Sudan University of Science and Technology
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Power System Harmonics Sources, Effects and Elimination

مصادر التوافقيات في منظومة القوى الكهربائية و آثارها و طرق تقليلها

A Project Submitted In Partial Fulfillment for the Requirements of the Degree of B.Sc. (Honor) In Electrical Engineering (Power)

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الاية

قال تعالي :

" يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ"

صدق اللہ العظيم

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الأهداء:

الي والدتي التي أسقتني من دفاها في كل حين وذوتني بالصبر واليقين

والي كل أمهات بلادي اللاتي يسعين لتربيه ابناءهم وتعليمهم

الي والدي المعتق بالصبر الذي ذودني بالدعوات بكل سخاء والدي إلهامي

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و الصرح العظيم .

جامعة السودان للعلوم والتكنولوجيا

الي من حباه الله بالعلم والعطاء ....مشرف هذا البحث

د.صلاح الدين قاسم محمد

أهداء بطعم الصبر لكل معلمي بلادي الذين يذوبون لأجل غير

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ABSTRACT

The use of non linear loads is increasing day by day. This increasing use of non linear loads has created more distortions in current and voltage waveforms. This increased power quality disturbances has lead to various optimizations techniques and filter designs. Harmonic distortions are the major cause for power quality problems.

The harmonics in distribution systems come from transformers or satiable reactors, are furnace, welding machines, florescent lamps, rotating machines and power electronics devices. In general, the non linear loads in which the relationship between the voltage and current is not constant. It is considered that there is no risk of harmful perturbation from 5 to 10% above 10%, problems will certainly occur.

Equipments can be affected by the harmonics like transformers with increase of losses , risk of overheating , noise and even insulation stress problems .cables that can heat too much due to as Kelvin effect above 400HZ. Induction relays and meters that are permutated by harmonic torques incorrect tripping and readings.

The solutions that can be used to improve the power factor and to protect the capacitors are either de-rate the capacitors or using detuning reactors, and also by using harmonic filters.

This thesis presents the definitions of harmonic, generation, causes, effects on electrical power system and elimination.

المستخلص

إستخدام الأحمال اللأخطية في إزياد مستمر يوم بعد يوم ، هذا الأزدياد أحدث زيادة في تشوة موجة التيار وموجة الجهد مما أحدث زيادة في الأضطراب لجودة التغذية ، الاضطراب قاد الى تصميم المرشحات والكثير من التقنيات التي تسعى الى تحقيق الأمثلية حيث تعتبر التشوهات التوافقية من أهم أسباب مشكلات جودة القدرة .

إن وجود التوافقيات في شبكات توزيع القدرة الكهربائية ينتيج من التشبع في محولات القدرة،وأستخدام أفران القوس الكهربي ، وماكينات اللحام ولمبات الفلوريسنت ،والماكينات الدوارة وأدوات الكترونيات القدرة . وبمعنى أشمل ، الأحمال غير الخطية والتي تكون العلاقه بين الجهد والتيار فيها غير ثابتة .

كما أنه إذا تعدى معامل التشوه التوافقي عن نسبة معينة (10%) فانه ينتج ضرر كبير ومشاكل عدة، والتي تتمتل في زيادة الفقد في المحولات وتكمن الخطورة في أرتفاع الحرارة واجهادات الموصلات والعوازل ، كما أن الكوابل ترفع درجة حرارتها ، والمرحلات وأجهزة القياس تفصل وتتغير قراءتها نتيجة العزوم الأضافية الناتجة من التوافقيات .

وتكمن الحلول بالنسبة لمشاكل التوافقيات في تحسين معامل القدرة بواسطة المكثفات، وحماية هذة المكثفات بأستعمال الملفات مع المكثفات . بالأضافة إلي أستعمال المرشحات للحد من خطورةالتوافقيات .

تتناول هذه الرسالة تعريف التوافقيات ومولداتها وأسبابها وتاثيرها علي منظومة القدرة الكهربائية ومعالجتها.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
DC	Direct Current
AC	Alternate Current
RMS	Root Mean Square
IEEE	Institute of Electrical and Electronic Engineering
DF	Distortion Factor
IDF	Input Displacement Factor
THD	Total Harmonic Distortion
THDv	Total Harmonic Voltage Distortion
THDi	Total Harmonic Current Distortion
TDD	Total Demand Distortion
EMF	Electro Magnetic Force
PF	Power Factor
DPF	Distorted Power Factor
TPF	Total Power Factor
UPS	Uninterruptable Power Supply
VFD	Variable Frequency Drives
HVDC	High Voltage Direct Current
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
ETAP	Electrical transient Analyzer Program
SMPS	Single-Phase Switched Mode Power Supplies
PMW	Pulse Width Modulation
EMI	Electromagnetic Interference
RFI	Radio Frequency Interference
LHF	Line Harmonic Filters
PCC	Point of Common Coupling

CHAPTER ONE

INTRODUCTION

1.1 Background

Nowadays the world seen rapid increase of power electronics , based loads connected to the distribution system. These types of loads draw non sinusoidal current from the main power source, hence these loads called nonlinear loads. Normally power systems are designed to operate at frequencies of 50 HZ or 60HZ , but these nonlinear loads produce current and voltage with frequencies that are integer multiples of the 50 HZ or 60 HZ fundamental frequency. These higher frequencies are called electrical pollution is known as power system harmonics. The nonlinear loads appear to be prime sources of harmonic distortion in a power distribution system. In addition, the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power system equipment, most notably capacitors , transformers, and motor , causing additional losses , overheating , overloading and electromagnetic interferences .Also, Harmonics are caused by various reasons such as saturation , switching and winding connections in transformers , shunt capacitors resonance and nonlinear loads like switching mode power supply , wind and solar power generation.

Harmonic current is eliminated by using harmonic filters in order to protect the electrical equipment from getting damaged due to harmonic voltage distortion. They can also be used to improve the power factor. There can be three types of filters that to reduce the harmonic distortion an i.e. passive filter, active filters and hybrid filters. The passive filter consists of passive elements such as resistors, inductors and capacitors. On the other hand, the active filters consist of active components such as IGBT-transistors and eliminate many different harmonic frequencies. The signal types can be single phase AC, three phases AC. The three type of filters in hybrid from passive and active filters.

1.2 Problem Statement

Harmonics has become the common problem nowadays because there are many modern electronics equipment such as computers , TVs ,adjustable speed drives , and any other equipment powered by switched mode power supply equipment , these types of nonlinear loads generate harmonics so the research in general on harmonic reduction . Hence filters must be designed to eliminate the harmonic from the system. The single tuned notch filter is designed to cancel the 5 harmonic order at fluorescent lamp and Arc furnace and cancel 5th and 7th harmonics order at six pulse rectifier .The harmonic analysis of power system involves the calculation of power factor ,frequency responses , capacitor bank size , and filter reactor size , evaluating filter duty requirements , harmonic currents and voltage parameters .The peak voltage RMS voltage , RMS currents and KVAR values are calculated then compared with the standard limitations of IEEE. In addition, the MATLAB program used to analyze the problem is presented along with results in the Appendix .Comparisons are made between harmonics elimination by using passive filters and by using active filters based on MATLAB/SIMULINK package. Active filters more effective to eliminate harmonics distortions and also improve the power quality and compensate the reactive power at the fundamentals frequency.

1.3 Project Objectives

The main objectives of the research are

1- To study the main sources of harmonic in power system.

2- To study the effects of harmonic in power system.

3- To study the methods of eliminating harmonics in power system.

1.4 Project layout

Project is consists of five parts

- Chapter one: Gives an overview of the subject and the contents of the chapters in thesis.
- Chapter tow: Cover a literature survey of the thesis. The main topics discussed here are harmonics history, sources of harmonic, effect of harmonic distortion, three phases non-linear and harmonic elimination.
- Chapter Three: Cover a methodology and tools.
- Chapter Four: Mainly based on harmonic analysis then used a single tuned notch filter according to these values to eliminate the 5th and 7th harmonic.
- Chapter five: Conclusion and recommendations.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Power system harmonics is an area that is receiving a great deal of attention recently. This is primarily due to the fact that non-linear or (harmonic producing) loads are comprising an ever-increasing portion of the total load for a typical industrial plant. The increase in proportion of non-linear load has prompted more stringent recommendations in IEEE Std. 519 and stricter limits imposed by utilities. Incidence of harmonic related problems is low, but awareness of harmonic issues can help to increase plant power system reliability. On the rare occasions that harmonics are a problem, it is either due to the magnitude of the harmonics produced or a power system resonance.[1]

Until the 1960s the main harmonic sources in the power system were arc furnace and a very few converter loads. With the thyristor’s and static power supplies many variable speed drives were introduced in all industries in the 1970s. With the increase in the converter load in the power system, several new problems became noticeable such as:

- Flow of harmonic currents from the converter to the ac system.
- Poor power factor on the ac side.
- Poor voltage regulation on the ac side due to low power factor.
- Excessive interference induced into the telecommunication equipment due to mutual coupling.
- Distortion of ac supply voltages that affect the performance of computer equipment and numerical control devices.
- Error in the metering.

- Continuous neutral currents in the neutral conductors of the four wire systems.

Therefore, there is a need to understand the behaviour of the industrial power systems with the converter/inverter equipment. With the introduction of the new filtering devices, the need to improve the power factor and control the harmonics together in the utilities can encounter new system problems. In this Chapter, the sources of harmonics, the system response, modeling of the system for harmonic analysis, acceptable harmonic limits and the approach for the harmonic analysis are presented. [1]

2.2 Harmonic Definition

The typical definition for a harmonic is “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.”

Some references refer to “clean” or “pure” power as those without any harmonics. But such clean waveforms typically only exist in a laboratory.

Electrical generators try to produce electric power where the voltage waveform has only one frequency associated with it, the fundamental frequency. In the North America, this frequency is 60 Hz, or cycles per second. In European countries and other parts of the world, this frequency is usually 50 Hz. Aircraft often uses 400 Hz as the fundamental frequency. At 60 Hz, this means that sixty times a second, the voltage waveform increases to a maximum positive value, then decreases to zero, further decreasing to a maximum negative value, and then back to zero. The rate at which these changes occur is the trigo-metric function called a sine wave, as shown in Figure 2.1. This function occurs in many natural phenomena, such as the speed of a pendulum as it swings back and forth, or the way a string on a violin vibrates when plucked.

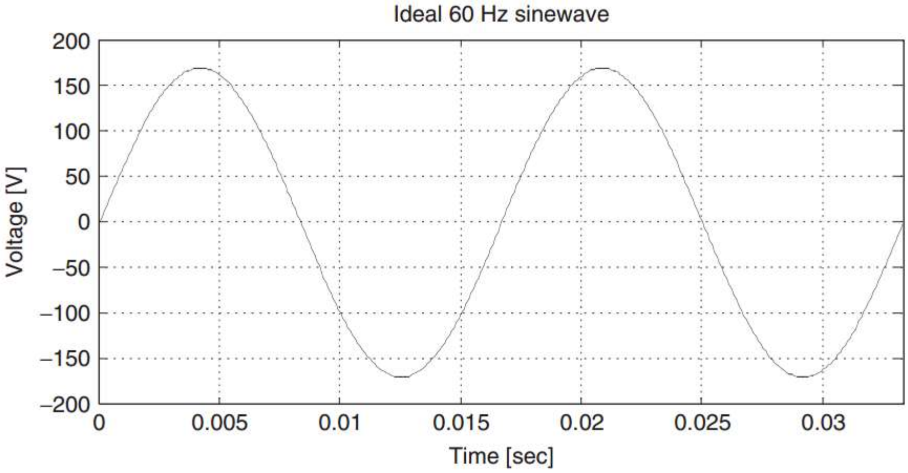

Figure 2.1: Normal pure Sine wave

The frequencies of the harmonics are different, depending on the fundamental frequency. For example, the 2nd harmonic on a 60 Hz system is 2*60 or 120 Hz. At 50Hz, the second harmonic is 2* 50 or 100Hz, 300Hz is the 5th harmonic in a 60 Hz system, or the 6th harmonic in a 50 Hz system.

Figure 2.*2:* Shows how a signal with two harmonics would appear on an oscilloscope-type display, which some power quality analyzers provide.

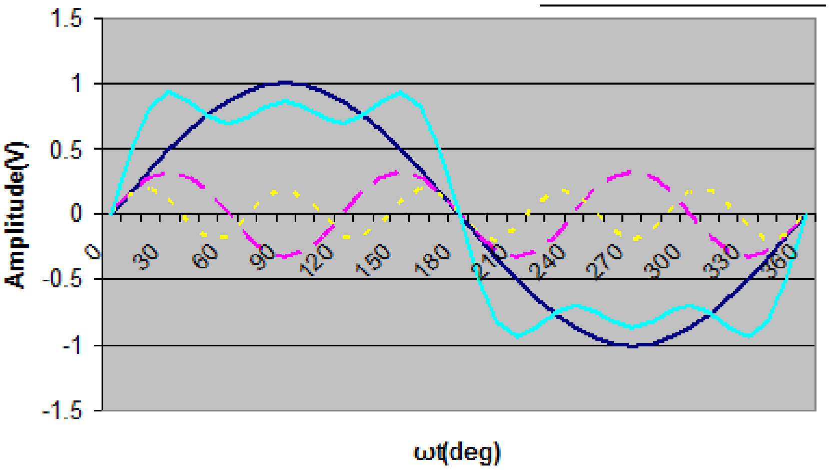

Figure 2.2: Waveform containing the fundamental plus third and fifth harmonics

In order to be able to analyze complex signals that have many different frequencies present, a number of mathematical methods were developed. One of the more popular is called the Fourier Transform. However, duplicating the mathematical steps required in a microprocessor or computer-based instrument is quite difficult. So more compatible processes, called the FFT for Fast Fourier Transform or DFT for Discrete Fourier Transform are used. These methods only work properly if the signal is composed of only the fundamental and harmonic frequencies in a certain frequency range (called the NY Quist frequency, which is one-half of the sampling frequency). The frequency values must not change during the measurement period. Failure of these rules to be maintained can result in misinformation.

For example, if a voltage waveform is comprised of 60 Hz and 200 Hz signals, the FFT cannot directly see the 200 Hz. It only knows 60, 120, 180, 240, etc. which are often called "bins". The result would be that the energy of the 200 Hz signal would appear partially in the 180Hz bin, and partially in the 240 Hz bin. An FFT-based processer could show a voltage value of 115V at 60 Hz, 18 V at the 3rd harmonic, and 12 V at the 4th harmonic, when it really should have been 30 V at 200 Hz.

These in-between frequencies are called "inter-harmonics". There is also a special category of inter-harmonics, which are frequency values less than the fundamental frequency value, called sub-harmonics. For example, the process of melting metal in an electric arc furnace can result large currents that are comprised of the fundamental, inter-harmonic, and sub-harmonic frequencies being drawn from the electric power grid.

These levels can be quite high during the melt-down phase and usually effect the voltage waveform.[2]

2.3 Harmonics indices

The two most commonly used indices for measuring the harmonic content of a waveform are the total harmonic distortion and the total demand distortion. Both are measures of the effective value of a waveform and may be applied to either voltage or current.

