, 7th, 9th, and 11th components in terms of magnitudes of the current in Figure 4.1 were approximately 0.12, 0.11, 0.08, 0.07, 0.06, and 0.05 all in Amperes respectively. These harmonics components did not comply with the IEEE 519-2014 harmonics standard limits as contained in Table 2.1. Meanwhile, the current total harmonic distortion was obtained as 135.50% also, this value was found to be not in conformity with the IEEE 20% limits. Therefore, the harmonics emission of the CFL was established.

The voltage total harmonic distortion was obtained to be 35.43%. This value did not also conform to the IEEE 8% standard limit. The individual voltage harmonics components were found to be approximately in Volt as 240, 75, 72, 60, 48, 47, 44, 25, 22, 5, and 2 which represent1st to 11th order of the harmonics as can be inferred on Figure 4.2. Furthermore, none of them conformed to the IEEE standards.

4.3 LTspice FFT Harmonics Analysis Results

Results obtained when FFT harmonics analysis was carried out on the CFL with LTspice were 130.13% and 33.64% for THDi and THDv. There was close agreement when these results obtained here were compared with those of the FFT simplified algorithm. Therefore, it was clear that the

equivalent circuit can be used to implement the filter network on Simulink as intended. The detailed results are in Appendix E.

4. 4 CFL Simulink Model FFT Harmonics Analysis Results

The CFL Simulink model is as shown in Figure 3.6. The results of FFT harmonics analysis carried out on the model were in relation to the fundamental current and voltage as 130.08% and 36.55% for current and voltage total harmonic distortions respectively. The CFL current waveform and amplitude spectrum were as depicted in Figure 4.3.

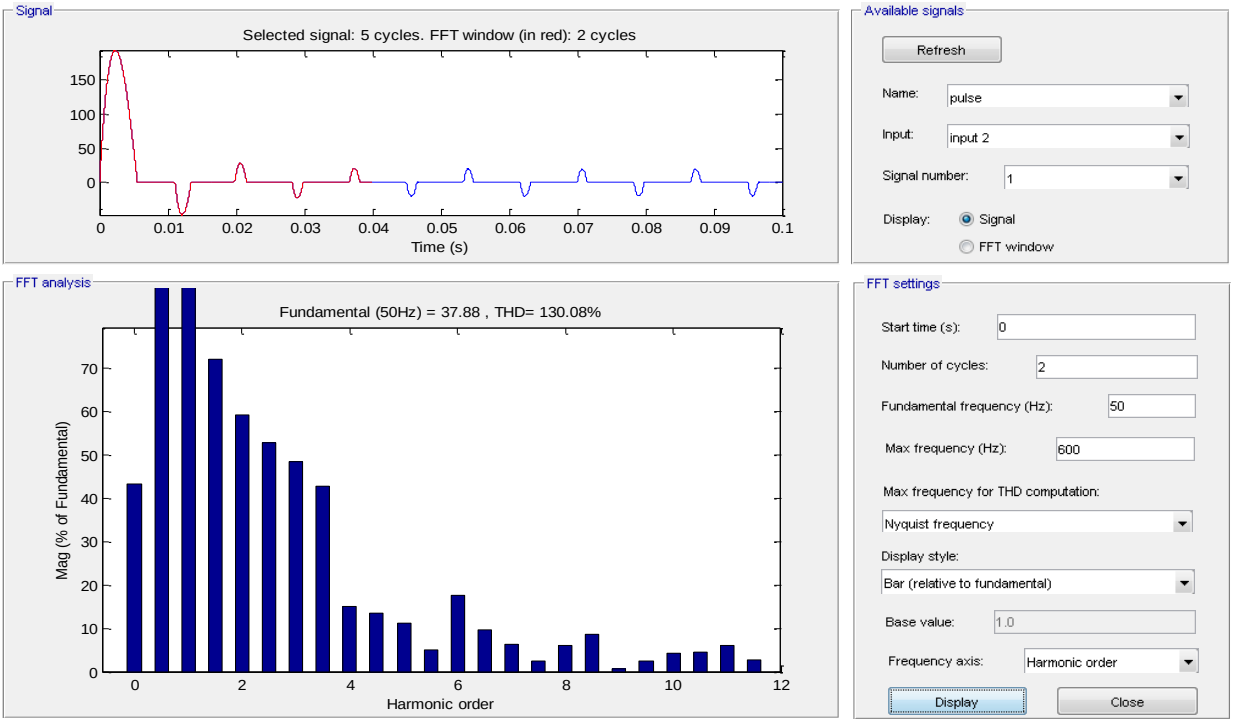


Figure 4.3: CFL Current Waveform and Amplitude Spectrum

The current total harmonic distortion obtained was 130.08% as earlier mentioned, and it did not comply with the IEEE acceptable standard limit of 20%. The results indicated that the waveform was distorted as a result of presence of high harmonics. The amplitude of the 2nd harmonics has crossed the threshold as indicated in Figure 4.3. The 3rd, 4th, 5th, 6th, 7th, 8th, and 9th harmonics components did not comply with the IEEE standard limits as contained in Table 2. The detailed FFT results sheet is as shown in Appendix F.

