Sudan University of Science and Technology

College of Engineering

Electrical Engineering

Harmonics Reduction in AC Drives

تقليل التوافقيات في مغيرات السرعه للتيار المتردد

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

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الأية

﴿اللَّهُ لاَ إِلَٰهَ إِلاَّ هُوَ الْحَيُّ الْقَيُّومُ لاَ تَأْخُذُهُ سِنَةٌ وَلاَ نَوْمٌ لَّهُ مَا فِي السَّمَاوَاتِ وَمَا فِي الأَرْضِ مَن ذَا الَّذِي يَشْفَعُ عِنْدَهُ إِلاَّ بِإِذْنِهِ يَعْلَمُ مَا بَيْنَ أَيْدِيهِمْ وَمَا خَلْفَهُمْ وَلاَ يُحِيطُونَ بِشَيْءٍ مِّنْ عِلْمِهِ إِلاَّ بِمَا شَاء وَسِعَ كُرْسِيُّهُ السَّمَاوَاتِ وَالأَرْضَ وَلاَ يَؤُودُهُ حِفْظُهُمَا وَهُوَ الْعَلِيُّ الْعَظِيمُ﴾

[255]

سورة البقرة

DEDICATION

We dedicate this work to God Almighty and to all the people who helped us to get to this point, and withstood the hard times and enjoyed the good times with us, to all our families, teachers, colleagues and friends.

ACKNOWLEDGEMENT

We would like to express our greatest gratitude first to our supervisor Dr. Salah Eldeen Gasim whom guidance and support inspired and encouraged us to complete this project in its current state. Thanks to him we have experienced true research and our knowledge on the subject matter has been expanded.

We also thank Eng. Osman Bashir for his valued contribution and support.

المستخلص

يستخدم مغير السرعة للتيار المتردد للتحكم في سرعة وعزم المحرك عن طريق تغيير جهد الدخل والتردد. معظم مغيرات السرعة مبدأ عملها يقوم على تحويل التيار المتردد الى تيار مستمر ثم تحويل التيار المستمر الى تيار متردد, هذه العملية جعلت مغير السرعة للتيار المتردد احد أكبر مصادر التوافقيات. هدف هذا المشروع هو حل هذه المشكلة, وتم هذا عن طريق إستخدام عدة طرق لتقليل التوافقيات. هذه الدراسة ذات أهمية بالغة لدى شركات الكهرباء نظرا لإهتمامهم بجودة الكهرباء المقدمة وأثرها على إستقرارية نظام القدرة, ومن جهة اخرى هذه الدراسة مهمة للقطاع الصناعي بسبب إلزامهم معايير توافقيات معينة.

في هذا المشروع تم إسنخدام مغير السرعة للتيار المتردد للتحكم في محرك ثلاثي الطور, وتم تغذية المغير من مصدر جهد ثلاثي الطور, لتمثيل هذا النظام تم إستخدام برنامج MATLAB/SIMULINK .وتم بواسطته إستخلاص النتائج وتحليلها. تم إستخدام برنامج ETAP لتأكيد النتائج المتحصل عليها ببرنامج MATLAB/SIMULINK .

النتائج المتحصل عليها تبين خطورة إستخدام مغيرات سرعة دون إستعمال طرق لتقليل التوافقيات, وتوضح ايضا خصائص وفوائد اي طريقة من طرق التوافقيات

ABSTRACT

A variable speed drive (VFD) is used to control the speed and torque of AC Induction motor by varying input voltage. Conventional motor drive convert AC to DC then DC to AC. This conversion made the drive one of the largest sources of harmonic distortion. The aim of this project is to reduce this issue. This is done by using different methods of harmonic mitigation techniques. This study is very important for the power companies because of their growing concern of the power quality issue and its effect on their system stability and its quality. On the other hand, this research is also of major importance to the industrial sector because they must keep their harmonic distortion under standard limits.

In this project, a variable speed drive had been used to drive a three phase induction motor, the drive is connected to a three phase source, MATLAB/SIMULINK tool had been used to simulate the whole system, the results are then obtained and analyzed. ETAP (electrical transient analysis program) had been used for the validation of the results.

The obtained results show the jeopardy of having a VFD without mitigation, also it highlights the properties and advantages of each mitigation technique.

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LIST OF ABBRIVIATION

PE	Power electronics.
ASD	Adjustable speed drive.
HVAC	Heating, ventilation, and air conditioning.
EMI	Electromagnetic interference.
SCR	Silicon controlled rectifier.
BJT	Bipolar junction Transistor.
FET	Field effect Transistor.
GTO	Gate turn-off Thyristor.
IGBT	Insulated gate bipolar transistor.
MOSFET	Metal-oxide field effect transistor.
PWM	Pulse width modulation.
VSD	Variable speed drive.
VFD	Variable frequency drive.

LIST OF SYMBOLS

V	the stator supply voltage
E_s	the stator induced voltage
E_R	the rotor induced voltage
R_S	Stator resistance
X_S	Stator leakage reactance at 50 Hz,
R_R	Rotor resistance
N_S	Stator turns
X_R	Rotor leakage reactance
N_R	Rotor turns
X_M	Magnetizing inductance
I_S	Stator current
I_R	Rotor current
I_M	Magnetizing current
R_C	Core losses, bearing friction, windage losses
N_r	Rotor speed. (r.p.m)
N_s	Stator speed.(r.p.m)
K_c	Machine constant.
E	Induced voltage.(V)
T_{st}	Starting torque. (N.m)
P_{counr}	Conductor losses.(W)
V_{rms}	rms value of voltage.(V)
I_{rms}	rms value of current. (A)
D	Distortion power.
TL	Load torque.(N.m)
T_{Max}	Maximum torque. (N.m)

U	The generated voltage. (V)
f	frequency.(Hz)
Φ	Phase angle in radians.
Uref	The reference signal.(V)
Vf	Forward voltage. (V)
Tm	the mechanical torque.
J	The machine Inertia.
Te	The internal electromagnetic torque. (N.m)
Llr	leakage inductance.(H)
S	The nominal apparent power.
P	pole pairs.
S	slip.
R	The resistor.(Ω)
C	The capacitance.(F)
X_{filt}	Net wye equivalent filter reactance.(Ω)
V	The fundamental RMS phase voltage. (V)
Q_c	The Required Compensation (reactive power) from filter.(Var)
P	The single phase power.(W)
PF_{old}	The old Power factor of the system.
PF_{new}	The new wanted power factor of the system.
X_{cap}	The capacitive reactance(Ω)
h	harmonic tuned order of the filter.
X_L	The filter reactor at fundamental frequency. (Ω)
L	The Inductance of the filter reactor.(H)

Q_{optm}	The reactive power.(Var)
Q_{coil}	The coils reactive power. (Var)
R_{coil}	The Reactor coil resistance, (Ω)
R_t	The total resistance of the filter. (Ω)
$R_{external}$	The external resistance of the filter which must be added to the filter. (Ω)
X_c	The capacitive reactance.(Ω)
X_{SC}	The short-circuit reactance. (Ω)
L_{ac}	Inductance of the 3-phase reactor.(H)
Z %	Percentage impedance of the line.
$V_{\emptyset}$	AC line phase voltage.(V)
I_{ac}	AC line current.(A)
L_{dc}	Inductance of the DC link.
V_{Am}	Phase A modulation voltage. (V)
V_{Bm}	Phase B modulation voltage. (V)
V_{Cm}	Phase C modulation voltage. (V)
f_{out}	The fundamental output frequency.
f_{res}	The resonance frequency of the system.(Hz)
f_{sw}	The inverter's switching frequency. (Hz)
Z_0	The natural frequency of the filter. (Hz)

CHAPTER ONE

INTRODUCTION

1.1 Overview

Both electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power. The term power quality has become one of the most prolific buzzwords in the power industry since the late 1980s. It is an umbrella concept for a multitude of individual types of power system disturbances.[1]

With their many benefits, Variable Frequency Drives (VFD's) have grown rapidly in their usage in recent years. This is particularly true in the Petrochemical Industry where their use in pumping and other applications has led to significant energy savings, improved process control, increased production and higher reliability.[2]

1.2 Problem Statement:

An unfortunate side effect of their usage (VFDs) however, is the introduction of harmonic distortion in the power system. As a nonlinear load, a VFD draws current in a non-sinusoidal manner, rich in harmonic components. [2]

Representing a big obstacle against the wide application of VFDs although they enhance system efficiency and provide great energy saving. The power system harmonics cause many harmful effects including:

-Overheating of generators, motors, transformers, and power cables that lead to early equipment failures.

- Failure of capacitor banks.

- Nuisance tripping to protection relays.

- Interference to communication systems and sensitive electronic devices.[3]

1.3 Objectives:

The main objectives of this project are:

- To design and simulate a 6 pulse VFD.

- To Study and analyze the harmonics at both sides of the VFD (supply side and motor side).

- To illustrate the different methods of harmonic mitigation techniques, design, simulate these different methods and check their performance when applied to VFDs.

- To compare these different methods at the base of their harmonic reduction capability and their compliance with IEEE STD 519.

- To compare these mitigation techniques in terms of both technical and economical point of view.

-To study the effect of motor size on harmonics.

1.4 Methodology:

For the fulfillment of these objectives both analytical work and simulation had been used. For simulation both MATLAB/SIMULINK software and ETAP software have been used.

MATLAB offers an intuitive language for expressing problems and their solutions both mathematically and visually. MATLAB Typical uses include Modeling and simulation. ETAP (Electrical Transit and analysis program) is software that contain several packages capable of performing analytical and electrical modeling tasks.[4]

Analytical work contains charts that had been used to compare the results obtained by each mitigation method.

MATLAB software had been used for modeling the VFD, illustration of the VFD harmonics and modeling of different mitigation techniques, ETAP software had been used for the validation of the results obtained by MATLAB, the goal was to check the compliance of the VFD's harmonic levels with the IEEE STD 519.

The model consists of:

- VFDs constructed using SIMULINK simpower system library blocks consist of a rectifier, dc link capacitor and an inverter.

- 5 HP asynchronous motor.

1.5 Project Layout:

Chapter two of this project report gives theoretical background of the project, Induction motors and its characteristics, power electronic devices and their switching, VFD construction, type of control, harmonic background, chapter three presents the methodology used, tools, methods of harmonic reduction including passive filters, multi pulse rectifiers, AC reactors and dc reactor use on supply side. On motor side LC passive filters, reactor and mitigation through increasing the switching frequency are used. Chapter four contains the MATLAB/SIMULINK model of the 6 pulse VFD and an examination of its harmonic content, modeling of all mitigation techniques and design calculation of their components, Evaluation of their compliance with IEEE STD 519 and a comparison based on their harmonic reduction capability, chapter five is the conclusion and recommendations.

CHAPTER TWO

LITREATURE REVIEW

2.1 Introduction:

There are many and diverse reasons for using variable speed drives. Some applications, such as paper making machines, cannot run without them while others, such as centrifugal pumps can benefit from energy savings.

In general, variable speed drives are used to:

• Match the speed of a drive to the process requirements.

• Match the torque of a drive to the process requirements.

• Save energy and improve efficiency.

2.2 Adjustable-Speed Drive Applications:

Adjustable-speed drives can be used in every environment where variable speed and torque are needed. ASDs are currently used in elevators, water and wastewater pumps, boiler fans, HVACs stems, wind turbines where speed of wind is not constant, hydroelectric plants where speed of water is not constant, and the automobile industry. Some of these applications will be discussed in detail below.