2.3.1 Total Harmonic Distortion

A common term that is used in relation to harmonics is THD or Total Harmonic Distortion. THD can be used to describe voltage or current distortion and is calculated as follows:

$$\mathrm{THD}(\%) = \sqrt{(\mathrm{ID}_1^2 + \mathrm{ID}_2^2 + \ \ldots\ldots + \mathrm{ID}_n^2)} \qquad (2.1)$$

Where

THD ≡ Total Harmonic Distortion

IDn ≡ Magnitude of the nth Harmonic as a Percentage of the Fundamental

2.3.2 Total demand distortion

Harmonic distortion is most meaningful when monitored at the point of common coupling (PCC) usually the customer's metering point over a period that can

reflect maximum customer demand, typically 15 to 30 minutes as suggested in Standard IEEE-519.7 Weak sources with a large demand current relative to their rated current will tend to show greater waveform distortion. Conversely, stiff sources characterized for operating at low demand currents will show decreased waveform distortion. The total demand distortion is based on the demand current, over the monitoring period:

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_l} \qquad (2.2)$$

where

TDD ≡ Total Demand Distortion.
I_h ≡ Harmonic Current.
I_l ≡ fundamental Current.

2.3.3 Power factor in the presence of harmonics

There are two different types of power factor that must be considered when voltage and current waveforms are not perfectly sinusoidal. The first type of power factor is the Input Displacement Factor (IDF) which refers to the cosine of the angle between the 60 Hz voltage and current waveforms. The second type is Distortion Factor (DF) is defined as follows:

$$\mathrm{DF} = \frac{1}{\sqrt{1+\mathrm{THD}^2}} \tag{2.3}$$

Hence

DF ≡ Distortion Factor

THD ≡ Total Harmonic Distortion

The Distortion Factor will decrease as the harmonic content goes up. The Distortion Factor will be lower for voltage source type drives at reduced speed and load. Total Power Factor (PF) is the product of the Input Displacement Factor and the distortion factor as follows:

$$\mathrm{PF} = \mathrm{IDF} \times \mathrm{DF} \tag{2.4}$$

Hence

PF ≡ Power Factor

IDF ≡ Input Displacement Factor

DF ≡ Distortion Factor

In order to make a valid comparison of power factor between drives of different topologies, it is essential to look at Distortion Factor. The Displacement Power Factor may look attractive for certain types of drives, but the actual power factor may be somewhat lower when the effect of harmonics is taken into account.[1]

2.4 Fourier Series and Coefficients

By definition, a periodic function, f(t), is that where f(t) = f(t + T). This function can be represented by a trigonometric series of elements consisting of a DC component and other elements with frequencies comprising the fundamental component and its integer multiple frequencies [2]. This applies if the following so-called Dirichlet conditions2 are met:

If a discontinuous function, f(t) has a finite number of discontinuities over
the period T

If f(t) has a finite mean value over the period T

If f(t) has a finite number of positive and negative maximum values

The expression for the trigonometric series f(t) is as follows:

$$f(t)=\frac{a_0}{2}+\sum_{h=1}^{\infty}\left[a_h\cos(hw_0t)+b_h\sin(h\omega_0t)\right] \qquad (2.5)$$

hence

f(t) ≡ Discontinuous Function

a_0 ≡ The Average Value of the Function f(t)

a_h, b_h ≡ The Coefficients of the Series, are the Rectangular Components of the *n*th Harmonic

$$\omega_0=\frac{2\pi}{T}$$

We can further simplify Equation (2.5), which yields:

$$f(t)=c_0+\sum_{h=1}^{\infty} c_h \sin(h\omega_0 t+\emptyset_h) \tag{2.6}$$

Where

$c_0=\frac{a_0}{2}$, $c_h=\sqrt{a_h^2+b_h^2}$, and $\emptyset_h=\tan^{-1}\left(\frac{a_h}{b_h}\right)$

Hence

$(h\omega_0)$ ≡ Hth Order Harmonic of the Periodic Function

c_0 ≡ Magnitude of the DC Component

Ch ≡ and Φh Magnitude and Phase Angle of the hth Harmonic Component

Equation (2.6) is known as a Fourier series and it describes a periodic function made up of the contribution of sinusoidal functions of different frequencies.

phase angle of each harmonic determine the resultant waveform *f*(*t*).

Equation (2.5) can be represented in a complex form as:

$$f(t)=\sum_{h=1}^{\infty} c_h e^{jh\omega_0 t} \tag{2.7}$$

where $h = 0,\pm1,\pm2, \ldots$

$$c_h=\frac{1}{T}\int_{-T/2}^{T/2} f(t)e^{-j\omega_0 t}\,dt \tag{2.8}$$

Generally, the frequencies of interest for harmonic analysis include up to the 40th or so harmonics.

The main source of harmonics in power systems is the static power converter. Under ideal operation conditions [2], harmonics generated by a *p* pulse power converter are characterized by:

$$Ih=\frac{I_1}{h} \qquad (2.9)$$

when $h=pn\pm1$

where

$h \equiv$ Stands for the Characteristic Harmonics of the Load; $n = 1, 2, \ldots$; and p is an Integer Multiple of Six

2.5 linear and Nonlinear Loads

2.5.1 Linear loads

Linear loads are those in which voltage and current signals follow one another very closely, such as the voltage drop that develops across a constant resistance, which varies as a direct function of the current that passes through it. This relation is better known as Ohm's law and states that the current through a resistance fed by a varying voltage source is equal to the relation between the voltage and the resistance [2] , as described by:

$$i(t)=\frac{v(t)}{R} \qquad (2.10)$$

where

$i(t) \equiv$ Current that Passes Through Resistance.

$v(t) \equiv$ Voltage.

$R \equiv$ Resistance.

This is why the voltage and current waveforms in electrical circuits with linear loads look alike. Therefore, if the source is a clean open circuit voltage, the current waveform will look identical, showing no distortion. Circuits with linear loads thus make it simple to calculate voltage and current waveforms. Even the amounts of heat created by resistive linear loads like heating elements or incandescent lamps can easily be determined because they are proportional to the square of the current.

Alternatively, the involved power can also be determined as the product of the two quantities, voltage and current.

Other linear loads, such as electrical motors driving fans, water pumps, oil pumps, cranes, elevators, etc., not supplied through power conversion devices like variable frequency drives or any other form or rectification/inversion of current will incorporate magnetic core losses that depend on iron and copper physical characteristics.

Voltage and current distortion may be produced if ferromagnetic core equipment is operated on the saturation region, a condition that can be reached, for instance, when equipment is operated above rated values.

2.5.2 Nonlinear loads

Nonlinear loads are loads in which the current waveform does not resemble the applied voltage waveform due to a number of reasons, for example, the use of electronic switches that conduct load current only during a fraction of the power frequency period. Therefore, we can conceive nonlinear loads as those in which Ohm’s law cannot describe the relation between V and I. Among the most common nonlinear loads in power systems are all types of rectifying devices like those found in power converters, power sources, uninterruptible power supply (UPS) units, and arc devices like electric furnaces and fluorescent lamps. nonlinear loads cause a number of disturbances like voltage waveform distortion, overheating in transformers and other power devices, over current on equipment neutral connection leads, telephone interference, and microprocessor control problems, among others.[2]

2.6 Harmonic Sources

These effects depend, of course, on the harmonics sources, its location on the power system, and the network characteristics that promote propagation of harmonics. These are numerous sources of harmonics. In general, the harmonics sources can be classified as, previously known harmonics sources and new harmonics sources.

The previously known harmonics sources include:

1. Tooth or ripples in the voltage waveform of rotating machines.

2. Variations in air-gap reluctance over synchronous machines pole pitch.

3. The flux distortion in the synchronous machine from sudden load changes.

4. No sinusoidal distribution of the flux in the air-gap of synchronous machines.

5. Transformers magnetizing currents.

6. Network nonlinearities from loads such as rectifiers, inventers, welders, arc furnaces, voltage controllers, frequency converters, etc.

While the establishment sources of harmonics are still present on the system, the power network is also subjected to new harmonics sources:

1. Energy conservation measures, such as those for improved motor efficiency and load matching which employ power semiconductor devices and switching for their operation. These devices often produce irregular voltage and current waveforms that are rich in harmonics.

2. Motor control devices such as speed controllers for traction.

3. High-voltage DC power transmission.

4. Interconnection of wind and solar power converters with distribution systems.

5. Static-var compensators which have largely replaced synchronous condensers as continuously variable-var sources .

6. Electrical arc furnaces.

7. Fluorescent lighting.

8. Computers switch mode power supplies.

9. Battery charges.

10. Imperfect AC sources.

11. Variable frequency motor drives (VFD).

12. Inverters.

13. Television power supplies.

14. Harmonics produced by synchronous machines

14.1 Voltage harmonics produced by synchronous machines

If the magnetic flux of the field system is distributed perfectly sinusoidal around the air gap, the e.m.f. (electro magnetic force) generated in each full-pitched armature coil is

$$emf=2\pi f\emptyset \sin\omega t \qquad (2.11)$$

Where

$\emptyset$ ≡ The Total Flux Per Pole

f ≡ Frequency Related to Speed and Pole Pairs

14.2 Synchronous machines –source of harmonic currents

Synchronous machines represent a source of harmonic currents on two counts: the frequency conversion effect, and the non-linear characteristic due to magnetic saturation.

The frequency conversion effect: a synchronous generator feeding an unbalanced, three-phase load may experience the flow of a negative sequence current in the rotor, which in turn may induce a third-order harmonic current on the stator winding. In special cases when the generator feeds static converter equipment the machine can be important source of harmonic generation. The saturation of the stator's circuit represents another harmonic source.

2.7 Effects of Harmonics in Power System

The power industry has recognized the problem of power system harmonics since 1920s when distorted voltage and current waveforms were observed on power lines. However, the levels of harmonics on distribution system have generally been insignificant in the past. Today, it is obvious that the levels of harmonic voltages and currents on distribution systems are becoming a serious problem. Some of the most important power system operational problems caused by harmonics have been reported to include the flowing:

1. Capacitor bank failure from dielectric breakdown or reactive power overload

2. Interference with ripple control and power-line carrier system, causing miss-operation of system which accomplish remote switching, load control and metering.

3. Excessive losses in and heating of induction and synchronous machines.

4. Overvoltage and excessive currents on the system from resonance to harmonic voltages or current on the network.

5. Dielectric instability of insulated cables resulting from harmonic over voltages on the system.

6. Inductive interference with telecommunication system.

7. Errors in induction watt-hour meters.

8. Signals interference and really malfunction, particularly in solid-state and microprocessor-controlled system.

9. Interference with large motor controllers and power plant excitation systems (reported to cause motor problems as well as no uniform output).
Also, harmonics increase the load current which than effect the operation of as following equipment's:
a- Overloading of neutrals

b- Overheating of transformers

c- Nuisance tripping of circuit breakers

d- Over-stressing of power factor correction capacitors
Also**,** the harmonics affect system voltage which produces the following results:
Voltage distortion & zero-crossing noise

e- Overheating of induction motors (oscillating torques).
In balanced three phase systems the fundamental current cancels, but triple-N harmonics add arithmetically! Non triple-N harmonics cancel in the neutral. Neutral currents can easily approach twice the phase currents - sometimes in a half-sized conductor.

IEEE 1100-1992 recommends that neutral bus-bars feeding non-linear loads should have a cross-sectional area not less than 173% that of the phase bars. Neutral cables should have a cross-sectional area that is 200% that of the phases, e.g. by using twin single core cables.[1]

2.8 Harmonic Elimination

Majority of large power (typically three-phase) electrical nonlinear equipments often requires mitigation equipment in order to attenuate the harmonic currents and associated voltage distortion to within necessary limits. Depending on the type of solution desired, the mitigation may be supplied as an integral part of nonlinear equipment (e.g., an AC line reactor or a line harmonic filter for AC PWM drive) or as a discrete item of mitigation equipment (e.g., an active or passive filter connected to a switchboard). There are many ways to reduce harmonics, ranging from variable frequency drive designs to the addition of auxiliary equipment. Few of the most prevailing methods used today to reduce harmonics are explained below:

1. Delta-Delta and Delta-Wyes Transformers.
2. Isolation Transformers.
3. Reactors.
4. Passive Harmonic Filters (or Line Harmonic Filters).
5. 12-pulse converter front end.
6. 18-pulse converter front end.
7. Active filters.
8. Active front end.

2.9 Load Side Harmonic Sources Effects and Eliminations

2.9.1 Load Side Sources of Harmonics

Many types of non-linear loads appeared and their usage rate increased rapidly. Non-linear loads such as rectifiers, power supplies, UPS units, TV's, Video recorders, Computers, Printers, Micro wave ovens, discharge lighting, adjustable speed motor drives, electric ballast, vapor mercury, halogen spot light, halogen with dimmer and arcing equipment became widely used these days besides the rapid increase of the industrial non-linear loads such as that in metal factories. In this paper different types of non-linear loads are considered, different measurements have been made, wave forms and spectrum of different harmonic orders have been shown for each of the non-linear loads considered. The experimental works have been performed in the Advanced Power Systems and Control Laboratory, Sudan University of Science and Technology. Different types of sources have been studied, effects of harmonics have been investigated and two harmonics eliminations methods have been applied. A power analyzer device has been used to obtain all required measurements.

Types of sources in load side:

1. Dimmer Controlled Halogen Lamp.
2. Vapor Mercury Lamp.
3. Halogen Spot Light Lamp.
4. Electric Ballast Lamp.
5. Magnetic Ballast Lamp.[4]

2.9.2 Effects of Load Side Harmonics

The existence of harmonics produces many problems in the power systems, it increases noise of electric machines and highly affects its iron loss, besides increasing the current as given by equation below:

$$I=\sqrt{I_n^2} \tag{2.12}$$

Where

In ≡ RMS Current Value of the nth Harmonic Order

Due to current increase the active power loss increases in generators, transmission lines, transformers and load resistances. Harmonics frequencies increase the eddy current and hysteresis loss, these lead to equipment heating and malfunctioning and fuse and circuit breaker miss-operation.

The existence of harmonics frequencies increases the absorption of reactive power due to current increase and more clearly due to appearance of a new reactance for each harmonic's frequency as given by equation below.

$$Xl=2\pi fl \tag{2.13}$$

The existence of harmonics reduces the total power factor (TPF) due to the increasing of reactive power absorption and distortion power. It also causes current flow in the neutral conductor and power elements over-age, power system capacity reduction, power system overstress and maintenance and installations cost increase the thing makes it essential to eliminate the harmonics level in the power systems.[4]

2.9.3 Elimination of load sides harmonics

Harmonic distortion in power distribution systems can be suppressed using two approaches namely, passive and active filters. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion another approach is using (Δ/Y) transformers.[4]

CHAPTER THREE

TOOLS AND METHODS

3.1 Introduction

In this modern era , it is necessary for regulated power sectors to properly monitor power system signals in order to be able to access and maintain the quality of power according to the set standards . Harmonics are sinusoidal voltages or currents having frequencies, that are integer multiples of the fundamental frequencies (50 or 60 HZ), at which the supply system operate.

The identification, classification, quantification and mitigation of power system harmonic signals is the burning issue for various stake holders including utilities, consumer and manufacturers word widely.

To accomplish this task mathematical and computational tool like MATLAB and ELECTRICAL TRANSIENT ANALYER PROGRAM (ETAP) have been used while conducting research.

Experimental work and simulation, pertaining to harmonic, will really help the scientific community to understand this phenomenon comprehensively to gain in-advance information, acquired for remedial measures.[9]

3.2 MATLAB Environment

3.2.1 Development environment MATLAB

This is the set of tools and facilities that help you use MATLAB functions and files. Many of these tools are graphical user interfaces. It includes the MATLAB desktop and Command Window, a command history, and browsers for viewing help, the workspace, files, and the search path.