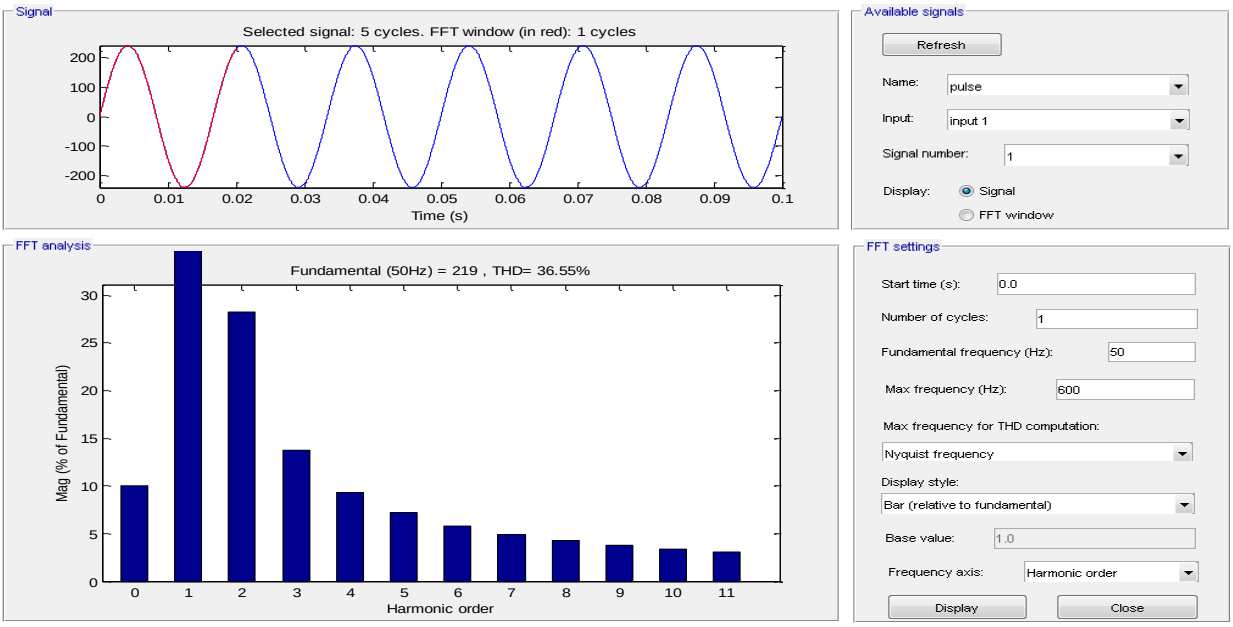


Figure 4.4: CFL Voltage Waveform and Amplitude Spectrum

The CFL voltage waveform and amplitude spectrum are as shown in Figure 4.4 The voltage total harmonics distortion was 36.55%. This value of the THDv was also not in conformity with the 8% acceptable standard limit of the IEEE. The detailed FFT harmonics analysis results are in Appendix G.

4. 5 Passive Harmonics Filters Results

The Analog passive series and shunt filter networks were developed based on the calculated values of the inductances and resistances as tabulated in Table 4.1. Also, the capacitance of the capacitor (Cn) which was used to develop the filters was calculated to be 0.8µF using equation (2.19).

Table 4.1: Inductance (Ln) and Resistance (Rn) of the Filters Calculated Values

Harmonics Order	**3rd**	**5th**	**7th**	**9th**	**11th**

Calculated values for S, P, Qc, Cn, Ln and Rn were used for the development of both series and shunt analog passive filter networks.

Ln (Henry)	1.4	0.5	0.2	0.1	0.1
Rn (ohms)	13	7	4	2	11

4. 5 .1 Series passive harmonics filter results

The Simulink model of the implemented developed series filter is as presented earlier in Figure 3.7. The current waveform and its amplitude spectrum are as shown in Figure 4.5. Current total harmonics distortion obtained was 3.64%. The most prominent harmonics as in Figure 4.5 were 3rd, 5th and 7th. All of these harmonics components were found to be within the IEEE harmonics standard limits as in Table 2.1. The detailed results are as shown in Appendix H.

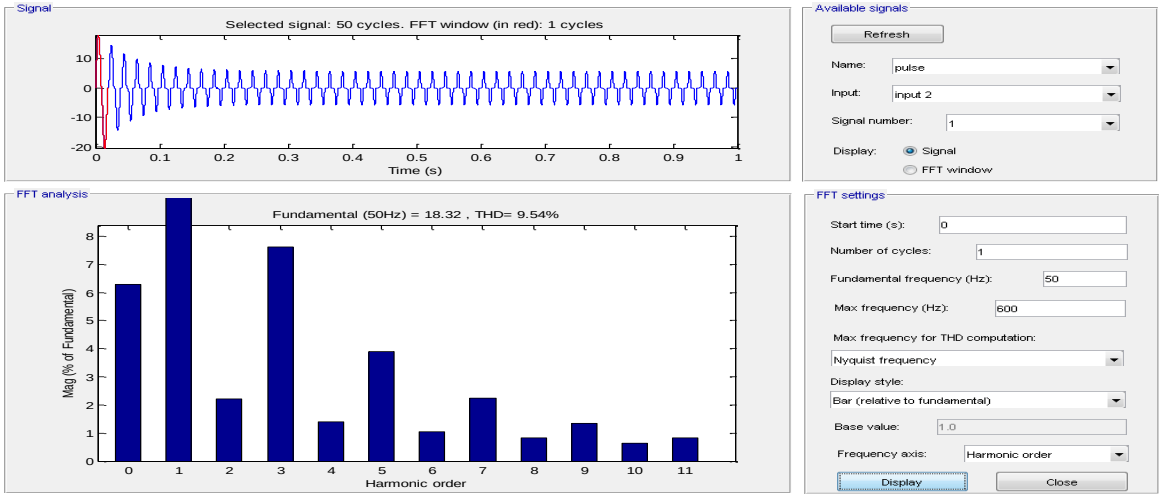


Figure 4.5: CFL with the Developed Series Filter Current Waveform and Amplitude Spectrum

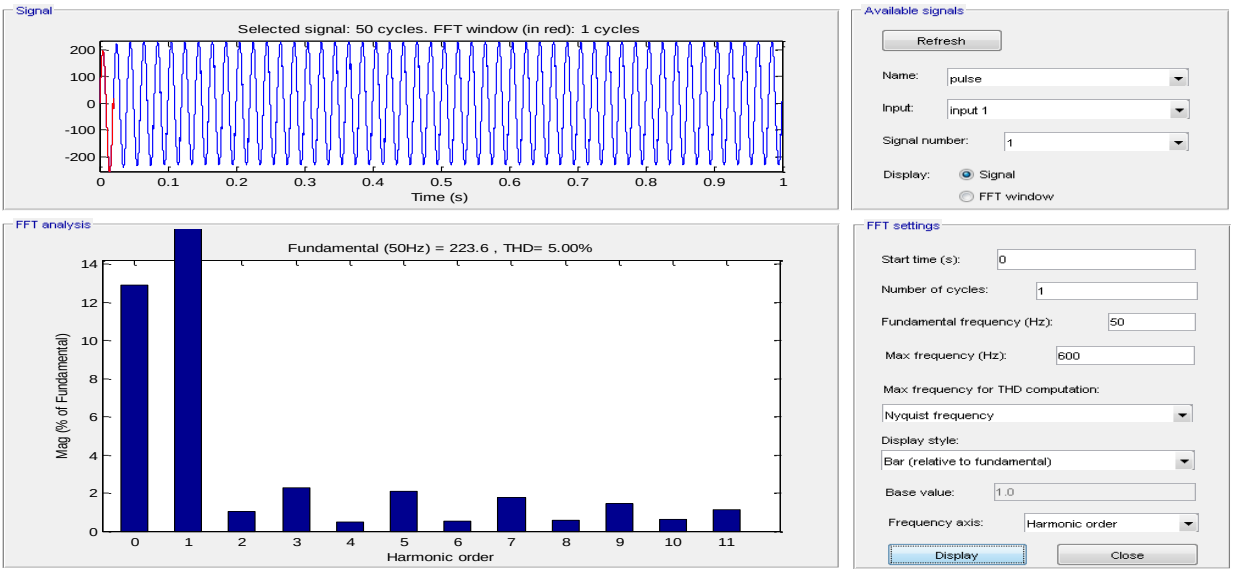


Figure 4.6: CFL with Developed Series Passive Filter Voltage Waveform and Amplitude Spectrum