1. In home automation application, convinced of remotely controlling the speed of fan is achieved.

2. Many industrial applications require adjustable speed and constant speed for improvement of quality product.

3. Intensity of light can also be controlled with the help of android application.

4. Bell drive application like small conveyors, large blowers, pumps as well as many direct drive or geared application.

5. Wood working machinery air compressors, high processors, water pumps, vacuum pump and high torque application.[5, 6]

2.3 Variable Speed Drive Types:

The most common types of variable speed drives used today are summarized below:

2.3.1 Electromagnetic coupling or 'Eddy Current' coupling:

Using the principles of electromagnetic induction, torque is transferred from a rotating drum, mounted onto the shaft of a fixed speed electric motor, across the air gap to an output drum and shaft, which is coupled to the driven load. The speed of the output shaft depends on the slip between the input and output drums, which is controlled by the magnetic field strength. The field winding is supplied with DC from a separate variable voltage source, which was traditionally a variac but is now usually small single-phase thyristor converter.

Drawbacks: The losses, appears as heat in the coupling. These losses are dissipated through cooling fins on the rotating drums.

2.3.2 Ward-Leonard system

The Ward-Leonard system comprises a fixed speed 3-phase AC induction motor driving a separately excited DC generator that, in turn, feeds a variable voltage to a shunt wound DC motor. The basic principle of a DC variable speed drive is that the speed of a separately excited DC motor is directly proportional to the voltage applied to the armature of the DC motor. The output voltage of the DC generator, which is adjusted by controlling the field voltage, is used to control the speed of the DC motor

Drawbacks: It is no longer commonly used because of the high cost of the 3 separate rotating machines. In addition, the system requires considerable maintenance to keep the brushes and commutation of the two DC machines in good condition.

2.3.3 Electrical variable speed drives for AC motors (AC drives)

One of the lingering problems with thruster controlled DC drives is the high maintenance requirement of the DC motor. The main attraction of the AC VSDs is the rugged reliability and low cost of the squirrel cage induction motor compared to the DC motor. In the AC VSD, the mechanical commutation system of the DC motor has been replaced by a power electronic circuit called the inverter. However, the main difficulty with the AC variable speed drive has always been the complexity, cost and reliability of the AC frequency inverter circuit.

2.3.4 Cycloconverters:

A cycloconverter is a converter that synthesizes a 3-phase AC variable frequency output directly from a fixed frequency 3-phase AC supply, without going via a DC link. The cycloconverter is not new and the idea was developed over 50 years ago using mercury arc rectifiers.

Drawbacks:

-The main limitation of the cycloconverter is that it cannot generate frequencies higher than the AC supply frequency.

-The cycloconverter requires a large number of thrusters, and the control circuitry is relatively complex but, with the advent of microprocessors and digital electronics, the implementation of the control circuits has become more manageable

-Because of the low frequency output, cycloconverters are suited mainly for large slow speed drives.[8]

2.4 Induction Motor:

As a general rule, conversion of electrical power into mechanical power takes place in the rotating part of an electric motor. In DC. motors, the electric power is conducted directly to the armature (i.e. rotating part). Through brushes and commutator. Hence in this sense a DC motor can be called a conduction motor. However, in AC. motors, the rotor does not receive electric power by conduction but by induction in exactly the same way as the secondary of a 2-winding transformer receives its power from the primary. That is why such motors are known as induction motors. In fact, an induction motor can be treated as a rotating transformer i.e. one in which primary winding is stationary but the secondary is free to rotate.

2.4.1 General constriction:

1. Frame. Made of close grained alloy cast iron.

2. Stator and Rotor Core.

3. Stator and Rotor Windings.

4. Air-gap.

5. Shafts and Bearings.

6. Fans.

7. Slip-rings and Slip-ring Enclosures. [7]

2.4.2 The equivalent circuit:

To understand the performance of an AC induction motor operating from a V/F converter, it is useful to electrically represent the motor by an equivalent circuit. This clarifies what happens in the motor when stator voltage and frequency are changed or when the load torque and slip are changed.[8]

Figure (2.1) below show the equivalent circuit of three phases Induction motor. Where V is the stator supply voltage, E_s is the stator induced voltage, E_R is the rotor induced voltage, R_S = Stator resistance, X_S = Stator leakage reactance at 50 Hz, R_R = Rotor resistance, N_S = Stator turns X_R = Rotor leakage reactance, N_R = Rotor turns X_M = Magnetizing inductance, I_S = Stator current, I_R= Rotor current, I_M= Magnetizing current and R_C = Core losses, bearing friction, windage losses, etc

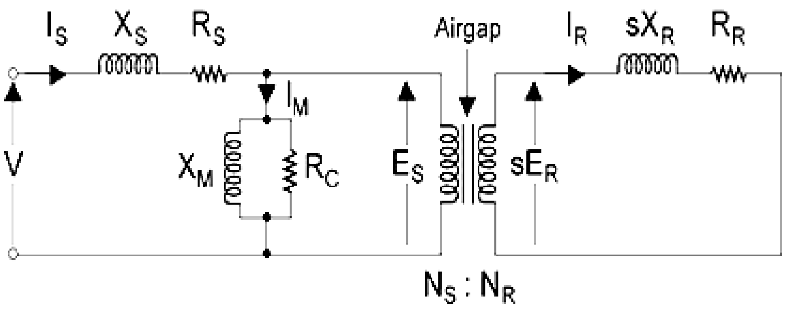

Fig 2.1: Equivalent circuit of Induction motor

2.4.3 Relation between torque and speed:

When matching motors to mechanical loads, the two most important considerations are the torque and speed. The torque–speed curve, which is the basis of illustrating how the torque changes over a speed range, can be

$$T_M = \frac{3 \times s \times V^2 \times R_R^{'}}{[(R_S + R_R^{'})^2 + s(X_S + X_R^{'})^2] n_o} \qquad (2.1)$$

Where T_M is the motor output torque, s is the slip, n_o is the motor speed, R_S = Stator resistance, X_S = Stator leakage reactance at 50 Hz, R_R = Rotor resistance, N_S = Stator turns and X_R = Rotor leakage reactance, Derived from the equivalent circuit and the equations above. The output torque of the motor can be expressed in terms of the speed as follows:

This equation and the curve in Figure (2.2) show how the motor output torque T_M varies when the motor runs from standstill to full speed under a constant supply voltage and frequency. The torque requirements of the mechanical load are shown as a dashed line.

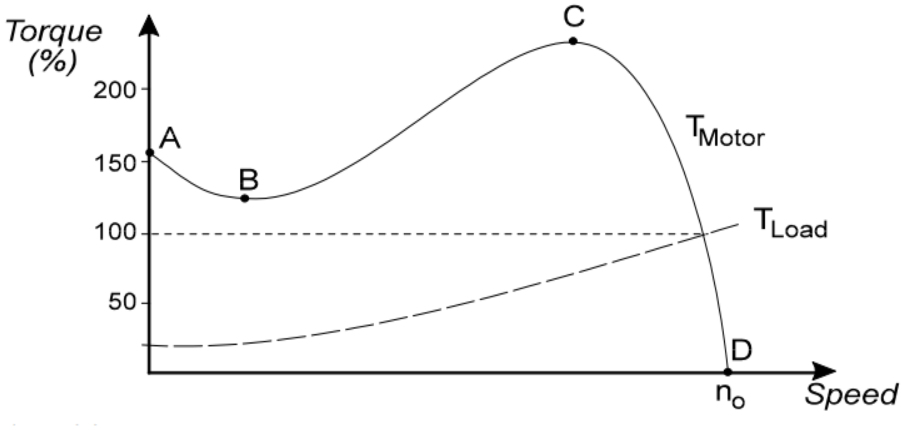

Fig 2.2: Torque–speed curve of Induction motor

A: is called the breakaway starting torque

B: is called the pull-up torque

C: is called the pull-out torque (or breakdown torque or maximum torque)

D: is the synchronous speed (zero torque)

At starting, the motor will not pull away unless the starting torque exceeds the load breakaway torque. Thereafter, the motor accelerates if the motor torque always exceeds the load torque. As the speed increases, the motor torque will increase to a maximum T_{Max}at point C.

On the torque–speed curve, the final drive speed (and slip) stabilizes at the point where the *load torque* exactly equals the *motor output torque*. If the load torque increases, the motor speed drops slightly, slip increases, stator current increases, and the motor torque increases to match the load requirements.

The range CD on the torque–speed curve is the stable operating range for the motor. If the load torque increased to a point beyond T_{Max}, the motor would stall because, once the speed drops sufficiently back to the unstable portion ABC of the curve, any increase in load torque requirements TL and any further reduction in drive speed, results in a lower motor output torque.[8]

- Torque-speed characteristics of three phase squirrel cage induction motor:

There are mainly two methods to control the speed of an induction motor:

1. Variable voltage control
2. Variable voltage variable frequency (V/F) control

$$N_s = \frac{120\, f}{P} \tag{2.2}$$

Where f is the frequency of the currents and P is the number of poles. If the rotor of the induction motor rotates at a speed, N_r, then the slip, s is defined by Equation (2.3) below.

$$s = \frac{N_S - N_r}{N_S} \tag{2.3}$$

The maximum torque developed T_m and the slip s_m at which T_m occurs is given by Equation (2.4).

$$T_m = \frac{3 * V_S{}^2}{2 * w_S * R_S \pm \sqrt{R_S{}^2 \pm (X_S + X_R)^2}} \tag{2.4}$$

Where T_m is the maximum torque develop, V_s is the stator voltage, ws is the synchronous speed, Rs is the stator resistant, X_s is the stator reactance and X_R is the Rotor reactance.

- T-N_r characteristics with V/f control:

If the motor is operated with a variable voltage- variable frequency source, we can implement constant V/f control of the induction motor, where the operating flux φ is kept constant.

$$E = 4.44 K_c \varphi f N_{st} \tag{2.5}$$

$$\phi \ \alpha \ \frac{E}{F} \tag{2.6}$$

Where K_c is the machine constant, E is the induced voltage in the stator, φ is the rated flux in the air-gap, N_{st} is the number of turns in the stator. Assuming $V_s = E$, if the V/f ratio is kept constant, φ will also be constant. If $V_s = KV_{srated}$ and $f = Kf_{rated}$, then the slip will be as follows.

$$s = \frac{K\omega_s - \omega_r}{K\omega_s} \tag{2.7}$$

$$sK = \frac{K\omega_s - \omega_r}{\omega_s} \tag{2.8}$$

Where the term sK is the slip speed, that is the drop in motor speed from no load speed ($K\omega_s$). The expression for the developed torque with V/f control will be given by Equation (2.9) below.

$$T = \frac{3}{K\omega_s}\frac{I_2^2R_2}{s} = \frac{3}{\omega_s}\frac{V_s^2R_2/sK}{(R_2/Ks)^2 + X_2^2} \tag{2.9}$$

The maximum torque developed, T_m and the slip at which T_m occurs, s_m are given by (2.10) and (2.11) below.

$$T_m = \frac{3}{2\omega_s}\frac{V_s^2}{X_2} \tag{2.10}$$

$$s_m = \frac{R_2}{KX_2} \tag{2.11}$$

So with V/f control, the maximum torque developed is independent of *K*, but $S_m$is inversely proportional to *K*. From (2.9), for any given torque, the drop in motor speed from no load speed, (*sK*) will be same for any value of K. Thus, with V/f control, the T-N_r characteristics for different values of K will be parallel to each other.