3.2.2 The MATLAB mathematical function library

This is a vast collection of computational algorithms ranging from elementary functions like sum, sine, cosine , and complex arithmetic, to more sophisticated functions like matrix inverse, matrix Eigen values Bessel functions, and fast Fourier transforms.

3.2.3 The MATLAB language

This is a high-level matrix/array language with control flow statements, functions, data structures, input/output, and object-oriented programming features. It allows both “programming in the small” to rapidly create quick and dirty throw-away programs, and “programming in the large” to create complete large and complex application programs.

3.2.4 The MATLAB application program interface

This is a library that allows you to write C and Fortran programs that interact with MATLAB. It include facilities for calling routines from MATLAB (dynamic linking), calling MATLAB as a computational engine, and for reading and writing MAT-files

3.2.5 MATLAB simulation

Simulink a companion program to MATLAB, is an interactive system for simulating nonlinear dynamic systems. It is a graphical mouse-driven program that allows you to model a system by drawing a block diagram on the screen nonlinear, continuous-time, discrete-time, multirate, and hybrid systems. Block sets are add-ons to Simulink that provide additional libraries of blocks for specialized applications like communications, signal processing, and power systems. Real-Time Workshop is a program that allows you to generate C code from your block diagrams and to run it on a variety of real-time systems.

3.2.6 Advantages of MATLAB

- It is built to handle mathematical operations.
- Writing user defined functions in MATLAB is easy and can be saved in separate files.
- Ability of importing data from a txt or excel file using single command.
- Is also comes with feature that allows you to design a graphical user interface using add and drop boxes.
- It comes with numerous tools that are built for specific applications such as simulation of dynamic system.

3.3.1 ETAP environment

ETAP is the most comprehensive solution for the design, simulation, and analysis of generation, transmission, distribution, and industrial power systems. ETAP organizes your work on a project basis. Each project that you create provides all the necessary tools and support for modeling and analyzing an electrical power system. A project consists of an electrical system that requires a unique set of electrical components and interconnections. In ETAP, each project provides a set of users, user access controls, and a separate database in which its elements and connectivity data are stored. ETAP has been designed and developed by engineers for engineers to handle the diverse discipline of power systems in one integrated package with multiple interface views such as AC and DC networks, cable raceways, ground grid, GIS, panels, protective device coordination/selectivity, and AC and DC control system diagrams. Encompassing all these systems and views in one package allows engineers to model and analyze all aspects of an electrical system from control system diagrams to panel systems, as well as large transmission and distribution. All interface views are completely graphical and the engineering properties of each circuit element can be edited directly from these views. Calculation results are displayed on the interface views for your convenience. All ETAP systems take advantage of a common database. For example, a cable not only contains data representing its electrical properties but also contains the physical routing information to indicate the raceways through which it is routed. A relay not only contains information pertinent to analysis like load flow and short circuit but also contains time current characteristic information that allows the engineer to perform protection or coordination studies. Trip times set in these studies are also used by transient analysis to determine the total operating time of a breaker during a transient condition when the relay pickup value is reached. ETAP can therefore simulate automatic relay actions based on the relay settings. This type of integration makes ETAP a true power system simulator program. ETAP also contains built-in libraries that are accessible from project files. New libraries can be created or existing libraries can be modified to include custom manufacturer data. ETAP systems and interface views can be accessed using the System toolbar.[8]

3.3.2 Advantages of ETAP

- Harmonic analysis study.
- Short circuit analysis study.
- Load flow analysis study.
- Transient stability analysis study.
- Transformer sizing.
- Relay co ordinations.

3.4 Harmonic Sources

In general harmonic currents are the result of the non-linear behavior of electrical devices. The sources of harmonic currents and thus subsequently harmonic voltage in power systems are multiple and are varying in size (a few KVA up to several MVA) as well as significance. In earlier times devices with magnetic iron cores like transformers, generators or electric motors have been the most important group of harmonic sources. Also Arc furnaces and arc welders have been of high importance. Nowadays with the demand for energy efficient devices the group of power electronics and electronic equipment has to be considered the most serious source of harmonics. Besides the traditional industrial loads with still high harmonic producing equipment commercial and residential facilities became significant sources of harmonics. This is particularly true when the combined effects of all individual loads served by the same feeder are taken into account.

The harmonic spectra of all these non-linear loads are different but can be identified with some experience and knowledge. Thus, it is important to become familiar with the signatures of the different waveform distortions produced by specific harmonic sources. Without this knowledge the establishment of mitigation methods to lower or remove harmonics is not possible. The following chapters will give a brief overview about the most serious sources of harmonics.[5]

The harmonic sources that have been taken into account in this study are:

3.4.1Variable frequency drives (VFD)

VFDs are, in reality, power converters. The reason to further address them under a separate section is because, by themselves, VFDs constitute a broad area of application used in diverse and multiple industrial processes. In a very general context, two types of VFDs can be distinguished: those that rectify AC power and convert it back into AC power at variable frequency and those that rectify AC power and directly feed it to DC motors in a number of industrial applications. In both cases, the front-end rectifier, which can make use of diodes, thyristors, IGBTs, or any other semiconductor switch, carry out the commutation process in which current is transferred from one phase to the other. This demand of current “in slices” produces significant current distortion and voltage notching right on the source side, i.e., at the point of common coupling. Motor speed variations, which are achieved through firing angle control, will provide different levels of harmonic content on the current and voltage waveforms. Variable frequency drive designs also determine where harmonic currents will predominantly have an impact. For example, voltage source inverters produce complex waveforms showing significant harmonic distortion on the voltage and less on the current waveforms. On the other hand, current source inverters produce current waveforms with considerable harmonic contents with voltage waveforms closer to sinusoidal. None of the drive systems is expected to show large distortion on both voltage and current waveforms, in line with Finney’s observations Regarding VFDs, the ABB ACS6000 6P has been taken into account as it is available in ETAP harmonics library. [6]

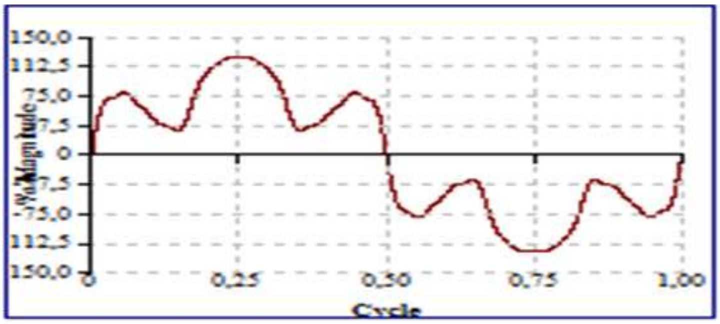

Figure 3.1 : Harmonic Source waveform for VFD

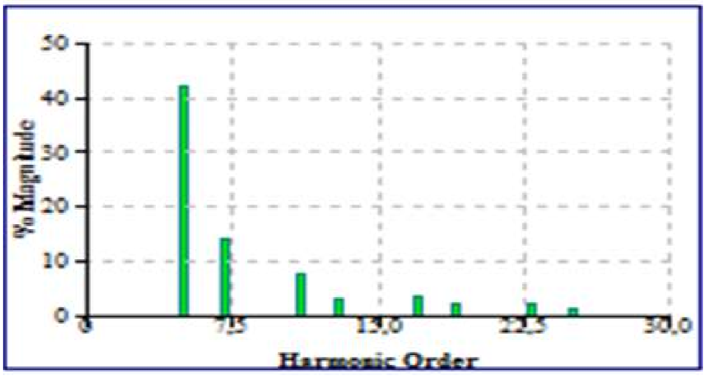

Figure 3.2 : Harmonic Source Spectrum for VFD

3.4.2 Uninterruptible power supply systems (UPS)

Uninterruptible power supply systems are usually used to provide "secure power" in the event of generator shutdown or other similar power failure. Dedicated individual computer UPS systems are usually single-phase and have an input current wave-shape and harmonic current spectrum similar to that produced by single-phase switched mode power supplies (SMPS). Three-phase UPS systems are also available. The majority of three-phase UPS systems have a controlled, SCR input bridge rectifier with characteristic harmonics based on the "pulse number ± 1" format. An IEEE standard spectrum as been considered for UPS devices due to the fact that no supplier information is available at project early stages.[6]

Figure 3.3: Harmonic Source waveform for UPS

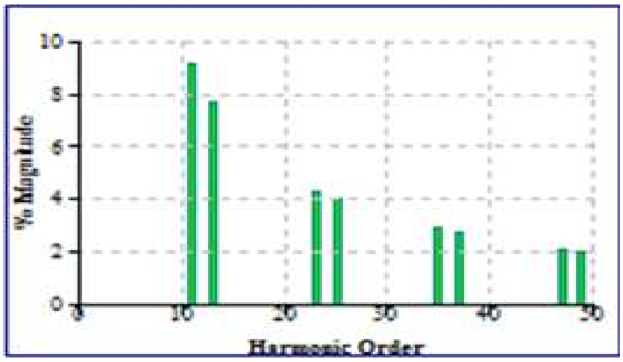

Figure 3.4 : Harmonic Source Spectrum for UPS

3.4.3 The rectifier

The rectifier can be thought of as a harmonic current source and produces roughly the same amount of harmonic current over a wide range of power system impedances. The characteristic current harmonics that are produced by a rectifier are determined by the pulse number. The following equation allows determination of the characteristic harmonics for a given pulse number:

$$h = kq \pm 1 \tag{3.1}$$

where

h is the Harmonic Number (Integer Multiple of the Fundamental)

k is Any Positive Integer

q is The Pulse Number of the Converter

This means that a 6-pulse (or 3-phase) rectifier will exhibit harmonics at the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, etc. multiples of the fundamental. As a rough rule of thumb, the magnitudes of the harmonic currents will be the fundamental current divided by the harmonic number (e.g. the magnitude of the 5th harmonic would be about 1/5th of the fundamental current). A 12-pulse (or 6-phase rectifier) will, in theory, produce harmonic currents at the 11th, 13th, 23rd, 25th, etc. multiples. In reality, a small amount of the 5th, 7th, 17th and 19th harmonics will be present with a 12-pulse system (typically the magnitudes will be on the order of about 10 percent of those for a 6-pulse drive). [7]

3.4.4 Fluorescent lighting

Lighting typically accounts for 40 to 60 percent of a commercial building load. Fluorescent lights are discharge lamps; thus they require a ballast to provide a high initial voltage to initiate the discharge for the electric current to flow between two electrodes in the fluorescent tube. Once the discharge is established, the voltage decreases as the arc current increases. It is essentially a short circuit between the two electrodes, and the ballast has to quickly reduce the current to a level to maintain the specified lumen output. Thus, a ballast is also a current-limiting device in lighting applications. There are two types of ballasts, magnetic and electronic. The iron-core magnetic ballast contributes additional heat losses, which makes it inefficient compared to an electronic ballast. An electronic ballast employs a switch-mode–type power supply to convert the incoming fundamental frequency voltage to a much higher frequency voltage typically in the range of 25 to 40 kHz. This high frequency has two advantages. First, a small inductor is sufficient to limit the arc current. Second, the high frequency eliminates or greatly reduces the 100- or 120-Hz flicker associated with an iron-core magnetic ballast.[electrical power system quality .[6]

3.4.5 Arc furnace

The harmonic produced by an electric arc furnace is very difficult to predict due to the variation of the arc impedance on a cycle by cycle basis. Therefore, the arc current is non-periodic and the analysis show both integer and non-integer harmonic. The harmonic content is different both for melting and refining periods.[7]

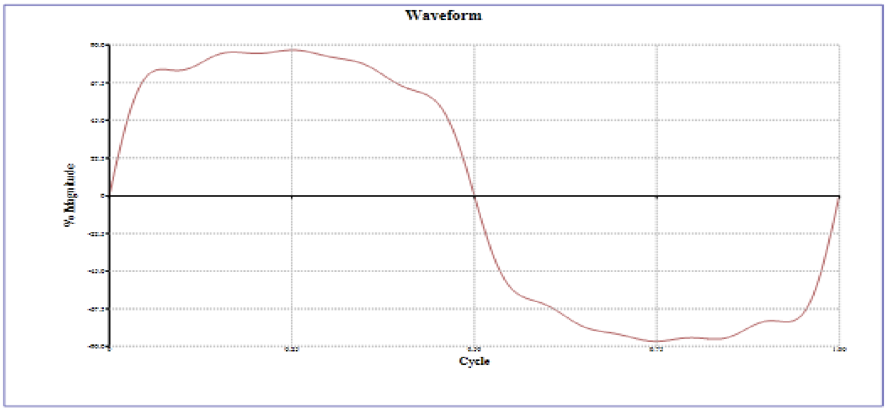

Figure 3.5: harmonic waveform of Fluorescent lamp for phase currents

Figure 3.6: harmonic spectra of Fluorescent lamp for phase currents

3.5 Effects of Harmonics

A considerable number of electricity users are left exposed to the effects of harmonic distortion on industrial, commercial, and residential loads. In abroad manner, these can be described as the following.

3.5.1 Generators

In comparison to shore-based utility power supplies, the effects of harmonic voltages and harmonic currents are significantly more pronounced on generators due to their source impedance being typically three to four times that of utility transformers. The major impact of voltage and current harmonics is the increase in machine heating caused by increased iron losses, and copper losses, both frequency dependent. [On shore installations, it is relatively common practice to “derate” (reduce the output of) generators when supplying nonlinear loads to minimize the effects of harmonic heating.] In addition, there is the influence of harmonic sequence components, both on localized heating and torque pulsations. [3]

3.5.1.1 Thermal losses

The iron losses comprise two separate losses, “hysteresis losses” and “eddy current losses”. The hysteresis loss is the power consumed due to nonlinearity of the generator’s flux density/magnetizing force curve and the subsequent reversal in the generator’s core magnetic field each time the current changes polarity (i.e., 120 times a second for 60 Hz supplies). Higher hysteresis losses occur at harmonic frequencies due to the more rapid reversals compared to those at fundamental frequency. Hysteresis losses are proportional to frequency and the square of the magnetic flux. Eddy currents circulate in the iron core, windings and other component parts of the generator induced by the stray magnetic fields around the turns in the generator windings. Eddy currents produce losses which increase in proportion to the square of the frequency. The relationship of eddy current losses and harmonics is given by:

$$\mathrm{PEC} = PEF \sum_{h=1}^{hmax} \mathrm{Ih}^2 * \mathrm{h}^2 \quad (3.2)$$

where

PEC = Total Eddy Current Losses.

PEF = Eddy Current Losses at Full Load at Fundamental Frequency.

Ih = RMS Current (per unit) Harmonic h h = Harmonic Number.

3.5.1.2 Effect of sequence components

Harmonic currents occur in pairs each having a negative or a positive sequence rotation. The 5th harmonic is negative sequence and induces in the rotor a negatively-rotating 6th harmonic; the 7th harmonic is positive and similarly induces a positively-rotating 6th harmonic in the rotor. The two contra-rotating 6th harmonic systems in the rotor result in “damper” winding currents which are stationary with respect to the rotor, causing additional, localized losses and subsequent heating. Within the rotor, this effect is similar to that caused by single-phase or unbalanced-phase operation and overheating is unlikely provided the rotor pole faces are laminated. Similarly, the 11th and 13th harmonics will induce both negatively and positively rotating 12th harmonics in the rotor. [3]

3.5.1.3 Voltage distortion

A generator is designed to produce sinusoidal voltage at its terminals, but when nonlinear current is drawn, the harmonic currents interact with the system impedances to produce voltage drops at each individual harmonic frequency, thereby causing voltage distortion.