The CFL with developed series filters current waveform and amplitude spectrum are as in Figure 4. 5. The current total harmonics distortion obtained was 9.54% in relation to the fundamental current. This value was within the acceptable IEEE 519-2014 standard limit. Meanwhile as can be inferred in Figure 4.5, there were less number of the Spectra than in Figure 4.4. This shows that some individual harmonics were cancelled out.

The prominent harmonic component was found to be the 3rd in Figure 4.6. This harmonics component was approximately 2%. The voltage total harmonic distortion in relation to the fundamental voltage was found to be 5%. This value conform to the standard limit.

4. 5. 2 Shunt passive harmonics filter results

Shunt passive harmonics filter was also developed and implemented with the CFL in MATLAB. The Simulink model of the implemented shunt filter is as shown in Figure 4. 7.

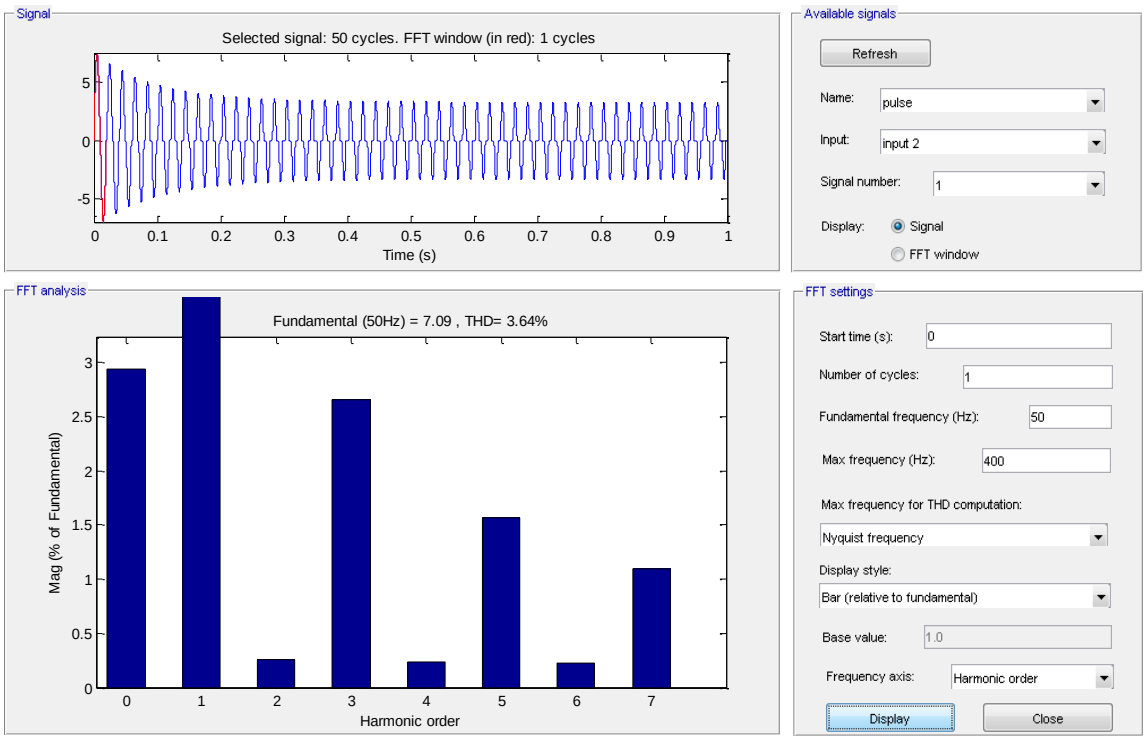


Figure 4.7: CFL with Developed Shunt Passive Filter Current Waveform and Amplitude Spectrum