The starting torque (for s=1), T_{st} is given by (2.12). Thus, $T_{st} \propto 1/K$.[9]

$$T_{st} = \frac{3}{\omega_s} \frac{{V_s}^2 R_2/K}{(R_2/K)^2 + {X_2}^2} \tag{2.12}$$

2.4.4 Motor losses:

When Induction motor is fed from PWM static power converter there are harmonics losses take place in the machine because of high Switching frequencies. These High carrier frequencies tend to reduce the current harmonics and thus reduce the conductor losses associated with them, but the higher frequency flux harmonics may lead to larger core loss.

At high carrier frequency, the skin effect, both in the conductors and iron cores, may not be neglected.

2.4.4.1 Conductor losses

The conductor losses could be divided into rotor conductor losses and stator conductor losses, the rotor conductor losses can be obtained by this formula

$$P_{counr} = \frac{v^2}{f^{1.18}} \tag{2.13}$$

Where:

V=harmonic voltage f=frequency

The rotor conductor losses drop notably as the time harmonic frequency Increases. The situation in the stator is different as there are many conductors in every slot (at least in small power induction machines). Stator losses can be obtained by this formula

$$P_{couns} = v^2 f^{0.32} \tag{2.14}$$

The stator conductor losses tend to increase slightly with frequency

2.4.4.2 Core losses

Traditionally iron loss had been divided up in to two components, hysteresis loss P_{hys} and eddy current or classical loss $P_{classical}$. Therefore, iron loss was expressed by

$$P_{Total} = P_{hys} + P_{classical} \tag{2.15}$$

Predicting the core loss at high frequencies is difficult because the flux penetration depth in lamination becomes comparable with (or smaller than) the lamination thickness.[10]

2.5 Power Electronics Devices and Their Characteristics:

Electronic switches capable of handling high voltage and current operations at High frequency are the most important devices needed in the design of energy Conversion systems that use PE.

A switch is considered ‘‘ideal’’ when it is open, it has zero current through it and can handle infinite voltage. When the switch is closed it has zero-voltage across it and can carry infinite current. Also, an ideal switch changes condition instantly, which means that it takes zero-time to switch from ON-to OFF or OFF-to-ON. Additional characteristics of an ideal switch include that it exhibits zero-power dissipation, carries bidirectional current, and can support bidirectional voltage.

In real life an ideal switch doesn’t exist but the closest similar devices are PE which have minimum turn ON and turn OFF time and are convenient for applications that require minimum time and power durability.

2.5.1 Diodes:

A diode is an uncontrolled switch that works as a conductor on Forward Bias

The basic working principle of PN junction is that the positive and negative regions of silicon are mixed with another material that releases a proton or an electron respectively when it bonds with silicon.

when connecting the positive side of a DC voltage source to the p region and the negative to the n region both the protons and electrons in those regions begin to scatter towards the PN junction away from the source (because they both have the same polarity) allowing the current to pass through the junction.

2.5.2 Thyristor SCR:

Silicon controlled Rectifier Diode. These are the diodes that have high forward-current carrying capability, typically up to several hundred amperes. They usually have a forward resistance of only a fraction of an ohm while their reverse resistance is in the mega ohm range. SCR is a power semiconductor switch whose turn-on can be activated from the control terminal Gate but once it turns ON, the control terminal becomes ineffective and the thyristor behaves similar to a diode. There for the thyristor is considered a semi-controlled switch. (can control it switching in one state only).

SCR Thyristors are genuinely used for rectifiers as they have the same capability of diodes add to that the controlled turn ON feature.

They also have the highest power handling capability. They have a rating of 5000V / 6000A with switching frequencies ranging from 1 KHz to 20 KHz. But they are slow compared to BJT and MOSFET.

2.5.3 GTO:

GTO thyristor is a device that operates similar to a normal thyristor except the device physics, design and manufacturing features allow it to be turned-off by a negative gate current which is accomplished through the use of a bipolar transistor. The turn-on mode is similar to a standard thyristor, but the gate current must remain continuous.

The structure of a GTO consists of a four-layer-PNPN semi-conductor device (similar to a SCR thyristor).

Turn off is accomplished by a "negative voltage" pulse between the gate and cathode terminals. Some of the forward current (about one-third to one-fifth) is "stolen" and used to induce a cathode-gate voltage which in turn causes the forward current to fall and the GTO will switch off (transitioning to the 'blocking' state.)

GTO Thyristors suffer from long switch off times, whereby after the forward current falls, there is a long tail time where residual current continues to flow until all remaining charge from the device is taken away. This restricts the maximum switching frequency to approximately 1 kHz. It may be noted however, that the turn off time of a GTO is approximately ten times faster than that of a comparable SCR.

2.5.4 Bipolar junction transistor (BJT):

A BJT is a current-controlled switch that can be considered as two diodes with a shared anode, BJT functions only when there's a continuous current flowing through its base otherwise there will be no flow of current from the collector to the emitter.

-Advantages over BJTs

- Higher voltage blocking capabilities.
- High on-state gain.

2.5.5 Field effect transistor FET:

The field effect transistor (FET) is a unipolar device compared to bipolar transistor. it consists of a bar of semi-conductor material whose resistance is modulated by varying either the cross sectional area of the bar or the density of the bar or the density of the current carriers in it. The input impedance of junction type is very high and its output impedance is moderate.

Two structures are used one is only modulated by the cross section of the conducting channel (junction FET) the other is controlled by both channel cross section and density of conductors (MOSFET).

A MOSFET is a voltage-controlled device - easy to control. It uses an electric field to control the conductivity of a channel of majority-charge carriers in the semiconductor material.

It is the fastest power switching device with switching frequency more than 1 MHz, with voltage power ratings up to 1 kV and current rating as high as 300A.

2.5.6 Isolated gate bipolar transistor (IGBT):

An IGBT, or insulated gate bipolar transistor, is a solid state device (with no moving parts). It is a switch that is used in order to allow power flow in the On state and to stop power flow when it is in the Off state. An IGBT works by applying voltage to a semiconductor component, therefore changing its properties to block or create an electrical path.

The IGBT is a hybrid or also known as double mechanism device. Its control port resembles a MOSFET and its output or power port resembles a BJT. Therefore, a IGBT combines the fast switching of a MOSFET and the low power conduction loss of a BJT. IGPT have higher current capability & higher switching speed than a BJT. and Higher current capability & higher switching speed than a BJT. (Switching speed lower than MOSFET).and has High input impedance like MOSFET Voltage controlled device like MOSFET.

An IGBT can change to the ON-state very fast but is slower than a MOSFET device. Discharging the gate capacitance completes control of the IGBT to the

OFF-state.[11-14]. Figure (2.3), below show a complete comparison between PE devices, their power handling and switching frequency.

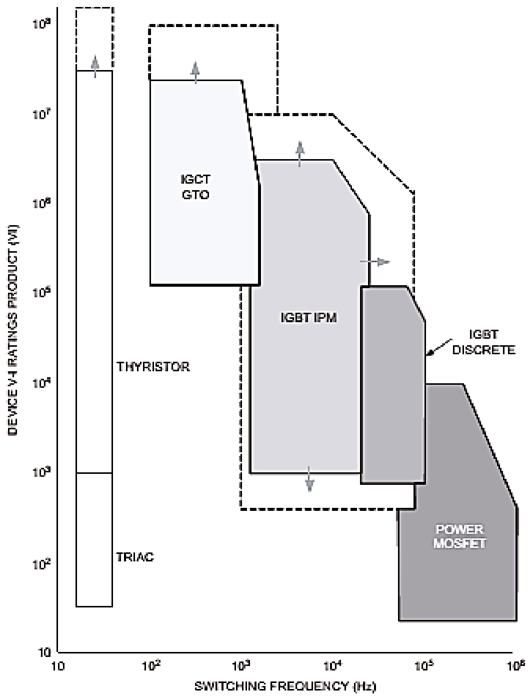

Fig 2.3: Comparison between PE devices in their power handling and switching frequencies

2.6 Rectifiers

There are two types of rectifier single phase and three phase. There are two type of single-phase diode rectifier that convert a single-phase AC supply into a DC voltage, namely, single phase half-wave rectifiers and single phase full-wave rectifiers.

2.6.1 Single-phase half-wave rectifiers:

The simplest single-phase diode rectifier is the single-phase half-wave rectifier. A single-phase half-wave rectifier with resistive load is shown in Fig. (2.4). The circuit consists of only one diode that is usually fed with a secondary transformer as shown below.

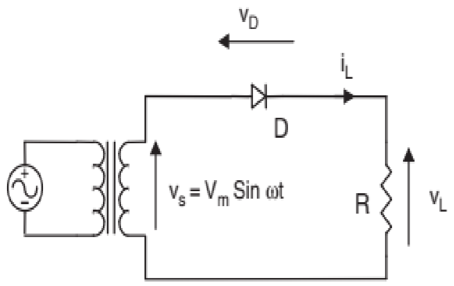

Fig 2.4**:** Single-phase Half-Wave Rectifier

2.6.2 Single-phase full-wave rectifiers:

There are two types of single-phase full-wave rectifier, namely, full-wave rectifiers with center-tapped transformer and bridge rectifiers.

2.6.2.1 single phase rectifier with center-tapped transformer:

A full-wave rectifier with a center-tapped transformer is shown in Fig. (2.5). It is clear that each diode, together with the associated half of the transformer, acts as a half-wave rectifier. The outputs of the two half-wave rectifiers are combined to produce full-wave rectification in the load.

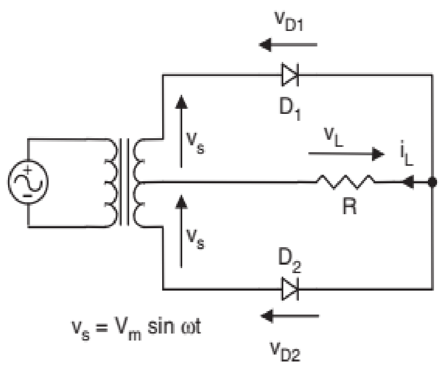

Fig 2.5**:** Single phase center-tapped Rectifier

2.6.2.2 single phase rectifier with bridge rectifier:

a bridge rectifier as shown in Fig. (2.6) can provide full-wave rectification without using a center-tapped transformer. During the positive half cycle of the transformer secondary voltage, the current flows to the load through diodes D1 and D2. During the negative half cycle, D3 and D4 conduct

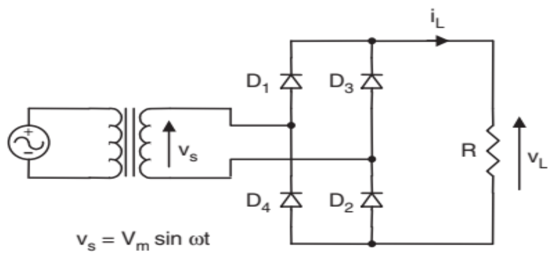

Fig 2.6: Single-phase bridge Rectifier

2.6.3 Three-phase diode rectifiers:

For power output higher than 15 kW, three-phase or poly-phase diode rectifiers should be employed. There are two types of three-phase diode rectifier that convert a three-phase ac supply into a dc voltage, namely, star rectifiers and bridge rectifiers.

2.6.3.1 Three-phase star rectifier:

A basic three-phase star rectifier circuit is shown in Fig. (2.7) This circuit can be considered as three single-phase half-wave rectifiers combined together. Therefore, it is sometimes referred to as a three-phase half-wave rectifier.