3.5.1.4 Shaft generators

Shaft generators are generally unaffected by the import of external power system harmonics due to the filtering effects of the generator converter, rotary condenser and line reactors.

3.5.2 Transformers

Modern industrial and commercial networks are increasingly influenced by significant amounts of harmonic currents. All of these currents are sourced through service transformers and are caused the following effects.

3.5.2.1 Thermal losses

Transformer losses comprise “no load losses”, which are dependent on the peak flux levels necessary to magnetize the transformer core and are negligible with respect to harmonic current levels, and “load losses”, which significantly increase at harmonic frequencies when transformers supply nonlinear current. The effect of harmonic currents at harmonic frequencies in transformers causes increases in core losses through increased iron losses (i.e., eddy currents and hysteresis). In addition, copper losses and stray flux losses which can result in additional heating, winding insulation stress, especially if high levels of dv/dt (i.e., rate of rise of voltage) are present. Temperature cycling and possible resonance between transformer winding inductance and supply capacitance can also cause additional losses. Potential small laminated core vibrations can appear as additional audible noise.

3.5.2.2 Unbalance, distribution transformers and neutral currents

Distribution transformers used in four-wire (i.e., three-phase and neutral) distribution systems (for example, those used in some cruise liners) have a delta-star configuration. Triplen (i.e., 3rd, 9th, 15th…) harmonic currents cannot propagate downstream but circulate in the primary delta winding of the transformer causing localized overheating. With linear loading, the three-phase currents will cancel out in the neutral conductor. However, when nonlinear loads are being supplied, the triplen harmonics in the phase currents do not cancel out, but instead add cumulatively in the neutral conductor, which can carry up to 173% of phase current at a frequency of predominately 180 Hz (3rd harmonic), overheating transformers and on occasion, overheating and burning out neutral conductors.

3.5.3 Induction motors

The effect of harmonic current generation in induction motors are:

3.5.3.1 Thermal losses

Harmonics distortion raises the losses in AC induction motors in away very similar to that apparent in transformers with increased heating, due to additional copper losses and iron losses (eddy current and hysteresis losses) in the stator winding, rotor circuit and rotor laminations. These losses are further compounded by skin effect, especially at frequencies above 300 Hz. Leakage magnetic fields caused by harmonic currents in the stator and rotor end windings produce additional stray frequency eddy current dependent losses. Substantial iron losses can also be produced in induction motors with skewed rotors due to high-frequency-induced currents and rapid flux changes (i.e., due to hysteresis) in the stator and rotor. The magnitude of the iron losses is dependent on the iron loss characteristic of the laminations and the angle of skew.

3.5.3.2 Effect of harmonic sequence components

Harmonic sequence components also adversely affect induction motors. Positive sequence components (i.e., 7th, 13th, 19th…) will assist torque production, whereas the negative sequence components (5th, 13th, 17th…) will act against the direction of rotation resulting in torque pulsations which are significant. Zero sequence harmonics (i.e., trip lens) do not rotate (i.e., they are stationary) any harmonic energy associated with them is dissipated as heat.

3.5.4 Variable speed drives

Electrical variable speed drives of all types (i.e., AC or DC) use power semiconductors to rectify the AC input voltage and current and thereby create harmonics. However, these can be also susceptible to disruption and component damage due to input line harmonics. However, harmonics can be beneficial for drives as they cause flattening of the peak voltage (i.e., termed “flat topping” – see Subsection 3/7, “Computers and Computer Based Equipment,” for more details) which reduces the stress on rectifiers. Conversely, large numbers of 2-pulse drives (or other single-phase nonlinear loads) can increase the peak-to-peak voltage magnitudes, increasing stress the on rectifiers. Generally, the larger rating a drive is, the more it is immune to the effects of harmonics and line notching. Line commutated inverters (LCIs, also known as “current source inverters” when used on smaller induction motor applications) and cycloconverters are more commonly used in higher ratings (i.e., above 2000 HP). These are assumed to be relatively immune to the normal level of harmonics. Both harmonics and line notching effect variable speed drives. The effect of line notching is more pronounced when the drive(s) is at low speed and high load. Ringing, associated with line notching is also problematic. Small, single-phase (2-pulse) PWM drives with no reactors have high levels of Ithd, often up to 130-140% including a large 3rd harmonic which adds cumulatively in the neutral conductor, significantly increasing the neutral current up to 173% of phase current and increasing neutral-to ground voltages. The resultant excessive localized harmonic current can be reflected into the DC bus, causing overheating on the smoothing capacitors. Ringing associated with line notching increases DC bus levels at no or light loading with consequential over-voltage tripping.

3.5.5 Lighting

The harmonic current generation in fluorescent lamps using magnetic and electronic ballast has several effects.

3.5.5.1 Flicker

One noticeable effect on lighting is the phenomenon of "flicker" (i.e., repeated fluctuations in light intensity). Lighting is highly sensitive to RMS voltage changes; even a deviation of 0.25% is perceptible to the human eye in some types of lamps.

The severity of the flicker is dependent on a number of factors including:

- The type of light (incandescent, fluorescent or high intensity discharge)
- The magnitude of the voltage fluctuations
- The "frequency" of the voltage fluctuations
- The "gain factor" of the lamp (relative change in light level divided by relative fluctuation in RMS voltage)
- The amount of ambient light in lighted area

Superimposed inter harmonic voltages in the supply voltage are a significant cause of light flicker in both incandescent and fluorescent lamps, albeit at different levels of intensity.

3.5.5.2 Effects of line notching on lighting

Line notching will also effects lighting to varying degrees. The consequential reduction in RMS voltage will cause a reduction in the intensity of illumination, especially in incandescent lamps. If the notches are severe or where ringing occurs, transient suppression may be necessary at lighting distribution board level to protect the individual light fittings. Fluorescent fittings used with occupancy sensors which are based on zero crossover detection may experience difficulties if the notching is severe and multiple crossovers result.

3.5.5.3 Potential for resonance

The interaction between harmonic current and power factor correction capacitors inside individual fluorescent lighting units can result in parallel resonances being excited between the capacitors and power system inductances resulting in damage of the lighting units. Ideally, individual power factor correction should be avoided and group power factor correction with detuning reactors should be installed at lighting distribution panel level.

3.5.6 Uninterruptible power supplies (UPS)

Due to the phenomenal increase in “power quality”-sensitive loads such as computers and navigation or radio communications equipment, uninterruptible power supplies (UPSs) are now commonly provided and can range from a 100 VA to several MVA. UPS are very similar in architecture to variable speed drives. Therefore, the effects of harmonics on components within UPS systems will be almost identical with additional heating on power devices, smoothing capacitors and inductors, where installed. Batteries may overheat due to excessive harmonics and inter harmonics on the DC side of the rectifier Excessive voltage distortion or notching/ringing can cause misfiring of input rectifier SCRs possibly resulting in fuse rupture. On high levels of distortion, bypass sensing circuits may disable the bypass circuit, inhibiting the alarm system advising of problems in the bypass system. If resonance occurs, perhaps due to the UPS input filter, UPS may shut down, displaying a "loss of AC supply" alarm and bypass to inverter mode. In the presence of harmonics, the UPS line side filter (to reduce the harmonics from the rectifier input stage) may act as a sink (i.e., attract harmonic currents from upstream) damaging the harmonic filter.

3.5.7 Cables

The effects of harmonic current on cables are:

3.5.7.1 Thermal losses

Cable losses, dissipated as heat, are substantially increased when carrying harmonic currents due to elevated I2R losses, the cable resistance, R, determined by its DC value plus skin and proximity effect.

3.5.7.2 Skin and proximity effects

The resistance of a conductor is dependent on the frequency of the current being carried. Skin effect is a phenomenon whereby current tends to flow near the surface of a conductor where the impedance is least. An analogous phenomenon, proximity effect, is due to the mutual inductance of conductors arranged closely parallel to one another. Both of these effects are dependent upon conductor size, frequency, resistivity and the permeability of the conductor material.

3.5.7.3 Neutral conductors in four-wire systems

On four-wire distribution systems, such as now installed on large passenger vessels, which may have a large percentage of nonlinear loads (e.g., computers, ballast lighting, etc.), a large component of triplen harmonics are often present. The phase currents do not cancel in the neutral conductors as with linear loading but sum in the neutral conductor. The overloading on the conductors (and the distribution transformer primary, assuming delta-star configuration), can be significant (up to 173% of phase current), therefore, the neutral current should be dimensioned accordingly or mitigation equipment installed to attenuate the level of triplen harmonics. In addition, triplen currents are problematic on generators due to the associated additional temperature rise on the machines.

3.5.7.4 Additional effects associated with harmonics

Harmonic currents can on occasion excite parallel resonance between cable capacitance and system inductances, especially when very long cable lengths are used. This has been documented on offshore installations when platforms with no onboard generating capacity are supplied from other platforms a considerable distance away by long subsea cables. Harmonic voltages increase the dielectric stress on cables, thereby decreasing the reliability and the working life of cables in proportion to the crest voltages. Power cables carrying harmonic loads act to introduce EMI (electromagnetic interference) in adjacent signal or control cables via conducted and radiated emissions. This “EMI noise” has a detrimental effect on telephones, televisions, radios, computers, control systems and other types of equipment. Correct procedures with regard to grounding and segregation within enclosures and in external wiring systems must be adopted to minimize EMI.

3.5.8 Measuring equipment

Conventional meters are normally designed to read sinusoidal-based quantities. Nonlinear voltages and currents impressed on these types of meters introduce errors into the measurement circuits which result in false readings. Conventional meters are calibrated to respond to RMS values. Root mean square (RMS) can be defined as the magnitude of sinusoidal current which is the value of an equivalent direct current which would produce the same amount of heat in a fixed resistive load which is proportional to the square of the current averaged over one full cycle of the waveform (i.e., the heat produced is proportional to the mean of the square; therefore the current is proportional to the "root mean square").

3.5.9 Telephones

On ships and offshore installations where power conductors carrying nonlinear loads and internal telephone signal cable are run in parallel, it is likely that voltages will be induced in the telephone cables. The frequency range, 540 Hz to 1200 Hz (9th harmonic to 20th harmonic at 60 Hz fundamental) can be troublesome. On four-wire systems where a large number of single-phase nonlinear loads are present (for example, large amounts of fluorescent lighting or large numbers of lighting dimmers and/or single-phase AC inverter drives on cruise liners), triplen harmonics are troublesome as they are present in all three-phase conductors and cumulatively add in the neutral conductor. The use of twisted pair cables and correct shielding/ grounding, as well as correct levels of spacing and segregation should minimize potential problems. There is also the possibility of both conducted and radiated interference above normal harmonic frequencies with telephone systems and other equipment due to variable speed drives and other nonlinear loads, especially at high carrier frequencies. EMI filters at the inputs may have to be installed on drives and other equipment to minimize the possibility of inference. However, this is often difficult when the vessel or offshore installation is based on an IT power systems (insulated neutrals), and in such instances, other measures have to be adopted.

3.5.10 Circuit breakers

The vast majority of low voltage thermal-magnetic type circuit breakers utilize bi-metallic trip mechanisms which respond to the heating effect of the RMS current. In the presence of nonlinear loads, the rms value of current will be higher than for linear loads of same power. Therefore, unless the current trip level is adjusted accordingly, the breaker may trip prematurely while carrying nonlinear current.

Circuit breakers are designed to interrupt the current at a zero crossover. On highly distorted supplies which may contain line notching and/or ringing, spurious “zero crossovers” may cause premature interruption of circuit breakers before they can operate correctly in the event of an overload or fault. However, in the case of a short circuit current, the magnitude of the harmonic current will be very minor in comparison to the fault current. The original type peak-sensing, electronic-type circuit breaker responds to the peak value of fundamental current. When carrying harmonic current this type of breaker may not operate correctly due to the peak value of nonlinear currents being higher than for respective linear loads. This type of breaker therefore may trip prematurely at relatively low levels of harmonic current. New designs of electronic breakers include both methods of protection; peak current detection and RMS current sensing. The peak detection method of protection, however, may still trip on relatively low values of peak harmonic current and trip levels therefore may have to be readjusted accordingly. Similarly, the RMS-sensing measures the heating effect of the RMS current (as per the conventional thermal-magnetic type) and may also have to be readjusted to prevent premature tripping on nonlinear loads.

3.5.11 Fuses

Fuse rupture under over current or short-circuit conditions is based on the heating effect of the RMS current according to the respective I2t characteristic. The higher the RMS current, the faster the fuse will operate. On nonlinear loads, the RMS current will be higher than for similarly-rated linear loads, therefore fuse debating may be necessary to prevent premature opening. In addition, fuses at harmonic frequencies, suffer from skin effect and more importantly, proximity effect, resulting in non-uniform current distribution across the fuse elements, placing additional thermal stress on the device.

3.5.12 Relays

Conventional electro-mechanical control relays are rarely susceptible to harmonic problems as the operating coils are usually low voltage (e.g., 24 V) or fed via step-down transformers which attenuate the harmonics. However, where the voltage supply to conventional control relays does contain harmonic voltages or current, they may tend to operate more slowly and/or with higher pickup values and may experience early life failure due to additional heating within the coil. Solid state relays may be stressed when subjected to high levels of harmonic distortion and/or line notching thus reducing reliability.

3.5.13 Radio, television, audio and video equipment

Radios and televisions are susceptible to interference by harmonics both radiated and conducted, especially on LW and AM bands, from DC up to 150 kHz, which is above normal harmonic frequencies (50th harmonic at 60 Hz fundamental is 3 kHz) and into RFI frequency ranges (radio frequency interference). Audio and video signals can be affected on four-wire systems due to high ground-to-neutral voltages.

3.5.14 Capacitors

Conventional power factor correction equipment is rarely installed on ships or offshore installations. Therefore, it is not necessary to describe the interaction between harmonics and power factor correction capacitors, which are generally installed in industrial plants and commercial buildings. Fluorescent lighting, as installed across the shore-based industries, does, however, normally have capacitors fitted internally to improve the individual light fitting's own power factor. In general, the effects of harmonics on general capacitors can be summarized as follows:

- Capacitors act as a "sink" for harmonic currents (i.e., they attract and absorb harmonics) due to the fact that their capacitive reactance decreases with frequency. The capacitors can become easily overloaded, destroying capacitors and blowing fuses where fitted.

- Capacitors (and on occasion, cable capacitance) combine with source and other inductances to form a parallel resonant circuit . In the presence of harmonics, the harmonics are amplified causing high, often localized, voltages and currents to flow, disrupting and/or damaging plant and equipment.

- The presence of harmonics, especially voltage harmonics, tend to increase the dielectric losses on capacitors increasing the operating temperature and reduces the reliability.[3]

3.6 Methods for Harmonic Mitigation

Majority of large power (typically three-phase) electrical nonlinear equipments often requires mitigation equipment in order to attenuate the harmonic currents and associated voltage distortion to within necessary limits. Depending on the type of solution desired, the mitigation may be supplied as an integral part of nonlinear equipment (e.g., an AC line reactor or a line harmonic filter for AC PWM drive) or as a discrete item of mitigation equipment (e.g., an active or passive filter connected to a switchboard). There are many ways to reduce harmonics, ranging from variable frequency drive designs to the addition of auxiliary equipment. Few of the most prevailing methods used today to reduce harmonics are explained below. The solutions of elimination harmonics in the system can be classified into three classes.

3.6.1 The first class

Is concerned with the distribution system planning to determine how the installation can be modified.