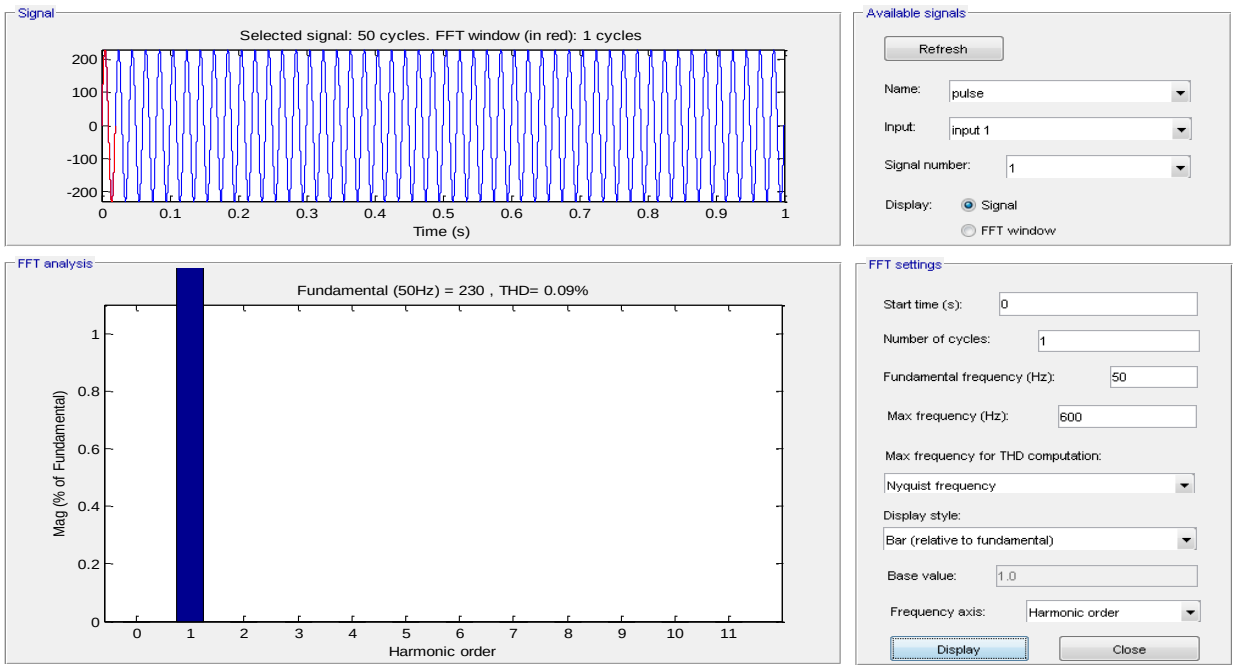


Figure 4.8: CFL with Developed Shunt Passive Filter Voltage Waveform and Amplitude Spectrum

Results for the current and voltage total harmonic distortion of the FFT harmonics analysis on the Simulink model as shown in Figures 4.7 and 4.8 in relation to the fundamental current and voltage were 3.64% and 0.09% respectively. As can be seen in Figure 4.7, the most prominent harmonics were 3^{rd}, 5^{th} and 7^{th}. Their harmonics components in relation to the fundamental current were 2.66%, 1.57% and 1.10% respectively. These values are all within the limit of IEEE as in Table 2.1. Detailed results are in Appendix J.

As can be clearly seen in Figure 4.8, all the voltage harmonics components cancelled out. The detailed results are in Appendix K.

4. 6. Experimental Fixed-bed Results

Results of total harmonics distortions were 128.90% for current and 31.60% for voltage. These results do not conform to the IEEE standard limits of 20% and 8% respectively.

4. 7 Results Summary

The Results obtained were summarized in Table 4. 2.

Table 4.2: General Results Summary

Sno	**Method of FFT Harmonic Analysis**	**Results**	
		THDi	**THDv**
1	FFT simplified Algorithm	135.50%	35.43%
2	LTspice	130.13%	33.64%
3	Simulink model without Filter	135.08%	36.55%
5	Simulink model with series Filter	**9.54%**	**5.00%**
6	Simulink model with shunt Filter	**3.64%**	**0.09%**
7	Experimental Fixed-bed	128.90%	31.60%

4.8 Results Validation

When all the results obtained without the developed filter networks as in Table 4.1 were compared with those of the experimental Fixed-bed also as in Table 4.1, they were found to be in agreement. However, none of the results was found to be in compliance with IEEE 519-2014 standard harmonics limits. The current and voltage waveforms obtained from the experimental fixed-bed are depicted as in Figures 4.9 and 4.10 respectively. The block diagram of the fixed-bed is depicted in Figure 4.11.