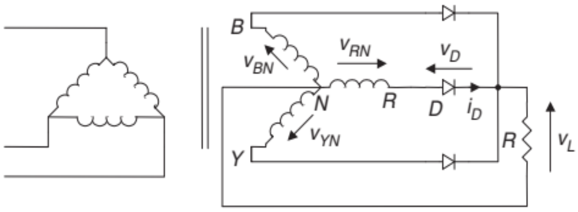

Fig 2.7**:** Three-phase Star Rectifier

2.6.3.2 Three-phase bridge rectifiers:

Three-phase bridge rectifiers are commonly used for high power applications because they have the highest possible transformer utilization factor for a three-phase system. The circuit of a three-phase bridge rectifier is shown in Fig (2.8). [15]

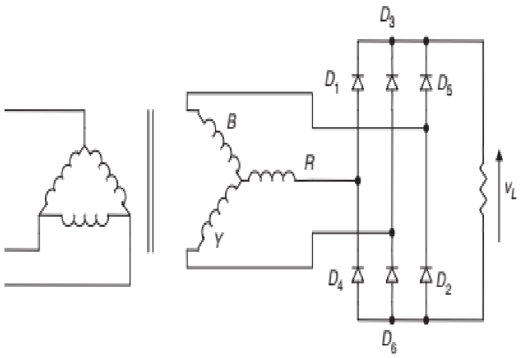

Fig 2.8: Three-phase Bridge Rectifier

2.7 Inverter:

Inverter is that type of converter which function is to change a DC input voltage to a symmetrical AC output voltage of desirable magnitude and frequency. Available output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by pulse width modulation

(PWM) control within the inverter. The inverter gain is the ratio of the ac output voltage to DC input voltage.

They come in all shapes and sizes, from low power functions such as powering a car radio to that of backing up a building in case of power outage. Inverters can come in many different varieties, differing in price, power, efficiency and purpose. The purpose of a DC/AC power inverter is typically to take DC power supplied by a battery, such as a 12-volt car battery, and transform it into a 120-volt AC power source operating at 60 Hz, emulating the power available at an ordinary household electrical outlet.

The standard frequency inverter is designed to operate from both a single phase & three phase power supply making it ideal for Single Wire Earth Return Line or single phase supply systems. And the standard frequency inverter can operate from a 480V AC single phase power supply (Single Wire Earth Return) and provide a controlled 415V three phase output to the motor. And the standard frequency inverter (or equivalent) can operate from a 220V AC single phase power supply and provide a controlled 220V 3 phase output to the motor.

2.7.1 Single-phase square wave inverter:

Fig (2.9) below shows a Single phase inverter. This circuit can be considered to be an electronic reversing switch, which allows the input DC voltage VD to be connected to the inductive load in any one of the following ways:

(1) S1 = on, S4 = on, giving +VD at the load

(2) S2 = on, S3 = on, giving –VD at the load

(3) S1 = on, S2 = on, giving zero volts at the load S 3 = on, S4 = on, giving zero volts at the load

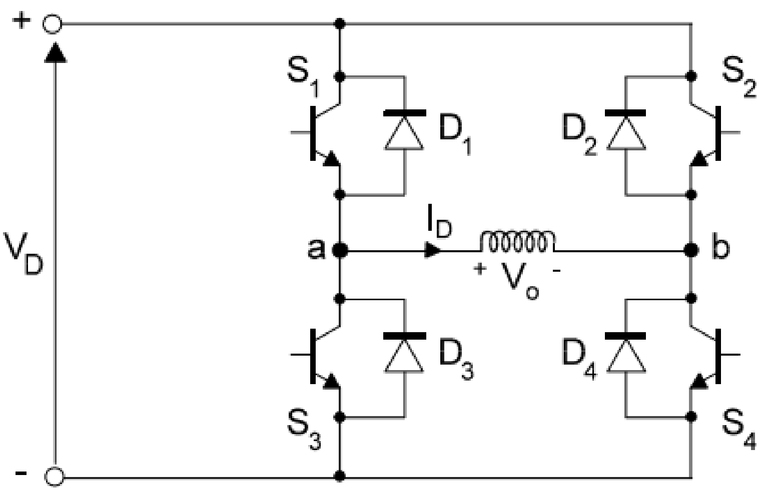

Fig 2.9: Single phase inverter

(4) S1 = on, S3 = on, giving a short circuit fault S 2 = on, S4 = on, giving a short circuit fault

These four switches can be controlled to give a square waveform across the inductive load as shown in fig (2.10) below. This makes use of switch configuration (1) and (2). In the first part of the cycle, the current is negative although only switches S1 and S4 are on. Since most power electronic devices cannot conduct negatively, to avoid damage to the switches, this negative current would have to be diverted around them. Consequently, diodes are usually provided in anti-parallel with the switches to allow the current flow to continue.

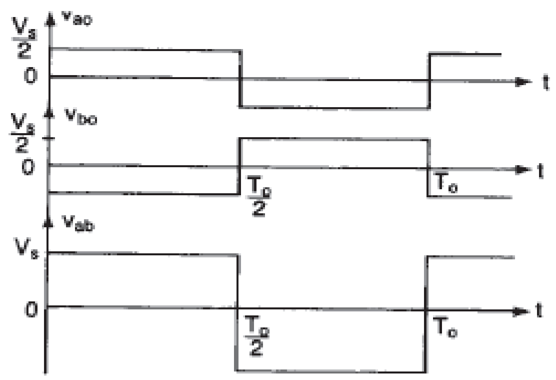

Fig2.10: Voltage waveform for single phase inverter

2.7.2 Three-phase inverter:

In its simplest form, a square output voltage waveform can be obtained from a configuration of six transistors and six diodes (as shown in fig(2.11) below) by switching each leg high for one half-period and low for the next half-period, at the same time ensuring that each phase is shifted one third of a period (120^0). The devices such as motor which work in the 1 kW to 500 kW range are based on gate commutated devices such as the GTO, MOSFET, BJT and IGBT, which can be turned ON and OFF by low power control circuits connected to their control gates.

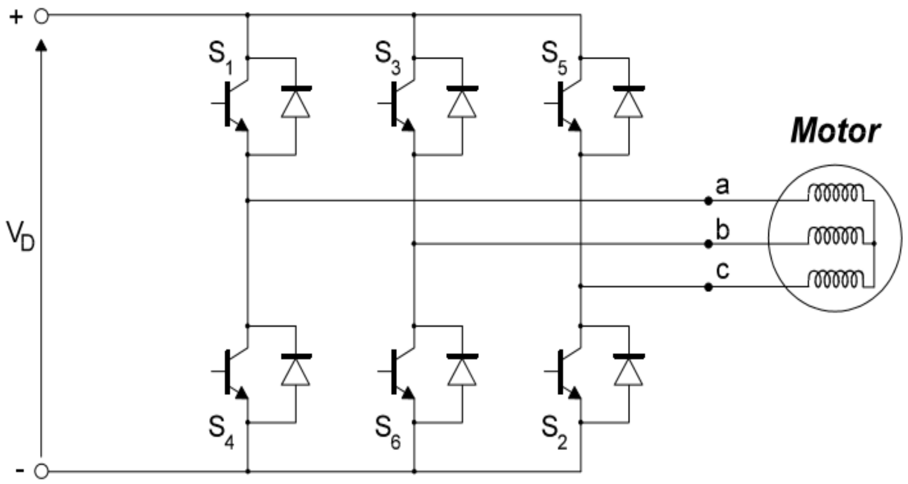

Fig 2.11: Three phase inverter circuit

Three phase inverters are normally used for high power applications. The advantages of a three phase inverter are:

-The frequency of the output voltage waveform depends on the switching rate of the switches and hence can be varied over a wide range.

-The direction of rotation of the motor can be reversed by changing the output phase sequence of the inverter.

-The ac output voltage can be controlled by varying the DC link voltage.

Fig (2.12) below shows the typical Voltage waveform of a three phase inverter for resistive load.

The electric motors used in any applications are required to have large speed ranges. Large speed ranges can be achieved by feeding the motor with voltages of different frequencies and also different voltage magnitudes. One

of the most convenient voltage control technique to generate variable frequency and magnitude voltages is Pulse Width Modulation (PWM).

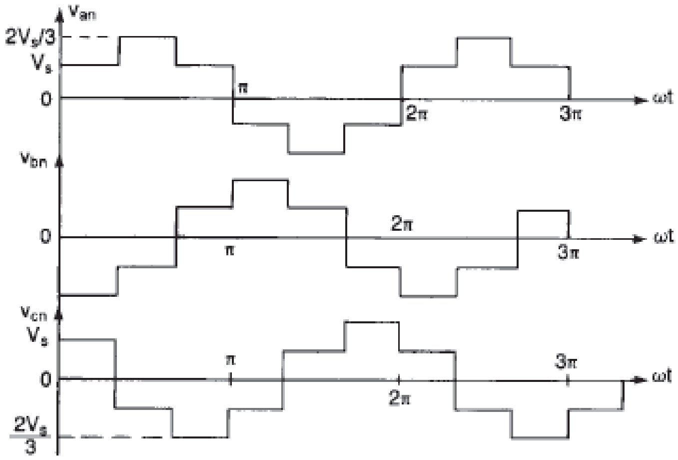

Fig 2.12: Voltage waveform to three phase inverter for resistive load

2.8 Measurements of Harmonics:

The Basic equipment used for the analysis of non-sinusoidal voltages and currents:

1. Oscilloscope: The display of the waveform on the oscilloscope gives immediate qualitative information on the degree and type of distortion. Sometimes cases of resonances are identifiable through the visible distortion that is present in the current and voltage waveforms.

2. Spectrum Analyzers: These instruments display the power distribution of a signal as a function of frequency. A certain range of frequencies is scanned, and all the components, harmonics, and interharmonics of the analyzed signal are displayed. The display format maybe a CRT or a chart recorder.

3. Harmonic Analyzers or Wave Analyzers: These instruments measure the amplitude (and in more complex units, the phase angle) of a periodic function. These instruments provide the line spectrum of an observed signal. The output can be recorded; or it can be monitored with analog or digital meters.

4. Distortion Analyzer: These instruments indicate total harmonic distortion (THD) directly.

5. Digital Harmonics Measuring Equipment: Digital analysis can be performed with two basic techniques:

-By means of digital filter.

-The Fast Fourier Transform technique.

-Requirements for Instrument Response: For accurate harmonics measurements, the following important requirements must be met:

1. Accuracy: The instrument must perform the measurement of a constant (steady state) harmonic component with an error compatible with the permissible limits.

2. Selectivity: The selectivity of the instrument is an indication of its ability to separate harmonic components of different frequencies.

3. Averaging or Snapshot: If the measured harmonics vary in time, it is necessary to "smooth out" the rapidly fluctuating components over a period of time. Two factors become important in this case dynamic response and bandwidth. [16]

2.9 Power System Quantities under Non-Sinusoidal Conditions

There are three standard quantities associated with power:

1. Apparent power (S)[volt-ampere(VA)].

2. Active power (P)[watt(W)].

3. Reactive power (Q)[volt-ampere-reactive] (VAR)].

The apparent power S applies to both sinusoidal and non-sinusoidal conditions. The apparent power can be written as equation (2.16):

$$S = V_{rms} \times I_{rms} \tag{2.16}$$

Where V_{rms} and I_{rms} are the RMS values of the voltage and current. In a sinusoidal condition both the voltage and current waveforms contain only the fundamental frequency component; thus the rms values can be expressed as

$$V_{rms} = \frac{1}{\sqrt{2}} V_1 \quad \text{and} \quad I_{rms} = \frac{1}{\sqrt{2}} I_1 \tag{2.17}$$

Where V_1 is the voltage amplitude and I_1 is the current amplitude.