3.6.1.1 Supplying the loads from upstream

This solution can be implemented by connecting the disturbing load upstream in the system regardless of the economics. It is preferable to connect the disturbing load as far upstream as possible (see figure below)

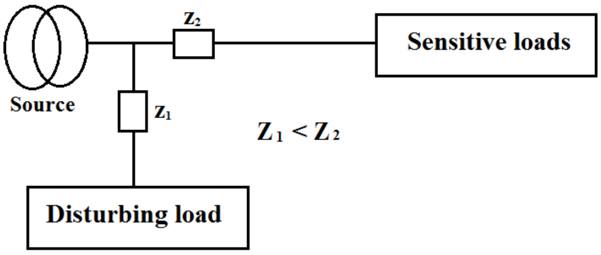

Figure 3.7: Illustrate Supplying the Loads from Upstream

3.6.1.2 Grouping the disturbing loads

Depending on the distribution system structure and the possibility of providing this solution, different types of loads should be supplied by different bus bars as seen in the single – line diagram of Figure below. By grouping the disturbing loads, the possibilities of angular recomposition are increased as the vector sum of the harmonic currents is less than their algebraic sum.

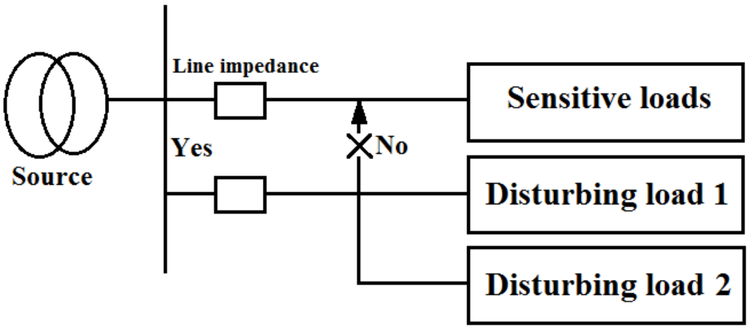

Figure 3.8: Illustrate Grouping the Disturbing Loads

3.6.1.3 Supplying the loads from different sources

In this method, additional improvement may be obtained by supplying different loads from separate transformers acting as different sources.

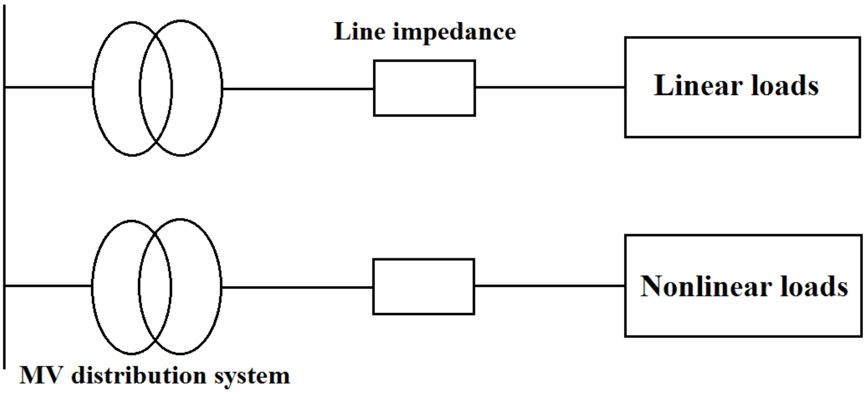

Figure 3.9: Illustrate Supplying the Loads from Different Sources

3.6.2 The second class

The Second Class of solutions deals with the use of special devices in the power supply system such as inductors and special transformers.

3.6.2.1 Transformers with special connections

Special types of connections may be used in transformers to eliminate certain harmonic orders. The harmonic order elimination depends on the type of connection implemented as described below:

- Δ - Y - Δ connection eliminates the 5th, 7th, 17th and 19th order harmonics.
- Δ - Y connection eliminates the third - order harmonic (the harmonic flows in each of the phases and loops back through the transformer neutral),
- Δ - Zigzag connection eliminates the harmonics looping back through the magnetic circuit.

3.6.2.2 Reactors

Use of reactor is a simple and cost effective method to reduce the harmonics produced by nonlinear loads and is a better solution for harmonic reduction than an isolation transformer. Reactors or inductors are usually applied to individual loads such as variable speed drives and available in standard impedance ranges such as 2%, 3%, 5% and 7.5%. When the current through a reactor changes a voltage is induced across its terminals in the opposite direction of the applied voltage which consequently opposes the rate of change of current . This induced voltage across the reactor terminals is represented by equation below.

$$E=L*\frac{di}{dt} \qquad (3.3)$$

where:

e = Induced voltage across the reactor terminals.

L = Inductance of the reactor, in henrys.

di/dt = Rate of change of current through reactor in ampere/second.

This characteristic of a reactor is useful in limiting the harmonic currents produced by electrical variable speed drives and other nonlinear loads. In addition, the AC line reactor reduces the total harmonic voltage distortion (THDv) on its line side as compared to that at the terminals of the drive or other nonlinear load. In electrical variable speed drives, the reactors are frequently used in addition to the other harmonic mitigation methods. On AC drives, reactor can be used either on the AC line side (called AC line reactors) or in the DC link circuit (called DC link or DC bus reactor) or both, depending on the type of the drive design and/or necessary performance of the supply. AC line reactor is used more commonly in the drive than the DC bus reactor, and in addition to reducing harmonic currents, it also provides surge suppression for the drive input rectifier. The disadvantage of use of reactor is a voltage drop at the terminals of the drive, approximately in proportion to the percentage reactance at the terminals of the drive. In large drives, both AC line and DC bus reactors may be used especially when the short circuit capacity of a dedicated supply is relatively low compared to the drive kVA or if the supply susceptible to disturbances.

3.6.2.3 Pulse drive

These produce harmonics the order of which is given by the expression $12n\pm1$ where n is an integer greater than or equal to 1. Thus, the line current contains harmonics of the order 11, 13, 23 … , each with a magnitude $I_n = I_{fund} / n$, which is an improvement over the spectrum generated by six - pulse equipment.

3.6.3 The third class

When harmonic level is too high harmonic filters are used. There are passive, active and hybrid filters.

3.6.3.1 Passive harmonic filters (or line harmonic filters)

Passive or Line harmonic filters (LHF) are also known as harmonic trap filters and are used to eliminate or control more dominant lower order harmonics specifically 5th, 7th, 11th and 13th. It can be either used as a standalone part integral to a large nonlinear load (such as a 6-pulse drive) or can be used for a multiple small single phase nonlinear loads by connecting it to a switch board. LHF is comprised of a passive L-C circuit (and also frequently resistor R for damping) which is tuned to a specific harmonic frequency which needs to be mitigated (for example, 5th, 7th, 11th, 13th etc). Their operation relies on the "resonance phenomenon" which occurs due to variations in frequency in inductors and capacitors. The resonant frequency for a series resonant circuit, and (in theory) for a parallel resonant circuit, can be given as:

$$fr=\frac{1}{2\pi\sqrt{LC}} \tag{3.4}$$

where:

fr = Resonant Frequency, Hz

L = Filter Inductance, Henrys,

C = Filter Capacitance, Farads

The passive filters are usually connected in parallel with nonlinear load(s) as shown in Figure 5.1, and are "tuned" to offer very low impedance to the harmonic frequency to be mitigated. In practical application, above the 13th harmonic, their performance is poor, and therefore, they are rarely applied on higher-order harmonics. Passive filters are susceptible to changes in source and load impedances. They attract harmonics from other sources (i.e. from downstream of the PCC), and therefore, this must be taken into account in their design. Harmonic and power system studies are usually undertaken to calculate their effectiveness and to explore possibility of resonance in a power system due to their proposed use.

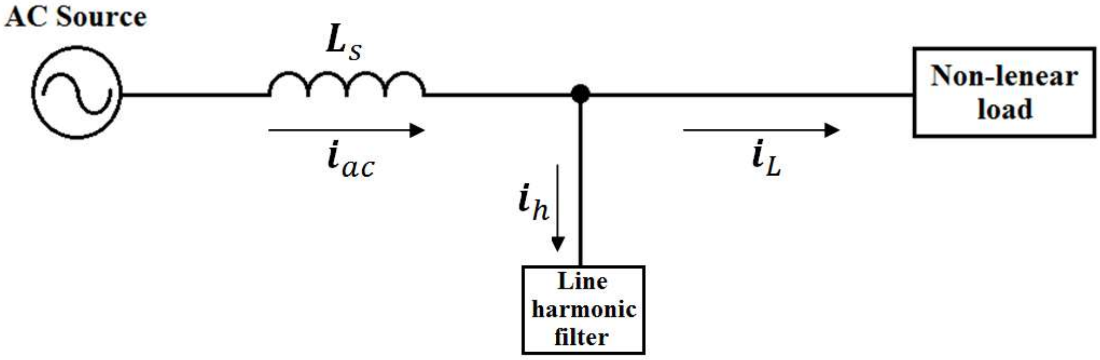

Figure 3.10 Typical connection of a passive harmonic filter

3.6.3.2 Active filters

Active filters are now relatively common in industrial applications for both harmonic mitigation and reactive power compensation (i.e., electronic power factor correction). Unlike passive L-C filters, active filters do not present potential resonance to the network and are unaffected to changes in source impedance. Shunt-connected active filters (i.e. parallel with the nonlinear load) as shown in Figure 5.4 below are the common configuration of the active filter. The active filter is comprised of the IGBT bridge and DC bus architecture similar to that seen in AC PWM drives. The DC bus is used as an energy storage unit.

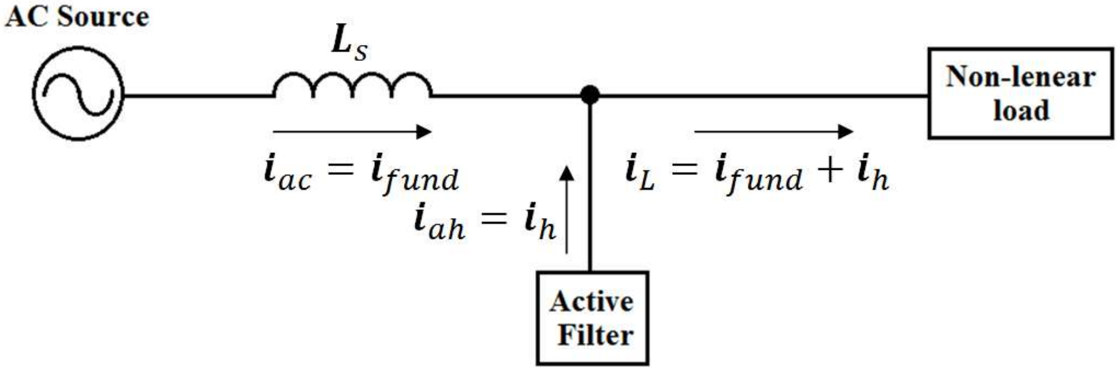

Figure 3.11 Typical connection of active filter

The active filter measures the "distortion current" wave shape by filtering out the fundamental current from the nonlinear load current waveform, which then fed to the controller to generate the corresponding IGBT firing patterns to replicate and amplify the "distortion current" and generate the "compensation current", which is injected into the load in anti-phase (i.e. 180° displayed) to compensate for the harmonic current. When rated correctly in terms of "harmonic compensation current", the active filter provides the nonlinear load with the harmonic current it needs to function while the source provides only the fundamental current. Active filters are complex and expensive products. Also, careful commissioning of active filter is very important to obtain optimum performance, although "self tuning" models are now available. However, active filters do offer good performance in the reduction of harmonics and the control of power factor. Their use should be examined on a project-by-project basis, depending on the application criteria.

3.6.3.3 Hybrid filter

The two types of filters presented above can be combined in a single device, thus constituting a hybrid filter. This type of filtering solution combines the advantages of the existing systems and provides a high - performance solution covering a wide power range. [9]

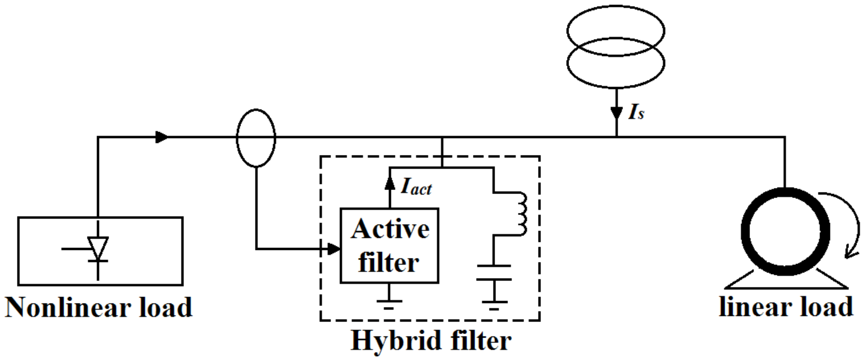

Figure 3.12 Typical connection of hybrid filter

CHAPTER FOUR

SIMULATION AND RESULTS

4.1 Introduction

This section represents the results of effects of the harmonic sources and eliminations. it studies different non linear load types that usually used in the distribution systems considering the voltage wave form, values of THD and the harmonics spectrum to show the contents of the harmonics of each load (harmonics orders and the magnitude). It also studies the effects of Harmonic on current, power factors and losses. Harmonics are filtered using a passive filter series combination of a capacitor and an inductance. Passive filters can be tuned to filter a single harmonics order or more than a harmonics order. The shown filter is mainly tuned to filter fifth and seventh harmonics order.

4.2 System Configuration

The power system under study has a part of power grid, four buses, two transmission lines and 12.47 KV/4.16 KV transformer. The transformer connection is delta/ star and the nonlinear load under study is connected at the receiving end. The system is shown in Figure 4.1.

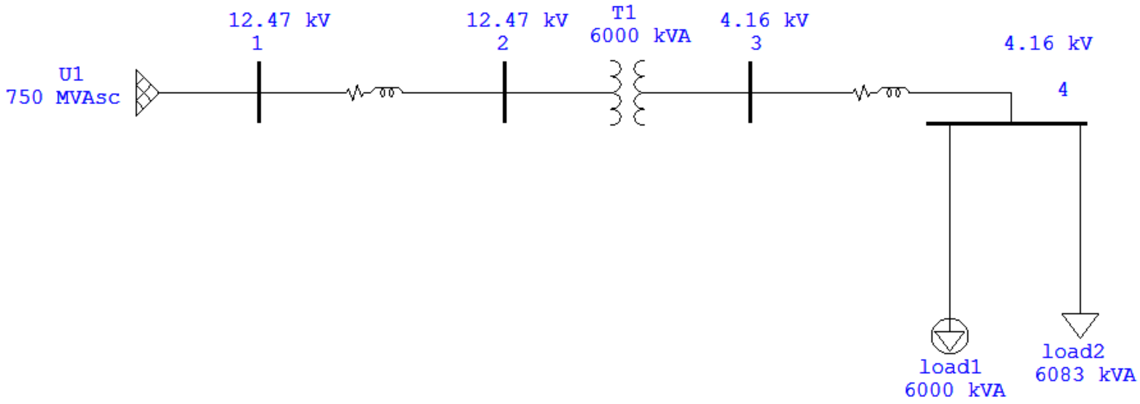

Figure 4.1: Shown the system

4.3 Results of Harmonics Sources

The study is limited to involve some types of harmonic sources. They are Fluorescent, Arc furnace, six pulse rectifier, single phase half wave controlled rectifier, single phase full wave controlled rectifier and TRIAC.