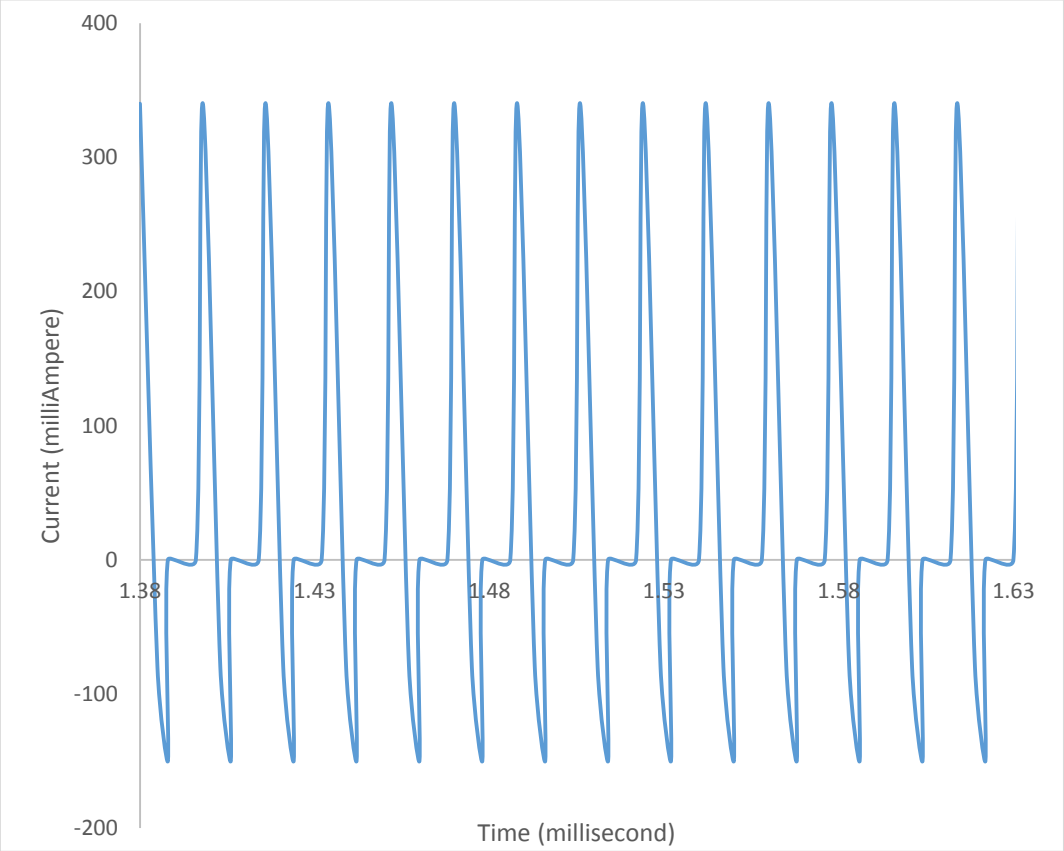


Figure 4.9 Experimental Fixed-bed CFL Current Waveform

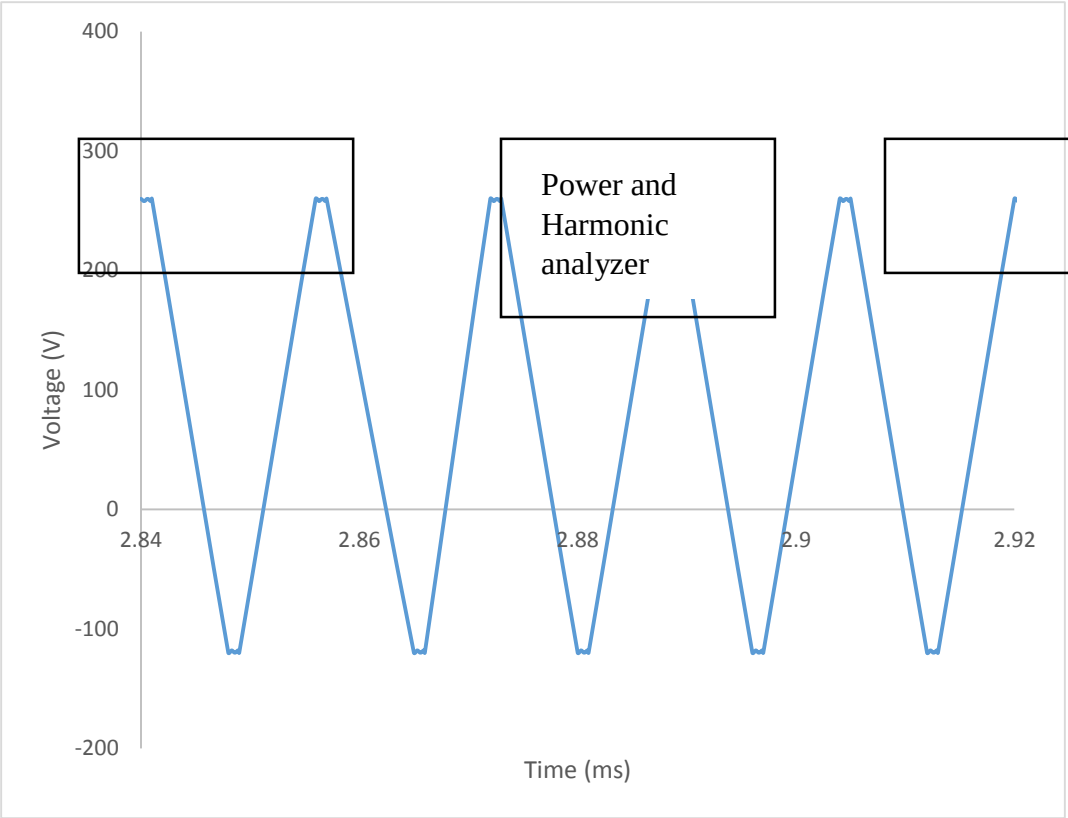


Figure 4.10: Experimental Fixed-bed CFL Voltage Waveform

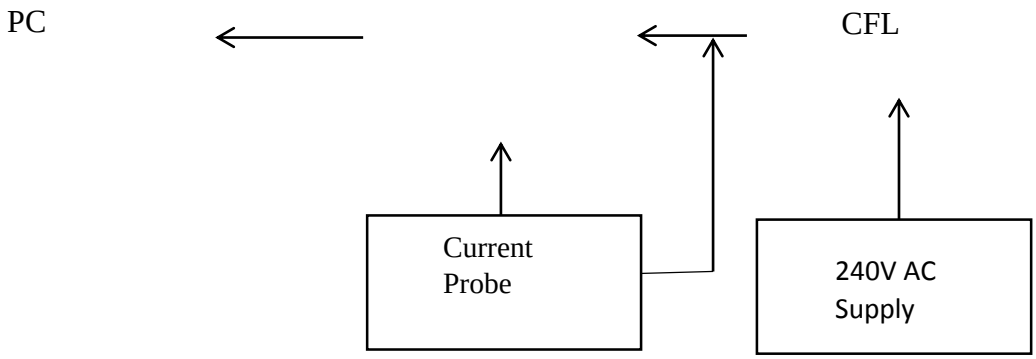


Figure 4.11: Block Diagram of Experimental Fixed-bed

The current and voltage waveforms in Figure 4.9 and Figure 4.10, revealed a good agreement with the simulated current and voltage waveforms obtained from the LTspice software. The two waveforms resembled those obtained from the LTspice as in Figure 3.2 and Figure 3.3 respectively. This shows that the replication of the CFL circuit on LTspice was properly done. The current and voltage total harmonics distortions obtained with the laboratory Fixed-bed were averagely 128.90% and 31.60% respectively. These results when compared with those obtained

with the simplified FFT algorithm, LTspice and Simulink model without filter also indicated agreement.

4.9 Conclusion

Current and voltage total harmonics distortions obtained through the FFT analyses with the FFT simplified algorithm, LTspice software, as well as Simulink models with and without filters were presented. Also, results of experimental Fixed-bed were presented.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Introduction

In this chapter, discussions on results and conclusion are presented. The entire dissertation is summarized in the conclusion. The scope of the work has been limited to simulation in visual environment. Meanwhile, recommendations for further work as well as limitations of the work are presented in this chapter.

5.2 Discussions on Results

The dissertation presented a step by step procedure for modeling and simulation of compact fluorescent lamp for the analysis and mitigation of harmonics injection into power distribution network. Three methods were used for the harmonics analysis. These were: simplified FFT harmonics analysis algorithm; LTspice; and Powergui software. The results obtained for THDi and THDv in relation to the fundamental current and voltage were: 135.50% and 35.43%; 130.13% and 33.64%; as well as 130.08% and 36.55% respectively. The results were observed to be in agreement with one another when compared. Laboratory test bed results were averagely 128.90% and 31.60% for THDi and THDv respectively. The fixed-bed results were compared with those obtained with the simplified FFT algorithm for validation.

Simulink models of the CFL circuit with series and shunt passive harmonics filter networks were also developed with a view to evaluating their performance in terms of the CFL harmonics emission reduction. The choice of the method of harmonic reduction was based on its simplicity.

FFT harmonics analysis was carried out on the developed Simulink models of the CFL circuits with the filters on powergui in MATLAB. The results obtained in relation to the fundamental current and voltage were 9.54% and 5.00% for the THDi and THDv with the series filter; 3.64% and 0.09% were obtained with the shunt filter.

It was observed that the reductions of THD of the CFL were achieved with the analog series and shunt passive filters.