The active power is simply defined as:

$$P = \frac{V_1 I_1}{2} \cos \theta_1 = V_{1rms} I_{1rms} \cos \theta_1 = S \cos \theta_1 \tag{2. 18}$$

The reactive power is simply defined as:

$$Q = S \sin \theta_1 = \frac{V_1 I_1}{2} \sin \theta_1 = V_{1rms} I_{1rms} \sin \theta_1 \tag{2.19}$$

using the definitions for S and P previously givens

$$S = \sqrt{P^2 + Q^2 + D^2} \tag{2.20}$$

$$Q = \sum_k V_k I_k \sin \theta_k \tag{2.21}$$

Therefore, D can be determined after S, P, and Q by

$$D = \sqrt{S^2 - P^2 - Q^2} \tag{2.22}$$

2.10 Effects of Harmonics:

2.10.1 Resonance:

All circuits containing both capacitances and inductances have one or more natural frequencies. When one of those frequencies lines up with a frequency that is being produced on the power system, a resonance may develop in which the voltage and current at that frequency continue to persist at very high values.[1]

2.10.2 Induction Motors:

Harmonics distortion raises the losses in AC induction motors in a similar way as in transformers and cause 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. Excessive heating can degrade the bearing lubrication and result in bearing collapse.

Harmonic currents also can result in bearing currents, which can be however prevented by the use of an insulated bearing, a very common practice used in AC variable frequency drive-fed AC motors. Overheating imposes significant limits on the effective life of an induction motor. For every 10 C rise in temperature above rated temperature, the life of motor insulation may be reduced by as much as 50%. Squirrel cage rotors can normally withstand higher temperature levels compared to wound rotors. The motor windings, especially if insulation is class B or below, are also susceptible to damage due high levels of *dv/dt*(i.e., rate of rise of voltage) such as those attributed to line notching and associated ringing due to the flow of harmonic currents.

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, 11th, 17th…) will act against the direction of rotation resulting in torque pulsations. Zero sequence components (i.e., triplen harmonics) are stationary and do not rotate, therefore, any harmonic energy associated with them is dissipated as heat.
The magnitude of torque pulsations generated due to these harmonic sequence components can be significant and cause shaft torsional vibration problems.

2.10.3 Transformers

The effect of harmonic currents at harmonic frequencies causes increase in core losses due to increased iron losses (i.e., eddy currents and hysteresis) in transformers. In addition, increased copper losses and stray flux losses result in additional heating, and winding insulation stresses, 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. The small laminated core vibrations are increased due to the presence of harmonic frequencies, which can appear as an additional audible noise.

The increased RMS current due to harmonics will increase the *I2R* (copper) losses.

The distribution transformers used in four-wire (i.e., three-phase and neutral) distribution systems have typically a delta-wye configuration. Due to delta connected primary, the 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 at a frequency of predominately 180 Hz (3rd harmonic), overheating the transformers and occasionally causing overheating and burning of neutral conductors. Typically, the uses of appropriate “K factor” rated units are recommended for non-linear loads.

2.10.4 Other negative effects of harmonics:

a) Power factor correction capacitors are generally installed in industrial plants and commercial buildings. Fluorescent lighting used in these facilities also normally has capacitors fitted internally to improve the individual light fittings own power factor. The harmonic currents can interact with these capacitances and system inductances, and occasionally excite parallel resonance which can over heat, disrupt and/or damage the plant and equipment.

b) 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.

c) Any telemetry, protection or other equipment which relies on conventional measurement techniques or the heating effect of current will not operate correctly in the presence of nonlinear loads. The consequences of under measure can be significant; overloaded cables may go undetected with the risk of catching fire. Bus bars and cables may prematurely age.

d) 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.[17]

CHAPTER THREE

METHODOLOGY

3.1 Tools Overview

There are tools which will be used for the effective implementation of this project, they include MATLB tool and Simulink tool.

3.1.1 MATLAB

MATLAB which derives its name from Matrix Laboratory, is a computing language devoted to processing data in the form of arrays of numbers. MATLAB integrates computation and visualization into a flexible computer environment, and provides diverse family of built-in functions that can be used in a straightforward manner to obtain numerical solutions to a wide range of engineering problems .[18]

3.1.2 Simulink

Simulink is a block diagram environment for multi domain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB, enabling you to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis.

Simulink has large library of component, many of them is used in this project. The following component is mentioned

1. Three phase Source

Implement an ideal sinusoidal voltage source The generated voltage **U** is described by the following relationship:

$U=A \sin(\omega t+\phi)$ $\omega=2\pi f$, ϕ=Phase in radians.

The figure below represents three phase source

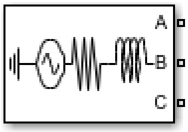

Fig 3.1: Three phase source

2. Universal bridge

Implement a universal three-phase power converter that consists of up to six power switches connected in a bridge configuration. The type of power switch and converter configuration are selectable from the dialog box.

The Universal Bridge block allows simulation of converters using both naturally commutated (or line-commutated) power electronic devices (diodes or Thyristors) and forced-commutated devices (GTO, IGBT, MOSFET). The figures below show IGBT bridge and Diode bridge.

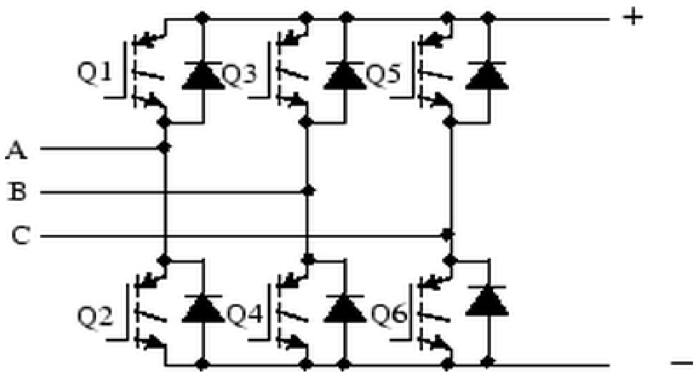

Fig 3.2: IGBT bridge

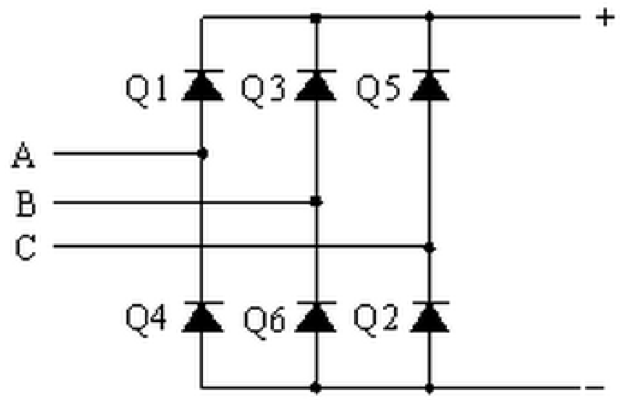

Fig 3.3: Diode bridge

-Number of bridge arms

The bridge arms were Set to 3 to get a three-phase converter connected in Graetz bridge configuration (six switching devices).

-Snubber resistance Rs

The snubber resistance, in ohms (Ω). Default is 1e5. the Snubber resistance Rs parameter was set to inf to eliminate the snubbers from the model.

-Snubber capacitance Cs

The snubber capacitance, in farads (F). Default is inf. the Snubber capacitance Cs parameter was set to 0 to eliminate the snubbers, or to inf to get a resistive snubber.

the continuous solver was used so snubbers was eliminated in all power electronic devices

-Ron

Internal resistance of the selected device, in ohms (Ω). Default is 1e-3.

-Lon

Internal inductance, in henries (H), for the diode or the thyristor device. Default is 0. When the bridge is discretized, the Lon parameter must be set to zero.

-Forward voltage Vf

This parameter is available when the selected Power electronic device is Diodes. Forward voltage, in volts (V), across the device when it is conducting. Default is 0.

-Forward voltages [Device Vf, Diode Vfd]

This parameter is available when the selected Power electronic device is IGBT/Diodes. Forward voltages, in volts (V), of the forced-commutated devices (GTO, MOSFET, or IGBT) and of the antiparallel diodes. Default is [0 0].

3. PWM Generator (2-level)

The PWM Generator (2-Level) block generates pulses for carrier-based pulse width modulation (PWM) converters using two-level topology. The Fig (3.4) below represents block PWM Generator, was used to control switching device (IGBTs) of three different converter types: single-phase half-bridge (1 arm), single-phase full-bridge (2 arms), or three-phase bridge (3 arms).

Fig 3.4: PWM Generator (2-Level) block

The reference signal (Uref input), also called modulating signal, is compared with a symmetrical triangle carrier. When the reference signal is greater than the carrier, the pulse for the upper switching device is high (1), and the pulse for the lower device is low (0).

-Generator type

The number of pulses generated by the block is proportional to the number of bridge arms to fire.to fire the self-commutated devices of a three-phase bridge converter 6 pulses were required. Pulses 1, 3, and 5 fire the upper devices of the first, second, and third arms. Pulses 2, 4, and 6 fire the lower devices.

-Mode of operation

The mode of operation is set to unsynchronized that mean the frequency of the unsynchronized carrier signal is determined by the Frequency parameter.

-Carrier Frequency (Hz)

Specify the frequency, in hertz, of the triangular carrier signal. Default is 27*60. This parameter is available only if the Mode of operation parameter is set to Unsynchronized.

-Initial phase (degrees)

Specify the carrier initial phase, in degrees. Default is 90. A value of 90 degrees means that the triangle carrier initial position is set to midpoint between its minimum and maximum value and the slope is positive.

-Internal generation of the reference signal

When selected, the reference signal is generated by the block. Default is cleared. This parameter is available only if the Mode of operation parameter is set to Unsynchronized.

The following parameters will be available only when the Internal generation of the reference signal parameter is selected.

-Modulation index

Specify the modulation index to control the amplitude of the fundamental component of the output voltage of the converter. The modulation index must be greater than 0 and lower than or equal to 1. Default is 0.8.

-Frequency (Hz)

Specify the output voltage frequency used to control the frequency of the fundamental component of the output voltage of the converter. Default is 60

-Phase (degrees)

Specify this parameter to control the phase of the fundamental component of the output voltage of the converter. Default is 0.

-Sample time

Specify the sample time of the block, in seconds. It was set to 0 to implement a continuous block. Default is 0.

- Characteristics of a PWM generator

Generator type Three-phase bridge (6 pulses)

Mode of operation Unsynchronized

Carrier frequency 2000 Hz

Internal generation of modulating signals Selected

Modulation index m 0.8

Output voltage frequency 60 Hz

Output voltage phase

Sample time 0

4. Asynchronous machine (induction machine)

The Asynchronous Machine block implements a three-phase asynchronous machine (wound rotor, single squirrel-cage, or double squirrel-cage). It operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque If Tm is positive, the machine acts as a motor. If Tm is negative, the machine acts as a generator. Figure below represents Squirrel-cage induction machine.

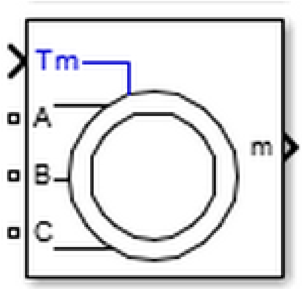

Fig 3.5: Squirrel-cage induction machine

-Rotor type

Rotor type parameter was set to Squirrel-cage. [01: 5 HP 460 V 60Hz 1750 RPM] these set was chosen for a set of predetermined electrical and mechanical parameters for various asynchronous machine ratings of power (HP), phase-to-phase voltage (V), frequency (Hz), and rated speed (rpm).