4.3.1 Harmonics generated by fluorescent

A fluorescent lamp is connected in the appropriate location in the network in ETAP and it is highly nonlinear in their operation and give rise to odd harmonic currents of important magnitude. Figure 4.2 voltage waveform of fluorescent, Figure 4.3 voltage spectrum of fluorescent.

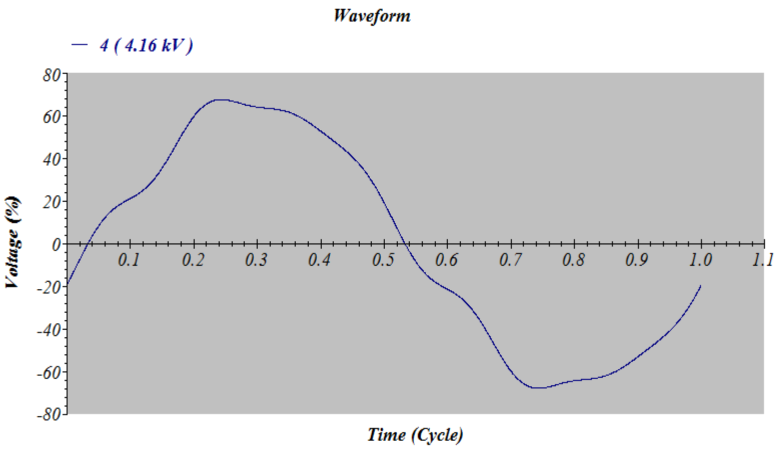

Figure 4.2: Voltage waveform of fluorescent

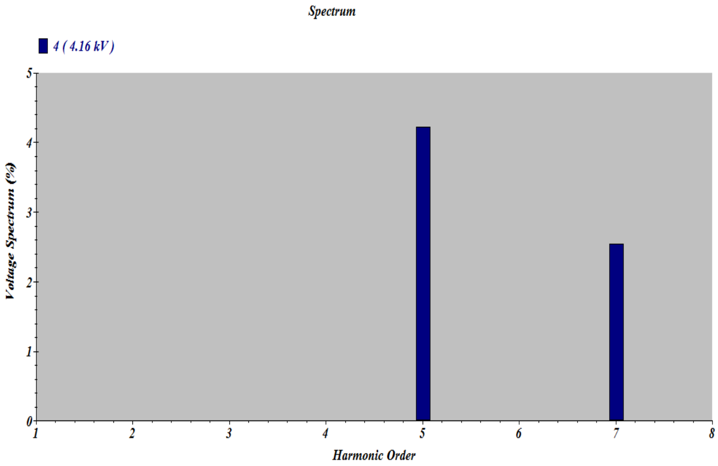

Figure 4.3: Voltage spectrum of fluorescent

4.3.2 Harmonics generated by arc furnace

The melting process in industrial electric furnaces is known to produce substantial amounts of harmonic distortion. The introduction of fundamental frequency harmonics develops from a combination of the delay in the ignition of the electric arc along with its highly nonlinear voltage-current character. Figure 4.4 voltage waveform of arc furnace and Figure 4.5 voltage spectrum of arc furnace.

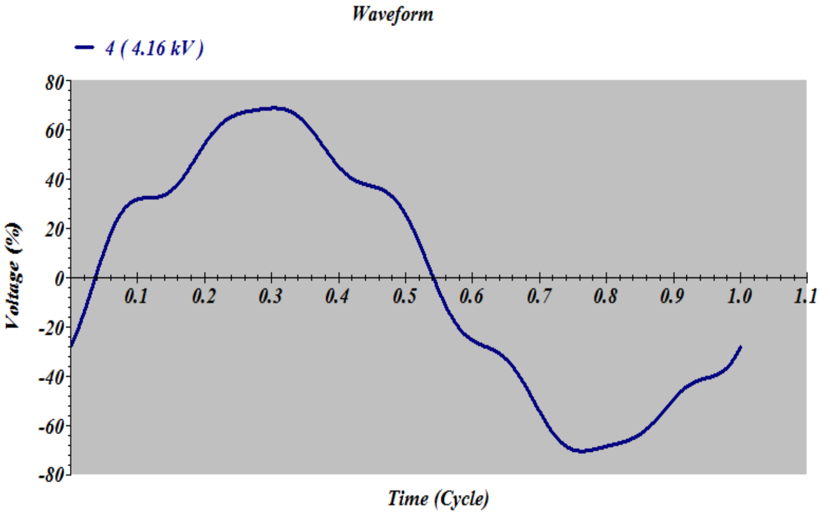

Figure 4.4: Voltage waveform of arc furnace

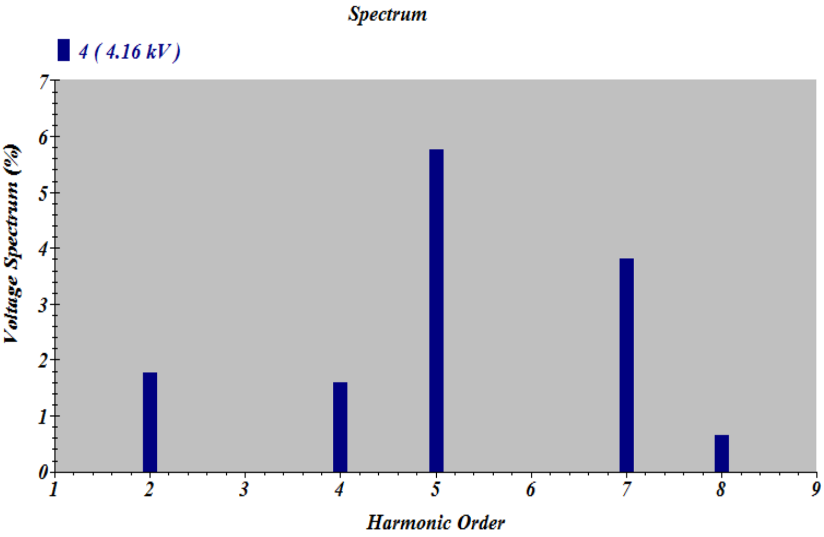

Figure 4.5: Voltage spectrum of arc furnace

4.3.3 Harmonics generated by six pulse rectifier

Six pulse rectifiers are connected to the network and are analyzed Figure 4.6 voltage waveform of six pulse rectifier and Figure 4.7 voltage spectrum of six pulse rectifier.

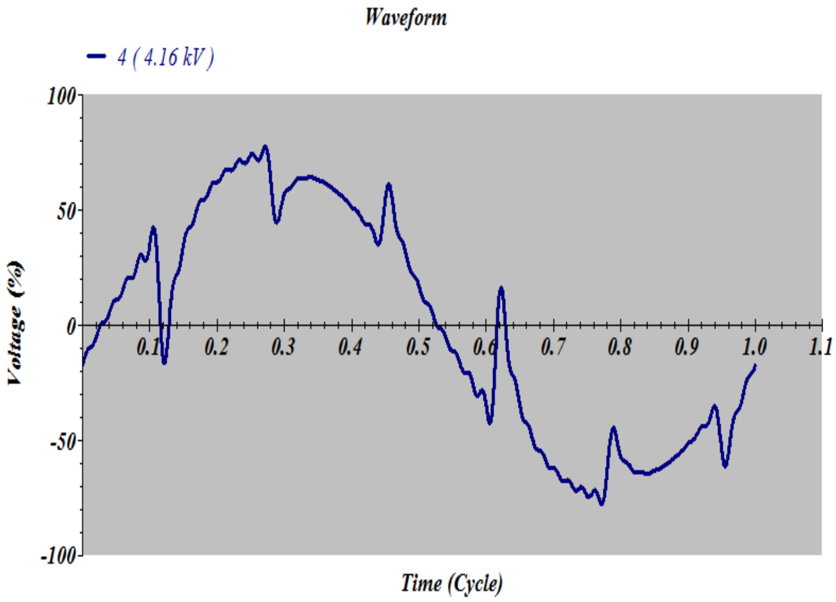

Figure 4.6: Voltage waveform of six pulse rectifier

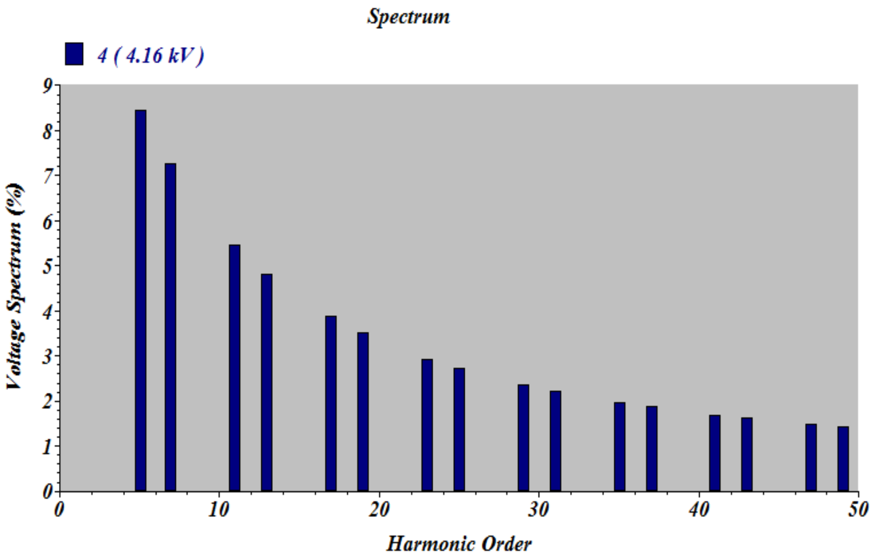

Figure 4.7: Voltage spectrum of six pulse rectifiers

4.3.4 Harmonics generated by fluorescent, arc furnace and six pulse rectifiers

Three loads are connected to the same bus in the network and are analyzed using harmonic analysis icon in ETAP, analyzed Figure 4.8 voltage waveform of fluorescent, arc furnace and six pulse rectifiers and Figure 4.9 voltage spectrum of fluorescent, arc furnace and six pulse rectifier.

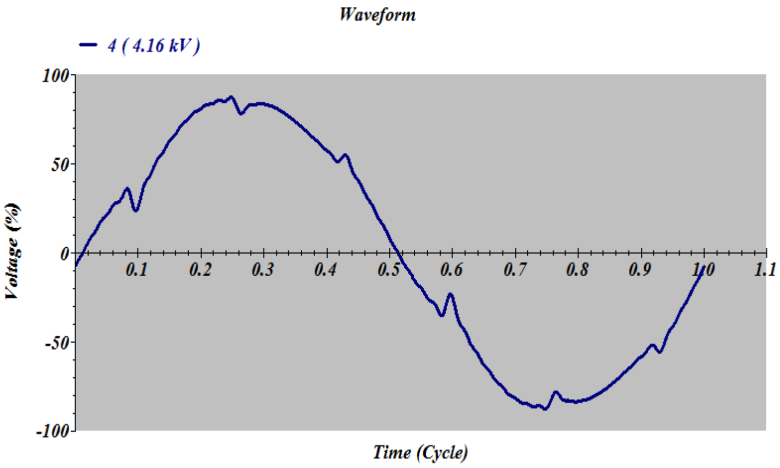

Figure 4.8: Voltage waveform of fluorescent, arc furnace and six pulse rectifiers

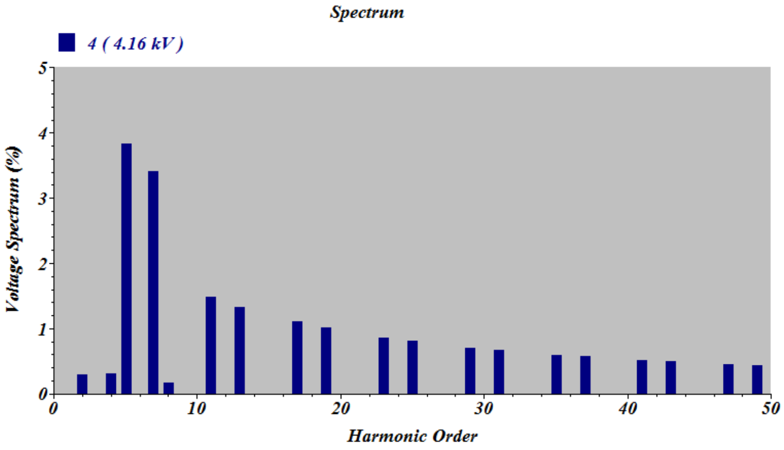

Figure 4.9: Voltage spectrum of fluorescent, arc furnace and six pulse rectifiers

4.3.5 Single phase half wave controlled rectifier

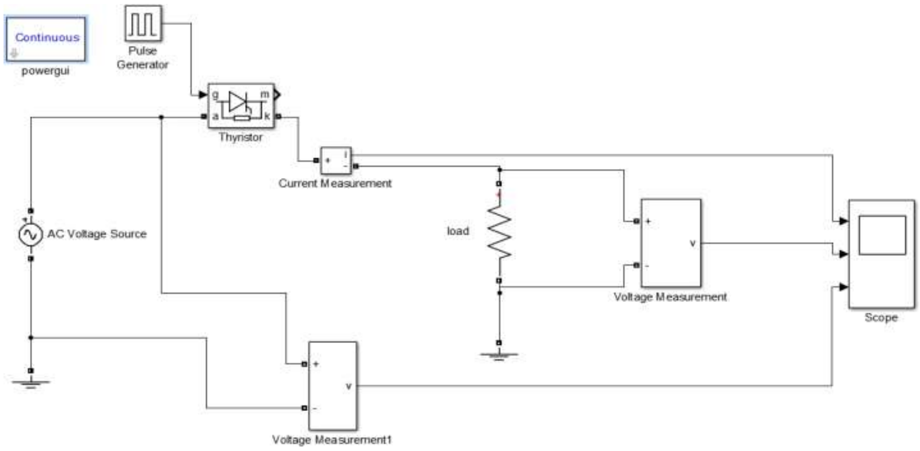

Figure 4.10: Single phase half wave controlled rectifier circuit model

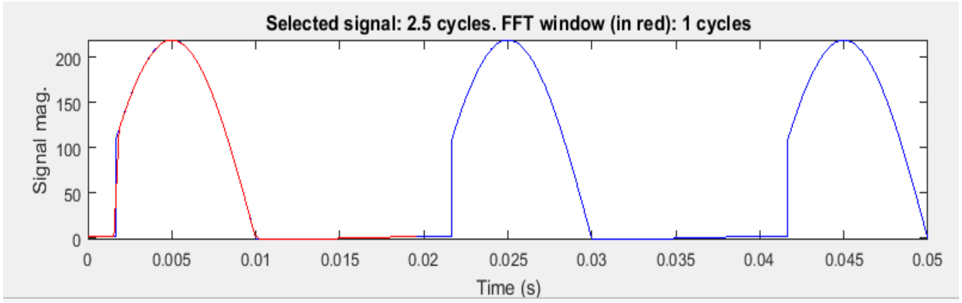

Figure 4.11: Voltage waveform of Single phase half wave controlled rectifier

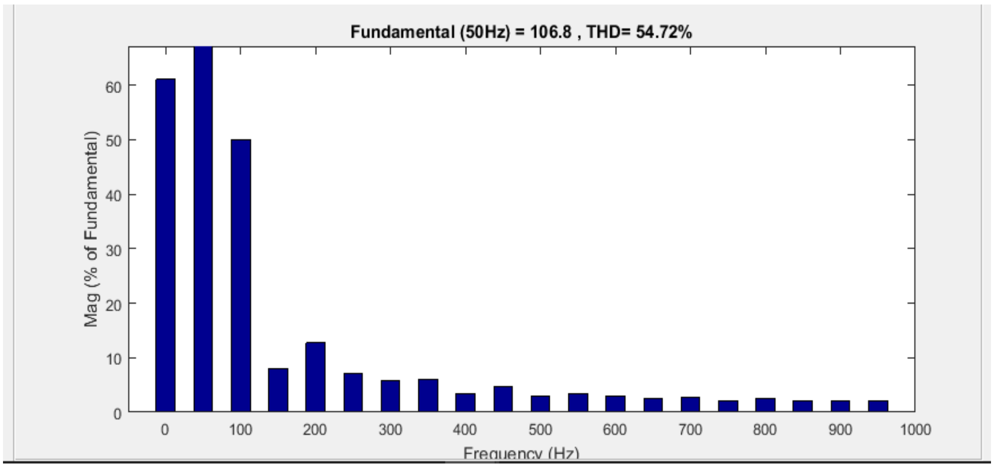

Figure 4.12: Voltage spectrum of Single phase half wave controlled rectifier

Table 4.1: List of harmonics of Single phase half wave controlled rectifier

Sampling time =0.000310559 g
Samples per cycle = 64
Dc component = 65.22
Fundamental = 106.8 peak (75.53 rms)
THD = 54.72%