5.3 Conclusion

Compact fluorescent lamp has been the most widely used lighting device due its energy efficiency and other advantages such as cost effectiveness and long life span. The lamp is a nonlinear load. However, this type of lamp is associated with one major technical challenge and that is emission of harmonics. Harmonic is a multiple integer of fundamental frequency. Even though CFL harmonics injections may be considered small, but when large number is used in a power distribution network its effect will be as large harmonics source. Mitigation of this harmonics becomes very difficult once injected into the distribution network. There have been many research works on the analysis and mitigation of the injection of Harmonics into the power distribution network. However, the methods used were characterized by inherent in-accuracy, complexity and other challenges due to large number of assumptions, and high demands of computational efforts. Consequently, this research work modeled and simulated compact fluorescent lamp for the analysis and mitigation of harmonics injection into power distribution network. Results achieved are summarized in this chapter.

5.4 Significant Contributions of the Research

a. CFL Harmonics analysis using simplified FFT analysis algorithm is presented. The THDi and THDv obtained were 135.50% and 35.43% respectively.

b. CFL Harmonics analysis using LTspice software is presented. The THDi and THDv were found to be 130.13% and 33.64%.

c. CFL Harmonics analysis using powergui software is presented. 135.08% and 36.55% were obtained as THDi and THDv respectively.

d. CFL Harmonics injection mitigation using analog series and shunt passive filters are

presented. The THDi and THDv were reduced to 9.54% and 5.00% with the series filter network as well as 3.64% and 0.09% with the shunt filter.

. 5.5 Recommendations for Further Works

The following are recommended for further works.

i. Develop CFL prototype with series and shunt filters and determine its current and voltage total harmonics distortions.

ii. Extend the research into other nonlinear loads such as fan, PC, etc with a view to mitigating the harmonics they generate.

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Appendices

Appendix A

Bill of Materials of the replicated CFL Circuit on LTspice

Ref.	Mfg.	Part No.	Description
C1	--	--	capacitor, 47nF
C2	--	--	capacitor, 680pF
C3	--	--	capacitor, 22nF
C4	--	--	capacitor, 47nF
C5	--	--	capacitor, 4.7nF
C6	--	--	capacitor, 10µF
D1	--	4004	diode
D2	--	4004	diode
D3	--	4004	diode
D4	--	4004	diode
D5	--	4004	diode
F1	--	--	resistor, 470m
L1	--	--	inductor, 1mH
L2	--	--	inductor, 1.5mH
Q1	--	13003	bipolar transistor
Q2	--	13003	bipolar transistor
R1	--	--	resistor, 330K
R2	--	--	resistor, 330K
R4	--	--	resistor, 10
R5	--	--	resistor, 10
U1	(unknown)	DB3	(unknown 3rd party model)
U2	(unknown)	CFL	(unknown 3rd party model)
U3	(unknown)	n=2 Le=10n	(unknown 3rd party model)
U4	(unknown)	n=2 Le=10n	(unknown 3rd party model)
U5	(unknown)	n=13 Le=0u3	(unknown 3rd party model)

Appendix B

Calculations of a_0, a_n and $i(t)$

Considering equation (3.3)

$$i(t) = \begin{cases} -6150t + 84.865; 1.38ms \leq t \leq 1.388ms \\ 0; 1.388ms \leq t \leq 1.396ms \\ 17000t + 238.39; 1.396 \leq t \leq 1.398ms \end{cases} \quad (3.3)$$

Applying

$$a_0 = \frac{1}{T}\int_0^T f(t)d(t) \quad (2.7)$$

$$a_0 = \frac{1}{0.018X^{-3}}\int_{1.38X^{-3}}^{1.388X^{-3}}[-6150t + 84.865]d(t) +$$

$$\frac{1}{0.018X^{-3}}\int_{1.396X^{-3}}^{1.398X^{-3}}[170000t + 238.34]d(t)$$

$$a_0 = 55.56X10^3[3075t^2 + 84.86t]_{1.38X10^{-3}}^{1.388X10^{-3}} +$$

$$55.56X10^3[85000t^2 + 238.34t]_{1.396X10^{-3}}^{1.398X10^{-3}}$$

$$a_0 = 188.2X10^{-3}s$$

using

$$a_n = \frac{2}{T}\int_0^T f(t)Cos(n\omega t)d(t) \quad (2.8)$$

$$a_n = \frac{2}{0.018X^{-3}}\int_{1.38X10^{-3}}^{1.388X10^{-3}}[-6150t + 84.865]Cosn\omega_0 td(t) +$$

$$\frac{2}{0.018X^{-3}}\int_{1.396X10^{-3}}^{1.398X10^{-3}}[170000t + 238.34]Cosn\omega_0 td(t)$$

$$= 111.1X10^3\left[\frac{-6150tsin(n\omega_0 t)}{n\omega_0} - \frac{6150Cos(n\omega_0 t)}{n^2{\omega_0}^2}\right]_{1.38X10^{-3}}^{1.388X10^{-3}} +$$

$$111.1X10^3\left[\frac{170000tsin(n\omega_0 t)}{n\omega_0} + \frac{170000Cos(n\omega_0 t)}{n^2{\omega_0}^2}\right]_{1.396X10^{-3}}^{1.398X10^{-3}}$$

$$\omega_0 = \frac{2\pi}{T} = \frac{2\pi}{0.018X^{-3}} = 111.1X10^3\pi\ rad/s$$

$$\omega_0{}^2 = 1.2345X10^{10}\pi^2 rad^2/s^2$$

$$a_n = 111.1X10^3\left[\frac{-6150tsin(111.1X10^3\pi nt)}{111.1X10^3\pi n} - \frac{6150Cos(111.1X10^3\pi nt)}{1.2345X10^{10}\pi^2 n^2}\right]_{1.38X10^{-3}}^{1.388X10^{-3}} +$$

$$= 111.1X10^3\left[\frac{170000tsin(111.1X10^3\pi nt)}{111.1X10^3\pi n} + \frac{170000Cos(111.1X10^3\pi nt)}{1.2345X10^{10}\pi^2 n^2}\right]_{1.396X10^{-3}}^{1.398X10^{-3}}$$

$$= \frac{1}{\pi n}\left[-6150tsin(111.1X10^3\pi nt) - \frac{6150Cos(111.1X10^3\pi nt)}{111.1X10^3\pi n}\right]_{1.38X10^{-3}}^{1.388X10^{-3}} +$$

$$\frac{1}{\pi n}\left[170000tsin(111.1X10^3\pi nt) - \frac{170000Cos(111.1X10^3\pi nt)}{111.1X10^3\pi n}\right]_{1.396X10^{-3}}^{1.398X10^{-3}}$$

Sin (πn) = 0; for n = 0, 1, 2 …

Cos (πn) = -1; for n = odd: 1, 3, 5 …

Cos (πn) = 1; for n = even: 2, 4, 6…

$$a_n = \frac{0.055}{n^2\pi^2}[Cos(153n\pi) + Cos(153n\pi)]$$

$$= \qquad |a_n| = \frac{0.11}{n^2\pi^2} \qquad (3.5)$$

$$i(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega_0 t) \qquad (3.4)$$

For n = odd numbers.