-Mechanical input

Torque Tm (default) was selected to specify a torque input, in N.m. The machine speed is determined by the machine Inertia J and by the difference between the applied mechanical torque Tm and the internal electromagnetic torque Te. The sign convention for the mechanical torque is: when the speed is positive, a positive torque signal indicates motor mode and a negative signal indicates generator mode.

When rotor type parameter was set to Squirrel-cage the following parameters appear

-Nominal power, voltage (line-line), and frequency

The nominal apparent power S (VA), RMS line-to-line voltage Vn (V), and frequency fn (Hz). Default is [1.845e+04 400 50]

-Stator resistance and inductance

The stator resistance Rs (Ω or pu) and leakage inductance Lls (H or pu). Default is [0.5968 0.0003495]

-Rotor resistance and inductance

The rotor resistance Rr' (Ω or pu) and leakage inductance Llr' (H or pu), both referred to the stator. Default is[0.6258 0.005473]

-Mutual inductance

The magnetizing inductance Lm (H or pu). Default is 0.0354

-Inertia constant, friction factor, and pole pairs

For the SI units' dialog box: the combined machine and load inertia coefficient J ($kg.m^2$), combined viscous friction coefficient F (N.m.s), and pole pairs p. The friction torque Tf is proportional to the rotor speed ω (Tf = F.w). Default is [0.05 0.0058792].

-Initial conditions

Specifies the initial slip s, electrical angle Θe (degrees), stator current magnitude (A or pu), and phase angles (degrees):

[slip, Θe, i_{as}, i_{bs}, i_{cs}, $phase_{as}$, $phase_{bs}$, $phase_{cs}$]

Default is [0 0 0 0 0 0 0 0]

5. Series RLC Branch

The Series RLC Branch block implements a single resistor, inductor, or capacitor, or a series combination of these. Fig (3.6) below represents Series RLC Branch. The **R** letter defines the resistor in ohms (Ω). Default is 1. the **L** letter defines the inductor, in henries (H). Default is 1e-3. and the **C** letter defines the capacitor, in farads (F). Default is 1e-6.

Fig 3.6: Series RLC Branch

6. Scope

The Scope block displays time domain signals with respect to simulation time. Here are some configuration properties

-Number of input ports

Specify number of input ports on a Scope block, specified by an integer. Maximum number of input ports is 96. This property does not apply to floating scopes and scope viewers.

-Layout button

Specify number and arrangement of displays. The maximum layout is 16 rows by 16 columns. If the number of displays are equal to the number of ports, signals from each port appear on separate displays. If the number of displays are less than the number of ports, signals from additional ports appear on the last display. Figure below represents scope block

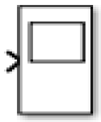

Fig 3.7: Scope

7. Current Measurement

The Current Measurement block shown in Fig (3.8) below is used to measure the instantaneous current flowing in any electrical block or connection line.

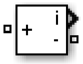

Fig 3.8: Current Measurement

8.Voltage Measurement

The Voltage Measurement block shown in Fig (3.9) below measures the instantaneous voltage between two electric nodes.

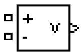

Fig 3.9: Voltage Measurement

3.2 Mitigation Techniques

When VSD is used there will be a need for the addition of mitigation equipment in order to attenuate the harmonic currents and associated voltage distortion to within the necessary limits. Users of adjustable speed drives (ASD) have many choices available when it comes to harmonic mitigation. In the consideration of various alternatives, much depends on the user's objectives as well as the severity of harmonics contributed by internal loads. The typical list of alternative three phase harmonic mitigation equipment includes:

.3.2.1 Passive filters:

Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics. They are commonly used and are relatively inexpensive compared with other means for eliminating harmonic distortion. However, they have the disadvantage of potentially interacting adversely with the power system and it is important to check all possible system interactions when they are designed. They are employed either to shunt the harmonic currents off The line or to block their flow between parts of the system by tuning the Elements to create a resonance at a selected frequency.

3.2.1.1 Single-tuned (notch) filter:

The most common type of passive filter is the single-tuned “notch” filter. This is the most economical type and is frequently sufficient for the application. The notch filter is series-tuned to present low impedance to a particular harmonic current and is connected in shunt with the power system. Thus, harmonic currents are diverted from their normal flow path on the line through the filter.

Notch filters can provide power factor correction in addition to harmonic suppression. In fact, power factor correction capacitors may be Used to make notch filters. Fig (3.10) below shows the components of single tuned filter.[1]

Fig 3.10: Single-tuned filter

-Calculations for the components:

the net wye equivalent filter reactance (capacitive) X_{filt} is determined by:

$$X_{filt} = \frac{KV^2}{Qc} \quad (3.1)$$

Where:

X_{filt}= net wye equivalent filter reactance.

V = fundamental RMS phase voltage.

Q_c = Required Compensation (reactive power) from filter.

Where Q_c is given by:

$$Q_c=P(\tan(PF_{old})-\tan(PF_{new})) \quad (3.2)$$

Where:

P = single phase power.

PF_{old} = old Power factor of the system.

PF_{new} = new desired power factor of the system.

$$X_{cap} = \frac{h^2 * X_{filt}}{h^2-1} \quad (3.3)$$

Where:

X_{cap} = the capacitive reactance.

h =harmonic tuned order of the filter.

The filter reactor size is computed from the wye – equivalent capacitive reactance as follows

$$X_L = \frac{X_{cap}}{h^2} \tag{3.4}$$

$$L = \frac{X_L}{2*pi*f} \tag{3.5}$$

Where:

X_L= the filter reactor at fundamental frequency.

L = the Inductance of the filter reactor.

f = the fundamental frequency.

-Filter added external resistance:

Filter should be provided by an external resistance, connected in series with the filter capacitor and reactor. External resistance is difference between total resistance and reactor resistance. Generally, Q_{optm} ranges between (35 to 45), while Q_{coil} lies in the range of 100.The reactor resistance is calculated on the base of Q_{coil}. total resistance R_t is calculated with this optimum quality factor Q_{optm}. External resistance is calculated by:

$$R_{coil} = \frac{X_L}{Q_{coil}} \tag{3.6}$$

$$R_t = \frac{X_L}{Q_{optm}} \tag{3.7}$$

$$R_{external} = R_t - R_{coil} \tag{3.8}$$

Where:

R_{coil}=the Reactor coil resistance,

R_t= the total resistance of the filter.

$R_{external}$= the external resistance of the filter which must be added to the filter.

$$R_{external} = R_t - R_{coil}$$

The resonance condition will occur when capacitive reactance is equal to inductive reactance as:

$X_c=X_L$

The characteristic of the single tuned filter is given in Fig (3.11) below [19]

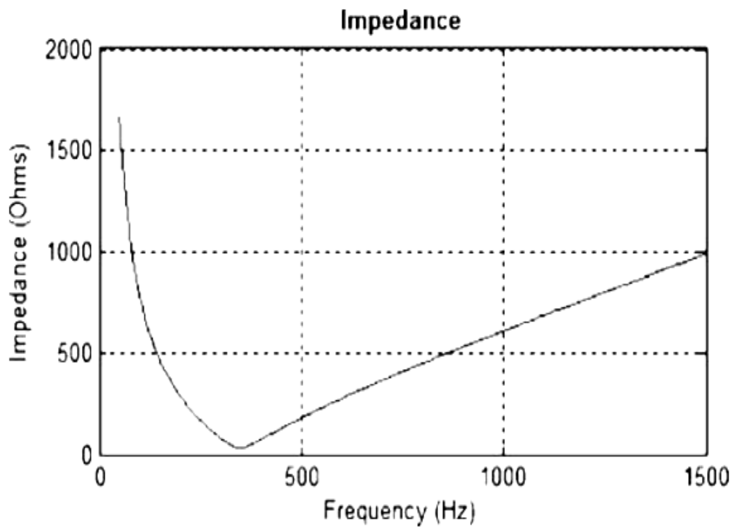

Fig 3.11: The characteristic of the single tuned Filter

3.2.1.2 Double-tuned filter:

These are filters which are tuned to two frequencies or to three frequencies simultaneously. Designs of these filters are usually made as two separate single tuned filters. Then the corresponding values of double tuned filter are to be found.

The elements of double tuned filter can be found as a function in the corresponding two single tuned filters elements (R_1,L_1,C_1) and (R_2,L_2,C_2 and R_3) as follows:

Two single-tuned filters tuned to different frequencies, are substantially identical, in terminal impedance, near the resonant frequencies, to a double tuned filter in the arrangements of Fig (3.12) below

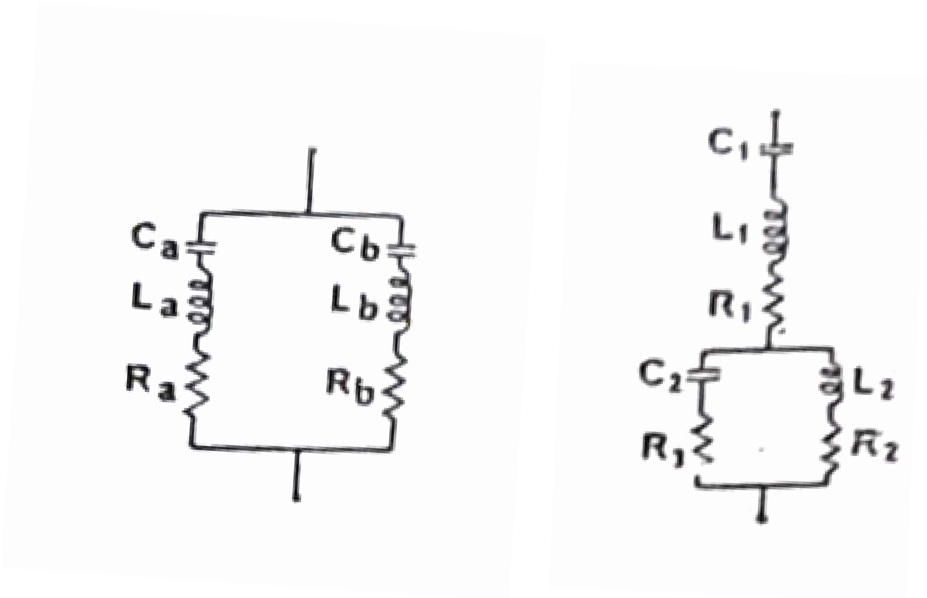

Fig 3.12: Components of double tuned filter constructed from two single tuned filters

The characteristic of the double tuned Filter is given by the Fig (3.13) below

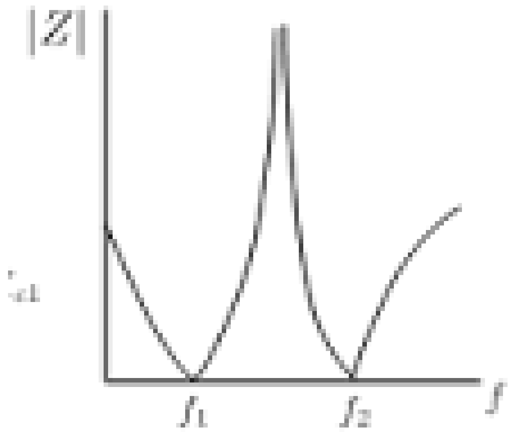

Fig 3.13: The characteristic of the double tuned Filter

-Calculating Components of double tuned filter:

$$C_1 = C_a + C_b \quad (3.9)$$

$$C_2 = \frac{C_a C_b (C_a + C_b)(L_a + L_b)^2}{(L_a C_a - L_b C_b)^2} \quad (3.10)$$

$$L_1 = \frac{L_a L_b}{L_a + L_b} \quad (3.11)$$

$$L_2 = \frac{(L_a C_a - L_b C_b)^2}{(C_a + C_b)^2 (L_a + L_b)} \quad (3.12)$$

$$R_2 = R_a \left[\frac{a^2(1-x^2)}{(1+a)^2(1+x^2)}\right] - R_b \left[\frac{(1-x^2)}{(1+a)^2(1+x^2)}\right] + R_1 \left[\frac{a(1-a)(1-x^2)}{(1+a)^2(1+x^2)}\right] \quad (3.13)$$

$$R_3 = -R_a\left[\frac{a^2x^4(1-x^2)}{(1+ax^2)^2(1+x^2)}\right] + R_b\left[\frac{(1-x^2)}{(1+ax^2)^2(1+x^2)}\right] + R_1\left[\frac{a(1-x^2)(1-ax^2)}{(1+x^2)(1+ax^2)}\right]$$
(3.14)

Where

$$a = \frac{C_a}{C_b} \tag{3.15}$$

And

$$x = \sqrt{\frac{L_b C_b}{L_a C_a}} \tag{3.16}$$

This filter has the same complex impedance of two parallel single-tuned filters, at all frequencies.