0 HZ (DC)	61.05%	90.0˚
50 HZ (Fnd)	100.00%	-4.8˚
100 HZ (h2)	50.08%	261.8˚
150 HZ (h3)	7.99%	209.1˚
200 HZ (h4)	12.70%	228.8˚
250 HZ (h5)	7.15%	165.3˚
300 HZ (h6)	5.78%	177.0˚
350 HZ (h7)	5.97%	120.5˚
400 HZ (h8)	3.44%	107.3˚
450 HZ (h9)	4.86%	72.7˚
500 HZ (h10)	3.00%	34.3˚
550 HZ (h11)	3.45%	19.7˚
600 HZ (h12)	3.01%	-26.9˚
650 HZ (h13)	2.54%	-41.7˚
700 HZ (h14)	2.84%	-81.8˚
750 HZ (h15)	2.14%	251.0˚
800 HZ (h16)	2.55%	223.7˚
850 HZ (h17)	2.13%	183.5˚
900 HZ (h18)	2.08%	163.9˚
950 HZ (h19)	2.12%	124.5˚

4.3.6 Single phase full wave controlled rectifier

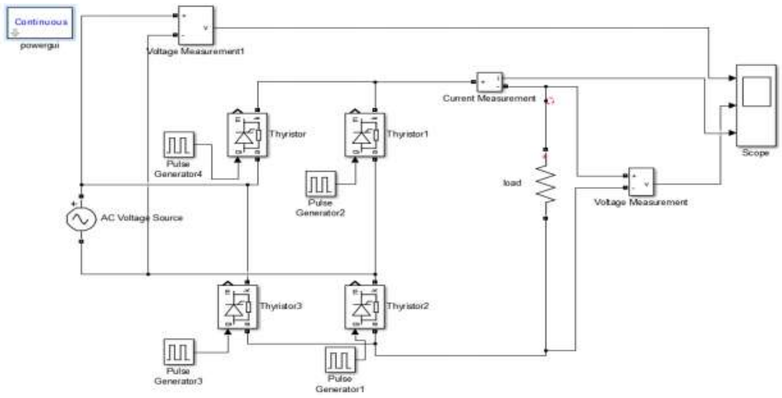

Figure 4.13: Single phase full wave rectifier circuit model

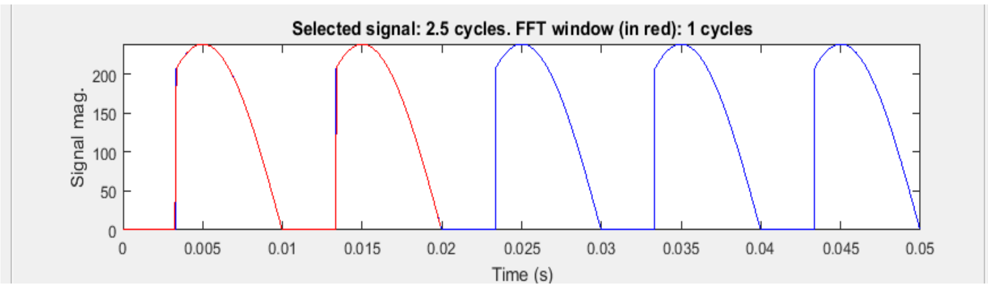

Figure 4.14: Single phase full wave rectifier Waveform

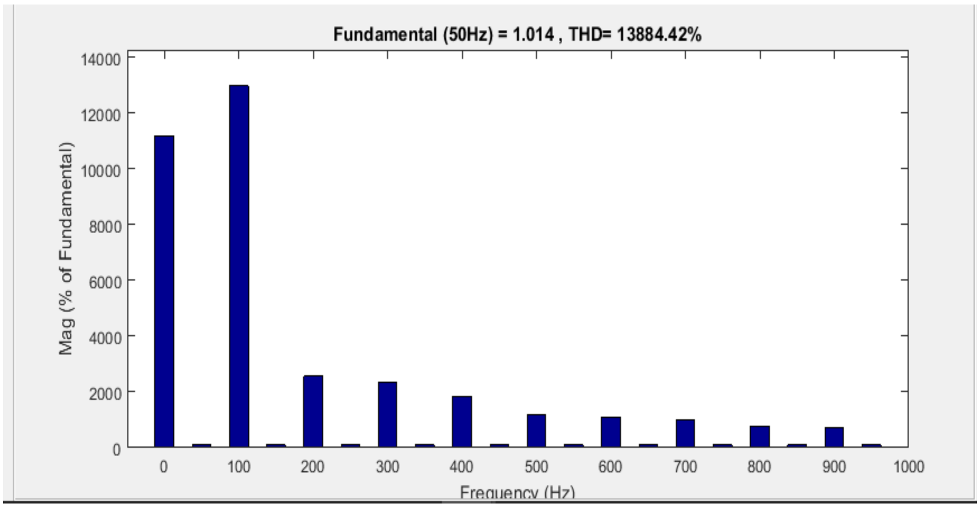

Figure 4.15: Single phase full wave rectifier spectrum

Table 4.2: List of harmonics Single phase full wave rectifier

Sampling time =9.86193e-05 g
Samples per cycle = 203
Dc component = 113.3
Fundamental = 1.014peak (0.7167 rms)
THD = 13884.42%

0 HZ (DC)	11182.05%	90.0°
50 HZ (Fnd)	100.00%	16.9°
100 HZ (h2)	12969.60%	240.6°
150 HZ (h3)	100.39%	-82.4°
200 HZ (h4)	2570.70%	119.9°
250 HZ (h5)	94.80%	151.8°
300 HZ (h6)	2334.23%	-15.1°
350 HZ (h7)	101.48%	30.5°
400 HZ (h8)	1842.67%	241.6°

450 HZ (h9)	101.94%	-86.9°
500 HZ (h10)	1174.03%	120.8°
550 HZ (h11)	98.86%	152.4°
600 HZ (h12)	112.01%	-6.3°
650 HZ (h13)	100.38%	31.4°
700 HZ (h14)	992.25%	242.5°
750 HZ (h15)	101.31%	-87.0°
800 HZ (h16)	760.86%	121.6°
850 HZ (h17)	100.12%	153.6°
900 HZ (h18)	735.01%	-2.6°
950 HZ (h19)	101.13%	33.0°

4.3.7 TRIAC

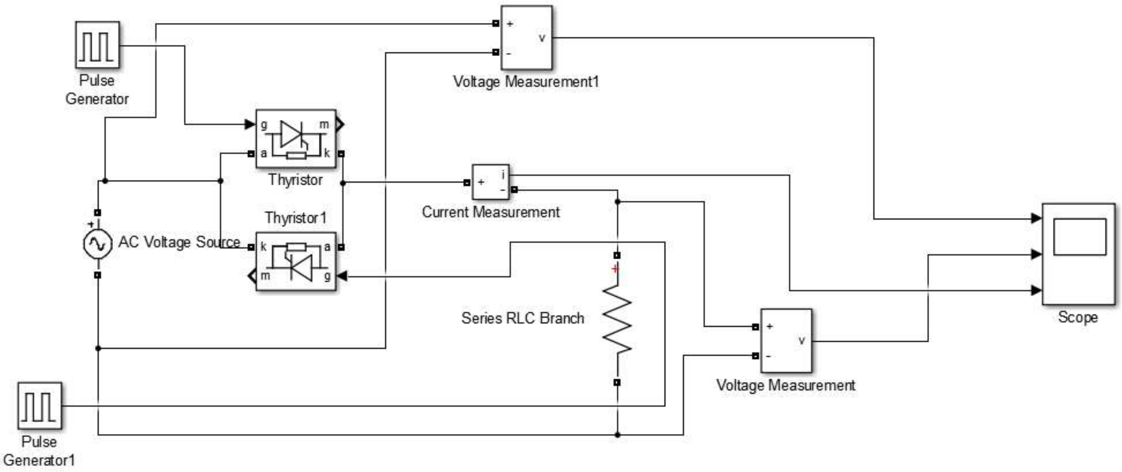

Figure 4.16: TRIAC circuit model

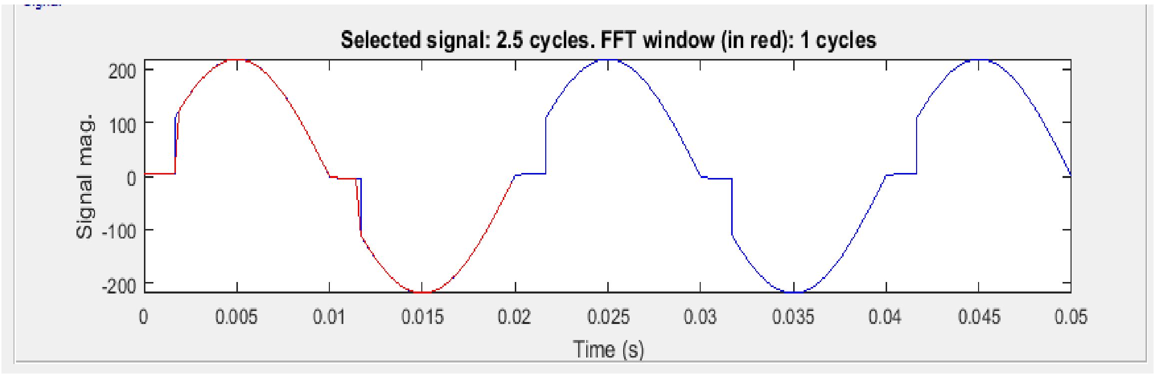

Figure 4.17: Waveform of TRIAC

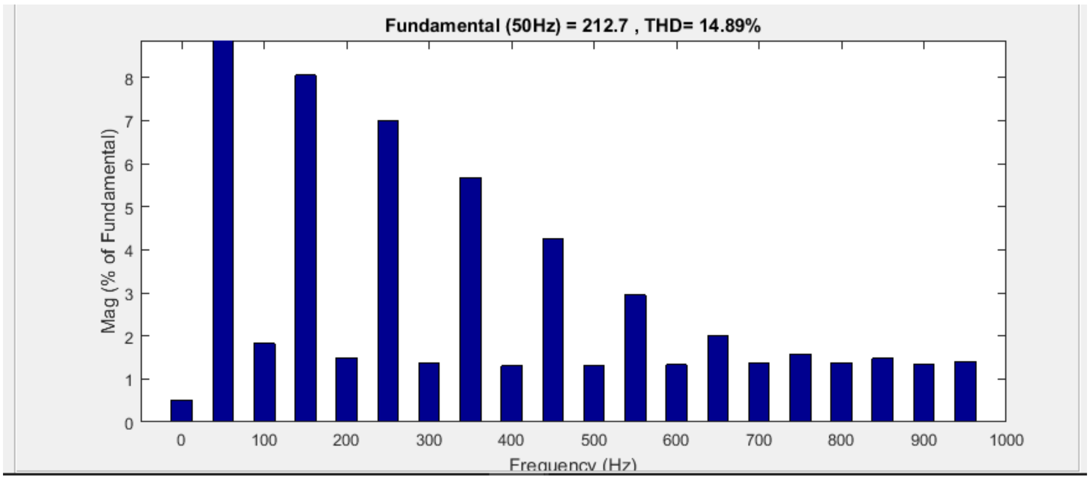

Figure 4.18: Spectrum of TRIAC

Table 4.3: List of harmonics of TRIAC

Sampling time =0.000271739 g
Samples per cycle = 74
Dc component = 1.09
Fundamental = 212.7 peak (150.4 rms)
THD = 14.89%

0 HZ (DC)	0.51%	270.0˚
50 HZ (Fnd)	100.00%	-3.3˚
100 HZ (h2)	1.83%	194.8˚
150 HZ (h3)	8.05%	208.8˚
200 HZ (h4)	1.50%	150.2˚
250 HZ (h5)	7.00%	171.1˚
300 HZ (h6)	1.37%	95.1˚
350 HZ (h7)	5.68%	130.9˚
400 HZ (h8)	1.30%	35.9˚
450 HZ (h9)	4.25%	87.4˚
500 HZ (h10)	1.30%	-24.1˚
550 HZ (h11)	2.95%	38.1˚
600 HZ (h12)	1.33%	-83.2˚
650 HZ (h13)	2.01%	-20.7˚
700 HZ (h14)	1.36%	218.9˚
750 HZ (h15)	1.57%	-88.1˚
800 HZ (h16)	1.37%	161.8.7˚
850 HZ (h17)	1.48%	208.0˚
900 HZ (h18)	1.35%	104.2˚
950 HZ (h19)	1.41 %	152.1˚

4.4 Results of Harmonics Mitigation

The mitigation is done using passive filter to eliminate the fifth harmonics in fluorescent, arc furnace and three fluorescent, arc furnace and six pulse rectifiers. Moreover two passive filters are used to eliminate the fifth and the seventh harmonics in six pulse rectifier.