Substituting the value of a_0 and equation (3.5) in equation (3.4),

$$i(t) = 0.1882 + \frac{0.11}{\pi^2}\sum_{n=odd}^{\infty}\left[\frac{\cos(2n\pi f_0 t}{n^2}\right] \qquad (3.6)$$

Appendix C

MATLAB M-FILE

```
% FFT Analysis and THD for Current

t = line space (0, 1,1e3);

   for ni = 1:2:30;

   t = line space (0,1,1e6);

   x = 0.1882 + ((0.11/(pi^2*ni)*cos(2*ni*pi*50*t))); % Current Signal

   hper = spectrum.periodogram; % Getting the mean-square spectrum. These are square magnitudes

   mspec = msspectrum(hper,x,'Fs',2e4,'NFFT',length(x)); % Creating a data vector with the fundamental and odd harmonics

   datavec = mspec.Data(61:60:181); % Calculating the THD

   THD = sqrt(sum(datavec(2:end)))/sqrt(datavec(1));

   xdft = fft(x);

   datavec = xdft(61:60:181);

   THD = norm(datavec(2:end),2)/norm(datavec(1),2);

   TDH_1 = sum(THD)

   fs = 1500;

   m = length(x); % Window length (number of samples)

   n = pow2(nextpow2(m)) ; % Transform length. This formula is used in order to accelerate the DFT computation, knowing that the computation is easiest if the %length is a multiple of two (prime number)

   %Y = fft(x,n)/n; %DFT computation

   f = fs/2*linspace(0,1,n/2+1);

   plot(f,abs(xdft(1:n/2+1)));

   xlabel('Frequency (Hz)');

   ylabel('Current Magnitude (mA)');

   end
```

```
% FFT Analysis and THD for Voltage
```

```
fs = 1500; %sampling frequency

Duree=1; %duration

freq=50; %fundamental frequency of the signal

t = linspace(0,Duree,Duree*fs);

x=240*cos(2*pi*50*t)+220*cos(2*pi*2*50*t)+180*cos(2*pi*3*50*t)+160*cos(2*pi*4*50*t)+
120*cos(2*pi*5*50*t)+100*cos(2*pi*6*50*t)+80*cos(2*pi*7*50*t)+60*cos(2*pi*8*50*t)+40*
cos(2*pi*9*50*t)+20*cos(2*pi*10*50*t)+10*cos(2*pi*11*50*t)+5*cos(2*pi*12*50*t);

DFT_bin = fs/length(x); % = (sampling frequency)/(sample length)

%Then now we use fft to compute the DFT and its power:

m = length(x); % Window length (number of samples)

n = pow2 (nextpow2(m)) ; % Transform length. This formula is used in order to accelerate the
DFT computation, knowing that the computation is easiest if the %length is a multiple of two
(prime number)

Y = fft(x,n)/n; %DFT computation

f = fs/2*linspace (0,1,n/2+1); % Frequency range (the maximum of the frequency %range is
nyquist frequency (Fs/2)+1

% Plot single-sided amplitude spectrum.

plot(f,abs(Y(1:n/2+1)))

xlabel('Frequency (Hz)')

ylabel('Voltage Magnitude (V)')

% Finally the computation is:

THD=sqrt(abs(Y(ceil((2*50)/bin+1)))^2+abs(Y(ceil((3*50)/bin+1)))^2+abs(Y(ceil((4*50)/bin+1
)))^2+abs(Y(ceil((5*50)/bin+1)))^2+abs(Y(ceil((6*50)/bin+1)))^2+abs(Y(ceil((7*50)/bin+1)))^2
)/sqrt(abs(Y(ceil(50/bin+1)))^2)
```

Appendix D

Bill of Materials used for the CFL Equivalent Circuit

Ref.	Mfg.	Part No.	Description
C1	--	--	capacitor, 10μF, 400V
D1	Rohm	RRE02VS4S	diode
D2	Rohm	RRE02VS4S	diode
D3	Rohm	RRE02VS4S	diode
D5	Rohm	RRE02VS4S	diode
Rs	--	--	resistor, 470m
RL	--	--	resistor, 2.5K

Appendix E

LTspice FFT Harmonics Analysis Results Sheet

Circuit: * E:\Desktop\sample Final.asc

Per .tran options, skipping operating point for transient analysis.
N-Period=1
Fourier components of V(out)
DC component: 27.1642V

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component	Phase [degree]	Normalized Phase [deg]
1	5.000e+01	5.261e+01	1.000e+00	73.31°	0.00°
2	1.000e+02	4.736e+01	9.003e-01	- 45.45°	-118.76°
3	1.500e+02	2.748e+01	5.224e-01	140.49°	67.18°
4	2.000e+02	2.825e+01	5.370e-01	- 14.90°	- 88.21°
5	2.500e+02	1.370e+01	2.605e-01	165.35°	92.04°
6	3.000e+02	1.679e+01	3.191e-01	- 9.76°	- 83.07°
7	3.500e+02	9.555e+00	1.816e-01	165.09°	91.78°
8	4.000e+02	1.308e+01	2.486e-01	-7.62°	- 80.92°
9	4.500e+02	7.410e+00	1.408e-01	170.98°	97.67°
10	5.000e+02	1.017e+01	1.934e-01	-5.70°	-79.01°

Total Harmonic Distortion: 130.135547%(33.647900%)

Date: Sun Mar 19 17:08:35 2017
Total elapsed time: 143.871 seconds.

tnom = 27
temp = 27
method = modified trap
totiter = 2000034
traniter = 2000034
tranpoints = 1000018
accept = 1000018
rejected = 0
matrix size = 9
fillins = 7
solver = Normal
Matrix Compiler1: 702 bytes object code size 1.3/1.0/[0.8]
Matrix Compiler2: 763 bytes object code size 0.6/1.0/[0.4]

Appendix F

CFL Current FFT Analysis Results Sheet

FFT Analysis

Sampling time = 1e-06s
Samples per cycle = 20000
DC component = 0.04

Fundamental = 0.19peak (0.14rms)