The main advantage of double tuned filter is the reduction in number of Indictors subject to full line impulse voltage, this is advantage in high voltage systems. A better practical method is to omit R_1 in double tuned circuit, although R_1 is not provided, the Indictor L_1 has some inherent physical resistance near the resonant frequency, which covers for the value of R_1 in the above equations.

Passive filters should always be placed on a bus where the short-circuit reactance X_{SC} can be expected to remain constant. While the notch frequency will remain fixed.

Series filters must carry full load current and be insulated for full line voltage, in contrast shunt filters can be designed for whatever rating needed, they are less expensive and can also provide reactive power at the fundamental frequency. Therefor it is usually more practical to use shunt filters.

-Disadvantages of passive filters:

-The source impedance strongly effects filtering characteristics.

-When the harmonic current components increases, the filter might get overloaded.

-Parallel resonance between the power system and the passive filters causes amplifications of harmonic currents on the source side at a specific frequency and lead to equipment damages.

-The passive filter may fall into series resonance with the power system so that voltage distortion produces excessive harmonic currents flowing into passive filter, which can damage it.[20]

3.2.1.3 Tuned multiple arm passive filters:

The principle of this filter is shown in Fig (3.14) below. This filter has several arms tuned to two or more of the harmonic components which should be the lowest significant harmonic frequencies in the system. The multiple filter has better harmonic absorption than the one arm type.

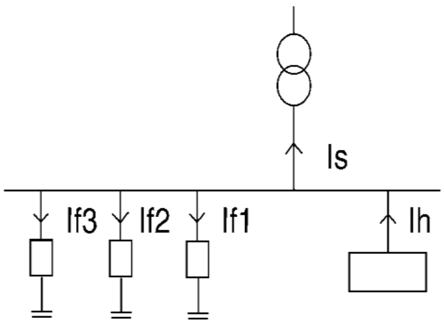

Fig 3.14: Tuned multiple arm passive filter

-Advantages:

-Capacitive below tuned frequency/Inductive above

Better harmonic absorption.

-The design puts in considerations the amplification of harmonics by the filter.

-Disadvantages:

-Limited by KVAR of the network.[21]

3.2.2 Reactors:

In electrical variable speed drives, reactors are used in both AC and DC types. They are often used in addition to other harmonic mitigation methods. On AC drives, reactors are used on the AC line side called AC line reactors, in the DC bus called DC reactors**.**

3.2.2.1 Input AC line reactor:

AC line reactor is simply a three phase coil placed in series between the source and the variable frequency drive (VFD), the calculation of the ac line reactor depends on the percentage impedance of the line (percentage of the voltage drop) 3% to provide damping and protection to the drive from power system disturbances, 5% to provide harmonic mitigation. AC line reactor is shown in Fig (3.15) below.

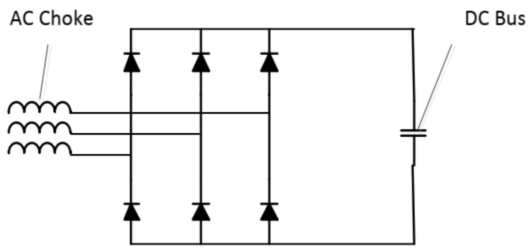

Fig 3.15: Input AC line reactor

$$L_{ac} = Z\% * \frac{V_{\emptyset}}{\sqrt{3} * 2\pi * f * I_{ac}} \tag{3.17}$$

AC line inductance equation

Where:

L_{ac}= inductance of the 3-phase reactor.

Z %= percentage impedance of the line.

$V_{\emptyset}$= AC line phase voltage.

f= AC source frequency.

I_{ac}= AC line current.

3.2.2.2 DC link reactor:

DC link reactor (Chock) is an inductor placed in the variable frequency drive between the rectifier and the inverter, the DC choke needs to be twice as much as the AC line reactor in order to provide the same effect.

$$L_{dc} = 2 * Z\% * \frac{V_{\emptyset}}{\sqrt{3} * 2\pi * f * I_{ac}} \tag{3.18}$$

DC link inductance equation

Where:

L_{dc} = inductance of the DC link.

Therefor the DC choke reactor is distributed into two equal inductors on the positive and negative terminals of the rectifier.as shown in Fig (3.16). [22, 23]

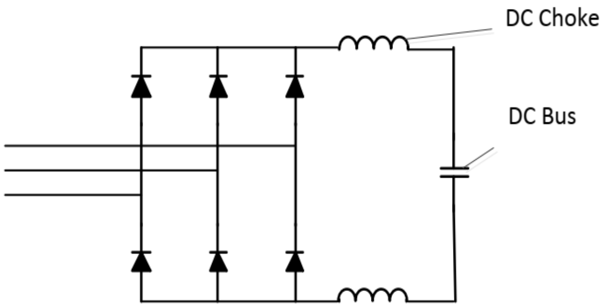

Fig 3.16: DC link Choke

3.2.3 12-pulse drive:

Fig (3.17) shows a basic block diagram for a variable frequency drive. Three phase power is applied to the converter. The converter transforms the three phase power into DC. Then the DC is applied to the inverter which transforms the DC into variable fundamental frequency pulse width modulated AC power that powers the motor

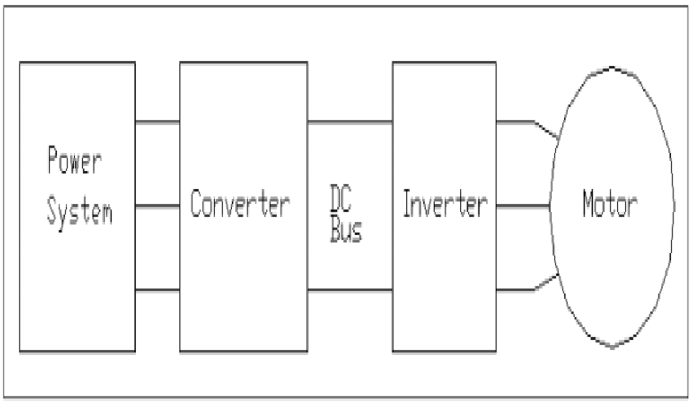

Fig 3.17: Basic VFD block diagram

Fig (3.18) shows the power system and converter for a 6-pulse converter. The Power system is typically a wye connected transformer secondary. The wye connection has three voltages that are 120° out of phase, and the converter has six rectifiers. The theoretical input current harmonics for rectifier circuits are a function of pulse number.

$h = (np +/-1)$

Where: n=1, 2, 3……

p =pulse number

The theoretical lowest harmonic for a six pulse converter is the fifth.

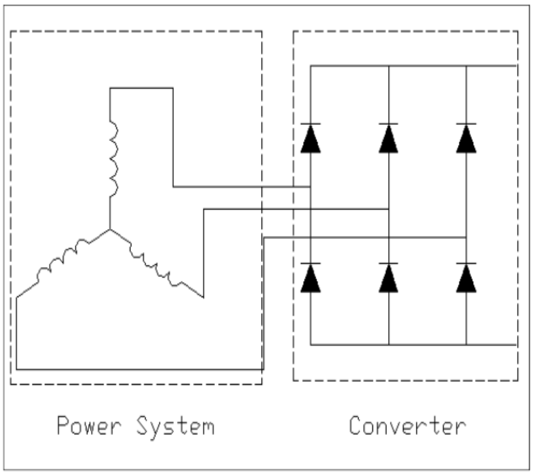

Fig 3.18: Six pulse power system and converter

Fig (3.19) shows a vector representation of the three phase power system voltages. When the power system provides balanced three phase power, the 6-pulse converter performs close to the theoretical harmonic performance. The three phases on the secondary of the typical delta-wye transformer provides balanced power to the converter.[24]

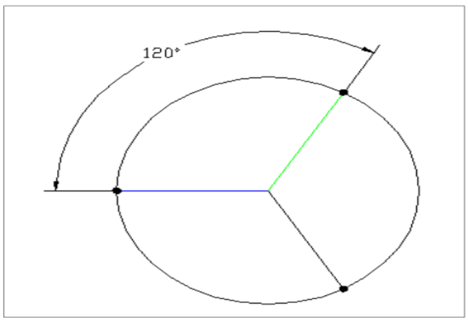

Fig 3.19: Three phase power system voltage vector representation

- Phase Shifting and harmonic:

Phase shifting involves separating the electrical supply into two or more outputs; each output being phase shifted with respect to each other with an appropriate angle for the harmonic pairs to be eliminated. The concept is to displace the harmonic current pairs in order to bring each to a 180° phase shift so that they cancel each other out. Positive-sequence currents will act against negative-sequence currents, whereas zero-sequence currents act against each other in a three-phase system. Triplen harmonics are zero-sequence vectors; 5th, 11th and 17^{th} harmonics are negative-sequence vectors, and 7th, 13th and 19th harmonics are positive-sequence vectors. Hence, an angular displacement of:

60° is required between two three phase outputs to cancel the 3rd harmonic currents.

30° is required between two three phase outputs to attenuate the 5th and 7th harmonic current pairs.

15° is required between two three phase outputs to cancel the 11th and 13th harmonic current pairs. [25]

For a six-pulse rectifier, the input current will have harmonic components at the following multiples of the fundamental frequency.

5, 7 , 11 , 13 , 17 , 19 , 23 , 25 , 29 , 31 , etc.