4.4.1 Harmonics mitigation of fluorescent

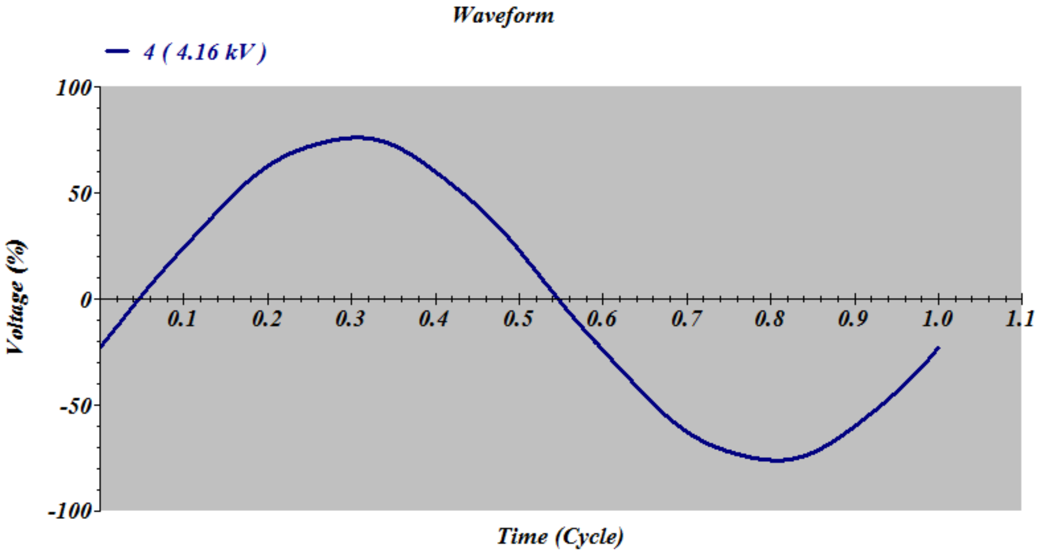

Figure 4.19: Voltage waveform of fluorescent

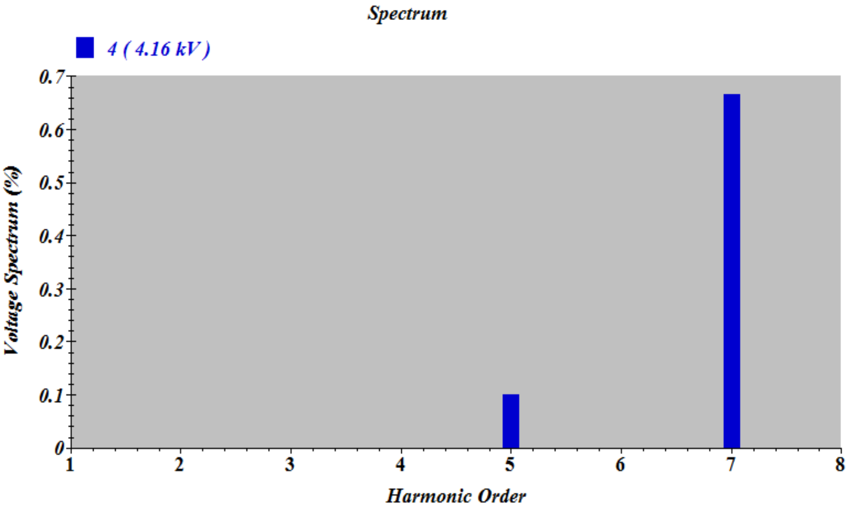

Figure 4.20: Voltage spectrum of fluorescent

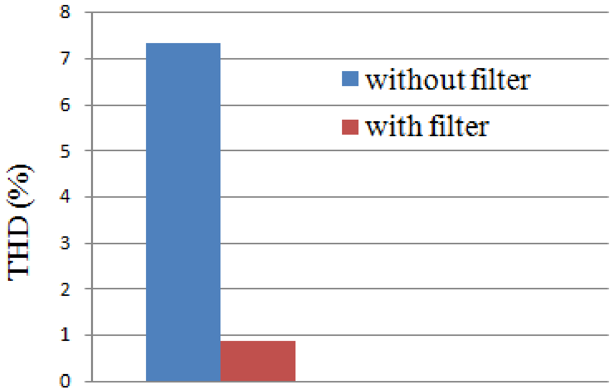

Figure 4.21: THD with and without of fluorescent

4.4.2 Harmonics mitigation of arc furnace

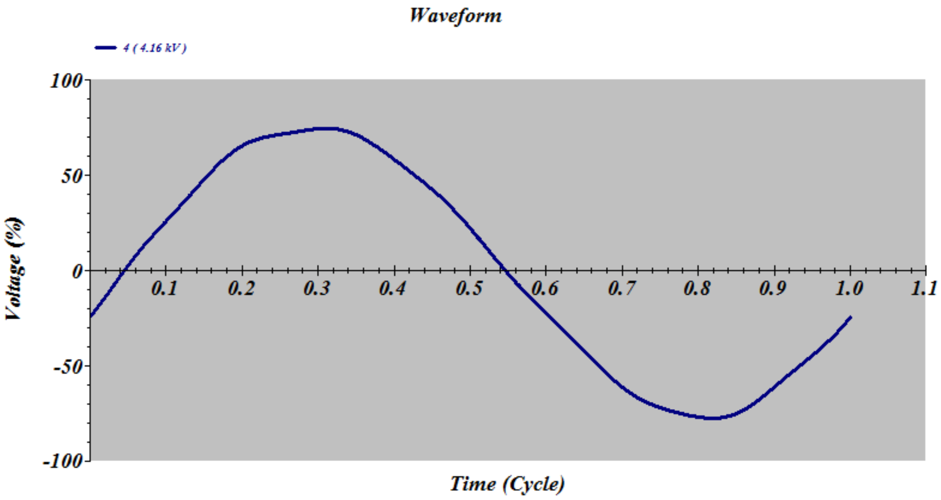

Figure 4.22: Voltage waveform of arc furnace

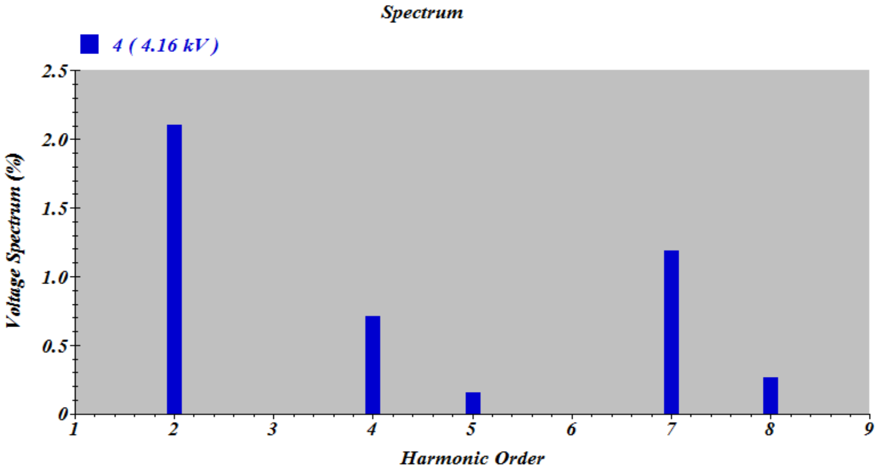

Figure 4.23: Voltage spectrum of arc furnace

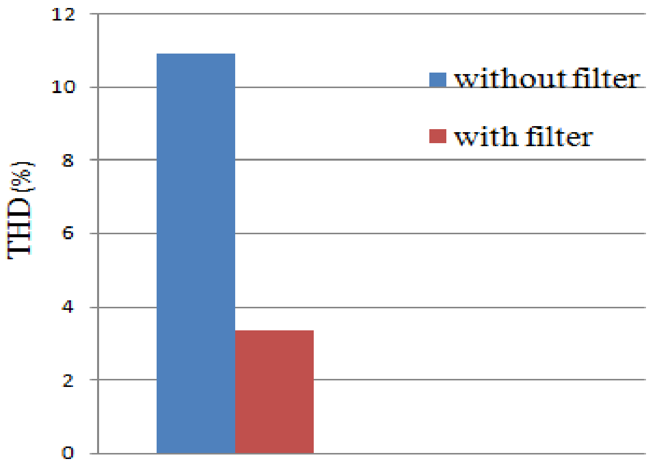

Figure 2.24: THD with and without filter of arc furnace

4.4.3 Harmonics mitigation of six pulse rectifiers

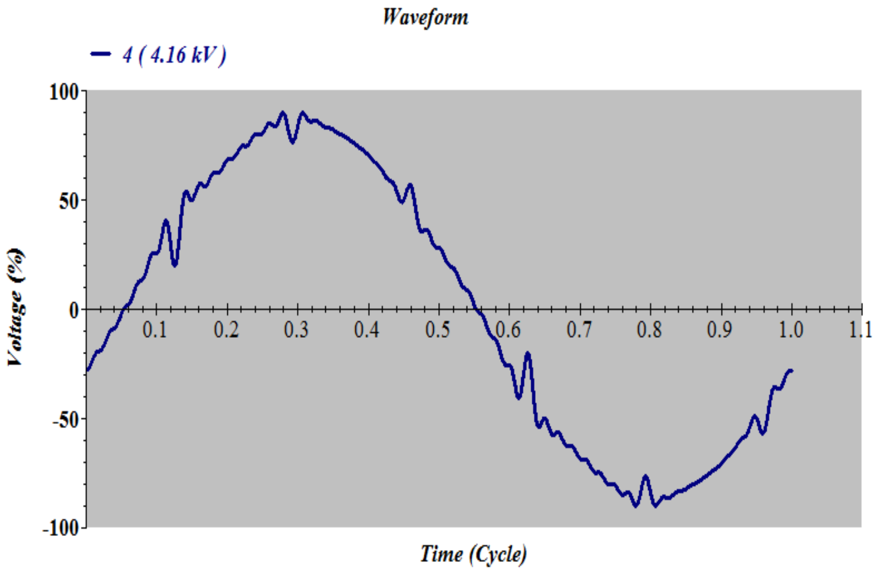

Figure 4.25: Voltage waveform of six pulse rectifier

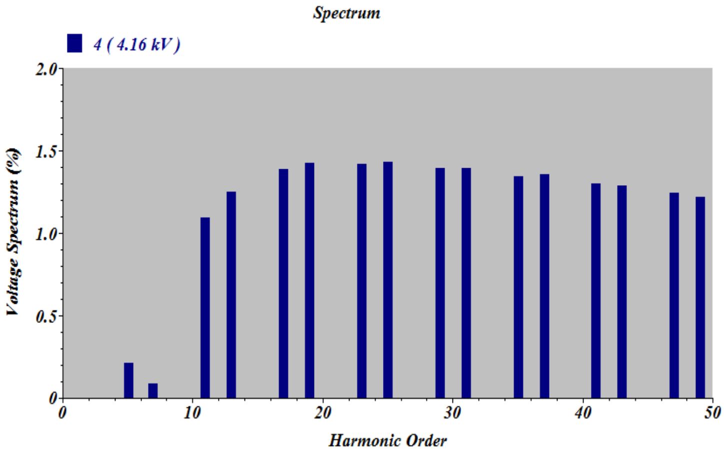

Figure 4.26: Voltage spectrum of six pulse rectifiers

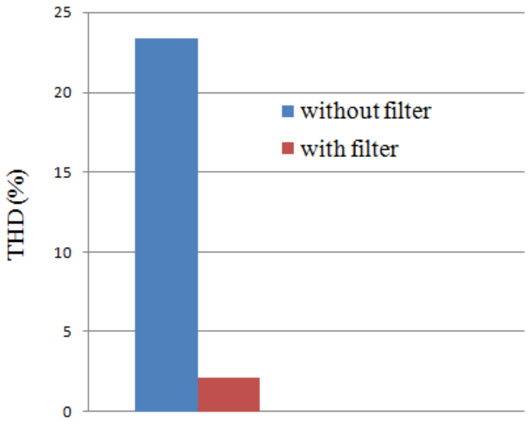

Figure 4.27: THD with and without filter of six pulse rectifiers

4.4.4 Harmonics mitigation of fluorescent, arc furnace and six pulse rectifier

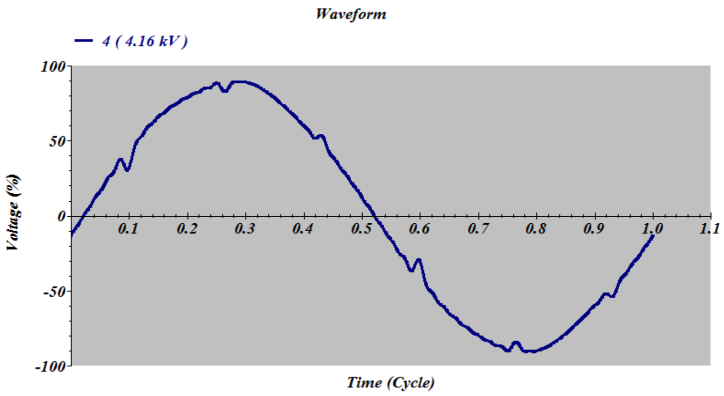

Figure 4.28: Voltage waveform of fluorescent, arc furnace and six pulse rectifiers

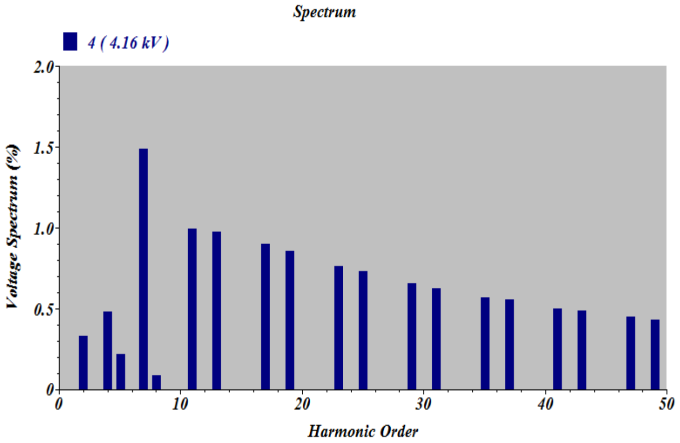

Figure 4.29: Voltage waveform of fluorescent, arc furnace and six pulse rectifier

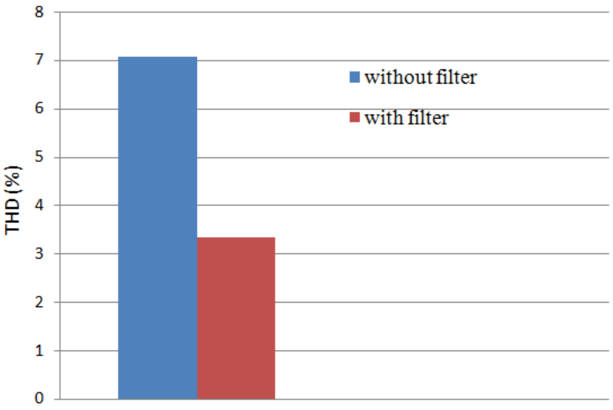

Figure 2.30: THD with and without filter of fluorescent, arc furnace and six pulse rectifiers

4.5 Results Discussion

The set of nonlinear-loads which is studied draw non-sinusoidal currents and produce odd high order harmonics, current waveforms are distorted. The results show that harmonics reduce the power factor when load flow analysis was run and this reduction in power factor produces distortion power. In three phase non-linear loads neutral current increases and in single phase non-linear loads phase and neutral current increases, this increases the voltage drop and resistive power loss besides increasing of iron and reactive power losses. Current increase result in cable size increases and circuit breakers cost. The fifth harmonics tuned passive filters reduced the fifth harmonics current component also reduced the seventh harmonic current component.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Industrial process and the electrical equipment and machines have led to considerable development in power electronics. These equipments represent "nonlinear" loads in which the current consumption does not reflect the supply voltage.

Arc furnaces, fluorescent lamps, types of rectifiers, VFD, ac drives and so on are types of harmonic sources using strong magnetizing current: saturated transformers are also type of harmonic sources. The harmonic currents circulate in the source; these harmonic currents induced voltage causing harmonic distortion of the supply voltage.

The effect of these harmonic is that they distorted the power system network voltage and current. Also it is reduced the power factor.

Single tuned passive filter is serial combination of a capacitor and an inductance was used to cancel fifth harmonic, two single tuned passive filters were used to cancel fifth and seventh harmonics.

5.2 Recommendations

The study is carried out for one bus bar and for specific types of harmonic sources. It is recommended to carry out study to the rest of bus bars and to the rest of harmonic sources. It is recommended to use transformer with delta/star connection to eliminate the third harmonic. Also it is recommended to use active filter, it is an effective, more sensitive and it can cancel more than one of harmonic orders. It is better to avoid resonance between the power system network and injected filters. Passive filter is serial combination of a capacitor and an inductance for which the tuning frequency corresponding to a harmonic voltage to be eliminated.

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