Total Harmonic Distortion (THD) = 130.08%

Maximum harmonic frequency
Used for THD Calculation = 499950.00Hz (9999th harmonics)

0	Hz	(DC):	43.47%	90.0^{o}
50	Hz	(Fnd):	100.00%	47.5^{o}
100	Hz	(h2):	80.18%	- 4.0^{o}
150	Hz	(h3):	68.01%	-43.3^{o}
200	Hz	(h4):	53.45%	-43.3^{o}
250	Hz	(h5):	50.21%	263.6^{o}
300	Hz	(h6):	48.13%	-7.5^{o}
350	Hz	(h7):	40.56%	252.1^{o}
400	Hz	(h8):	10.34%	-75.9^{o}
450	Hz	(h9):	9.41%	88.9^{o}
500	Hz	(h10):	8.01%	71.7^{o}
550	Hz	(h11):	3.62%	51.9^{o}

Appendix G

CFL Voltage FFT Analysis Results Sheet

FFT Analysis

Sampling time = 1e-06s
Samples per cycle = 20000
DC component = 21.9

Fundamental = 219 peak (154.86rms)

Total Harmonic Distortion (THD) = 36.55%

Maximum harmonic frequency
Used for THD Calculation = 499950.00Hz (9999th harmonics)

0	Hz	(DC):	14.14%	90.0^{o}
50	Hz	(Fnd):	100.00%	19.5^{o}
100	Hz	(h2):	27.71%	-11.6^{o}
150	Hz	(h3):	14.63%	-51.2^{o}
200	Hz	(h4):	9.52%	81.3^{o}
250	Hz	(h5):	8.81%	68.5^{o}
300	Hz	(h6):	7.59%	-247.5^{o}
350	Hz	(h7):	6.92%	-67.7^{o}
400	Hz	(h8):	6.01%	280.9^{o}
450	Hz	(h9):	5.97%	-66.1^{o}
500	Hz	(h10):	4.89%	78.3^{o}
550	Hz	(h11):	4.02%	S 65.8^{o}

Appendix H

CFL with developed Series Filter Current FFT Analysis Results Sheet

FFT Analysis

Sampling time = 1e-06s
Samples per cycle = 20000
DC component = 0

Fundamental = 0.18peak (0.13rms)

Total Harmonic Distortion (THD) = 9.54%

Maximum harmonic frequency
Used for THD Calculation = 499950.00Hz (9999th harmonics)

0	Hz	(DC):	6.30%	270.0º
50	Hz	(Fnd):	100.00%	7.4º
100	Hz	(h2):	2.22%	161.6º
150	Hz	(h3):	7.63%	199.9º
200	Hz	(h4):	1.40%	146.6º
250	Hz	(h5):	3.89%	209.3º
300	Hz	(h6):	1.06%	146.7º
350	Hz	(h7):	2.23%	223.3º
400	Hz	(h8):	0.82%	154.5º
450	Hz	(h9):	1.34%	240.8º
500	Hz	(h10):	0.63%	166.9º
550	Hz	(h11):	0.83%	261.6º

Appendix I

CFL with developed Series Filter Voltage FFT Analysis Results Sheet

FFT Analysis

Sampling time = 1e-06s
Samples per cycle = 20000
DC component = 12.99

Fundamental = 223.6 peak (158.1 rms)

Total Harmonic Distortion (THD) = 5.00%

Maximum harmonic frequency
Used for THD Calculation = 499950.00Hz (9999th harmonics)

0	Hz	(DC):	12.92%	270.0^{o}
50	Hz	(Fnd):	100.00%	1.6^{o}
100	Hz	(h2):	1.04%	166.2^{o}
150	Hz	(h3):	2.27%	127.5^{o}
200	Hz	(h4):	0.50%	121.7
250	Hz	(h5):	2.11%	129.8^{o}
300	Hz	(h6):	0.52%	92.6^{o}
350	Hz	(h7):	1.78%	140.7^{o}
400	Hz	(h8):	0.59%	89.1^{o}
450	Hz	(h9):	1.44%	155.6^{o}
500	Hz	(h10):	0.63%	96.8^{o}
550	Hz	(h11):	1.12%	173.2^{o}

Appendix J

CFL with developed Shunt Filter Current FFT Analysis Results Sheet

FFT Analysis

Sampling time = 1e-06s
Samples per cycle = 20000
DC component = 0

Fundamental = 0.19 peak (0.14rms)

Total Harmonic Distortion (THD) = 3.64%

Maximum harmonic frequency
Used for THD Calculation = 499950.00Hz (9999th harmonics)

0	Hz	(DC):	2.94%	90.0^{o}
50	Hz	(Fnd):	100.00%	1.6^{o}
100	Hz	(h2):	0.26%	-57.4^{o}
150	Hz	(h3):	2.66%	185.3^{o}
200	Hz	(h4):	0.23%	-68.4^{o}
250	Hz	(h5):	1.57%	188.0^{o}
300	Hz	(h6):	0.23%	-70.6^{o}
350	Hz	(h7):	1.10%	190.8^{o}
400	Hz	(h8):	0.22%	-70.6^{o}
450	Hz	(h9):	0.83%	193.8^{o}
500	Hz	(h10):	0.21%	-69.0^{o}
550	Hz	(h11):	0.65%	196.7^{o}

Appendix K

CFL with developed Shunt Filter Voltage FFT Analysis Results Sheet

FFT Analysis

Sampling time = 1e-06s
Samples per cycle = 20000
DC component = 0

Fundamental = 230 peak (162.6rms)

Total Harmonic Distortion (THD) = 0.09%

Maximum harmonic frequency
Used for THD Calculation = 499950.00Hz (9999th harmonics)

0	Hz	(DC):	0.00%	0.0^o
50	Hz	(Fnd):	100.00%	-0.1^o
100	Hz	(h2):	0.00	0.0^o
150	Hz	(h3):	0.00%	0.0^o
200	Hz	(h4):	0.00%	0.0^o
250	Hz	(h5):	0.00%	0.0^o
300	Hz	(h6):	0.00%	0.0^o
350	Hz	(h7):	0.00%	0.0^o
400	Hz	(h8):	0.00%	0.0^o
450	Hz	(h9):	0.00%	0.0^o
500	Hz	(h10):	0.00%	0.0^o
550	Hz	(h11):	0.00%	0.0^o