For the twelve-pulse system shown in Fig (3.20), the input current will have theoretical harmonic Components at the following multiples of the fundamental frequency:

11, 13, 23, 25, 35, 37, etc

Note that the 5th and 7th harmonics are absent in the twelve-pulse system. Since the magnitude of each harmonic is proportional to the reciprocal of the harmonic number, the twelve-pulse system has a lower theoretical harmonic current distortion. [26]

- 12-pulse VFDs general form:

as shown in Fig (3.20) consists of 12-pulse rectifier, formed by connecting two six-pulse rectifiers in parallel to feed the same dc bus voltage. These rectifiers are fed through a transformer with two secondary windings: one Δ and one y.[27]

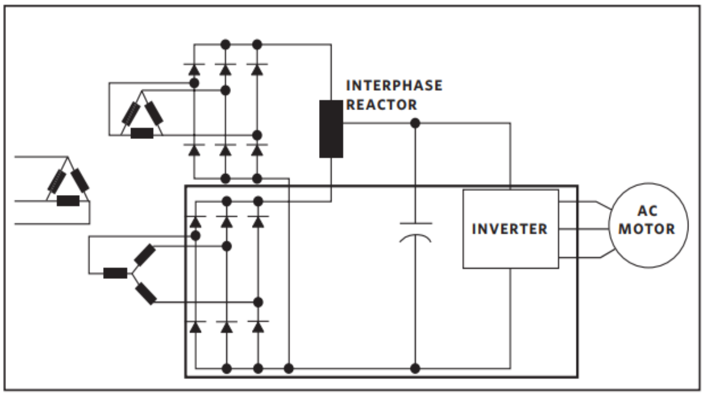

Fig 3.20: Schematic of 12-pulse VFD with one primary transformer and two secondary transformers

The problem with the circuit shown in Fig (3.20) is that the two rectifiers must share the exact current to achieve the theoretical reduction in harmonics. This requires that the output voltage of both transformer secondary windings to match exactly. Because of differences in the transformer secondary impedances and open circuit output voltages, this can be practically accomplished for a given load (typically rated load) but not over the range. This is a very significant problem of the parallel twelve-pulse configuration.

A twelve-pulse system can also be constructed from two six-pulse rectifiers connected in series. In this configuration, two six-pulse rectifiers, each generating one half of the DC link voltage, are series connected as shown in Fig (3.21). return to Fig (3.20) In this connection, problems associated with current sharing are avoided and an interphone reactor is not required. For applications where harmonics rather than high current ratings are the issue, this solution is much simpler to implement than the parallel connection.

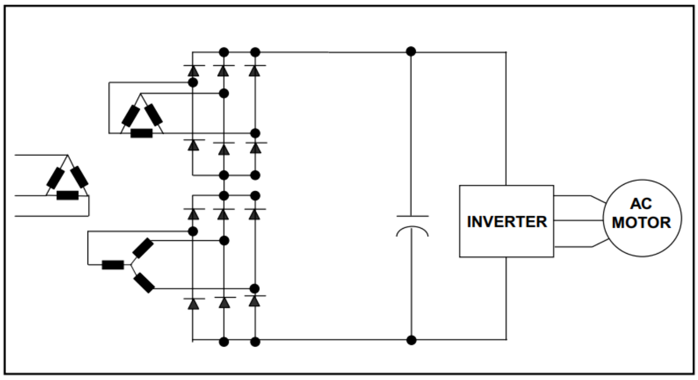

Fig 3.21: Series connection of 12-pulse ac drive with its transformer connection

- 12-pulse drive from a standard 6-pulse drive:

Using the series rectifier connection, makes it very easy to construct a twelve-pulse drive from a standard six pulse drive if the six-pulse drive has its DC bus terminals available or permits access to one side of the DC bus. Many standard AC drives provide terminals in the DC bus to accommodate an external DC link choke. These same terminals can be used to add an external rectifier converting the drive to twelve-pulse operation as shown in Fig (3.22). return to Fig (3.21) In this case there is no need for extra circuitry to control inrush current for the second rectifier. The net result is a system solution well within the means of many system integrators. [26]

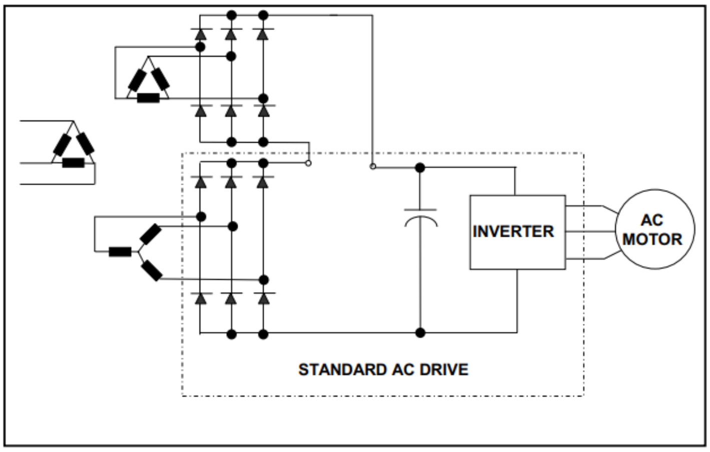

Fig 3.22: 12-pulse drive built from a standard 6-pulse drive

3.2.4 Switching frequency

In order to provide proper speed control of an AC motor, it is necessary to supply the motor with a three phase supply of which both the voltage and the frequency can be varied. [28]

Pulse-Width Modulation (PWM) is a technique which varies the width of a fixed signal by modulating pulse duration to represent a variable analog signal. PWM is applied to VFD's by using the fixed DC voltage from the VFD's DC bus capacitors. A set of Insulated Gate Bi-polar Transistors (IGBT's) on the output rapidly open and close to produce pulses. By varying the width of the output pulses in the output voltage waveform, a simulated AC sine wave is constructed See Fig (3.23). Even though the drives output voltage waveform consists of square waves due to DC pulsing, the current waveform will be sinusoidal since the motor is inductive.[29]

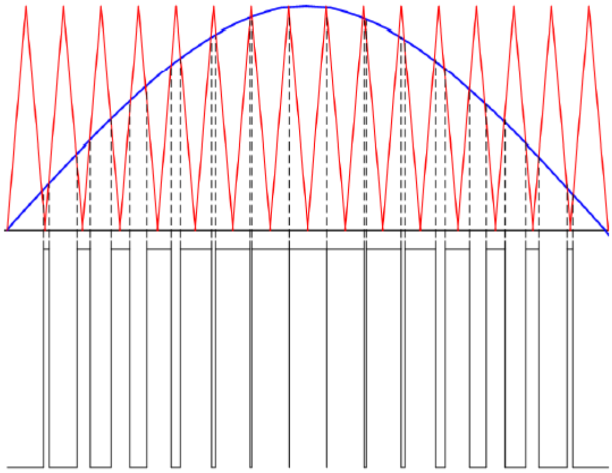

Fig 3.23: Pulse Width Modulation which used to Control an AC Motor

There are various techniques to vary the inverter gain. The most efficient method of controlling the inverter's output voltage is to incorporate pulse width modulation (PWM) control within the inverters. The used techniques in this project is Sinusoidal pulse width modulation.

- Sinusoidal pulse width modulation

In the carrier-based sinusoidal PWM method (SWPM), three-phase sinusoidal waves, are used for the modulating or control signal and compared with a high frequency triangular wave. One common triangular wave is used for the comparison for all three phases. The upper switch of leg A is ON when the modulating signal of phase A is greater than the amplitude of the triangular carrier wave, i.e. $V_{Am} \geq Vc$ The lower switch has a complimentary operation. This is shown in Fig (3.24) below which represents SPWM of a three-phase inverter this type of modulation is commonly used in industrial applications and abbreviated as SPWM.[30]

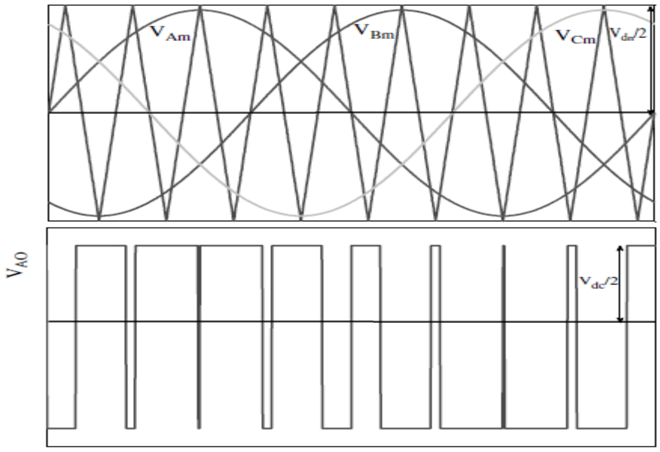

Fig 3.24: SPWM of a three-phase inverter

The inverter consists of three pairs of semiconductor switches (IGBT) with associated diodes. Each pair of switches provides the power output for one phase of the motor.

3.2.5 Motor side filter (sine filter)

The main goal of the sine filter is to transform the output of the PWM inverter into a smooth sinusoidal output entering the motor terminals in both current and voltage waveforms, they are designed to let low frequencies pass and high frequencies get shunted minimizing the stress on the motor and extending its lifetime. [31]

The filter eliminates the pulse reflections in the motor cable thus reducing the losses in the frequency converter, also it reduces the losses in the motor (hysteresis and eddy current losses) which are elevated by the harmonic content of the input voltage and current, Sine wave filters usually have a better performance compared to dv/dt chokes or dv/dt filters. [31, 32]

Sine filters are usually used for motor drives with long motor cable and motor drives with multiple motors in parallel. [32]

Advantages

• Protects the motor against voltage peaks hence prolongs the lifetime.

• Reduces the losses in the motor.

• Eliminates acoustic switching noise from the motor.

• Reduces semiconductor losses in the drive with long motor cables.

• Decreases electromagnetic emissions from motor cables by eliminating high frequency ringing in the cable.

• Reduces electromagnetic interference from unscreened motor cables.

• Reduces the bearing current thus prolonging the lifetime of the motor. [31]

Fig (3.25) below represents sine filter block diagram.

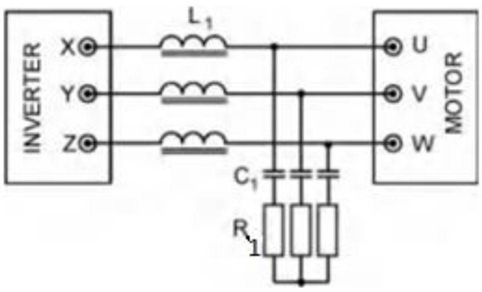

Fig 3.25: Sine filter

The calculation of the filter's inductance is as previously explained in the AC line reactor calculation with the percentage of the voltage drop set to 5% for harmonic mitigation.

The capacitor on the other hand is calculated through the resonance frequency which can be estimated from the equation below:

$$10f_{out} < f_{res} < \frac{1}{2}f_{sw} \qquad (3.19)$$

It is advised that the resonance frequency should be in between (2.5 to 3) times less than the switching frequency.

Where:

f_{out} = The fundamental output frequency.

f_{res} = The resonance frequency of the system.

f_{sw}= The inverter's switching frequency.

$$C_1 = \frac{1}{4\pi^2 * f_{res}{}^2 * L_1} \tag{3.20}$$

where:

C_1 = The filter capacitance.

L_1 = The filter inductance.

To calculate the resistance of the filter quality factor of the filter (Q) must be estimated which should be in range (5-8). [30]

$$Q = \frac{Z_0}{R_1} \tag{3.21}$$

Where:

Z_0 = The natural frequency of the filter.

R_1 = The filter's resistance.

$$Z_0 = \sqrt{\frac{L_1}{C_1}} \tag{3.22}$$

The resistance (R_1) is a damping element that protects the system from oscillation and voltage flickers. And can be neglected in the absence of high order harmonics to provide a less expensive filter, thus not to complicate the calculations it is neglected. [30]

3.2.6 Motor side reactor

the topology of the motor side reactor is the same as the source line reactor except in this case MATLAB/SIMULINK requires an additional component which is a parallel high resistance due to MATLAB'S illustration of the block of asynchronous motor as a current source.

Otherwise the calculations and implementation are the same as the input AC line reactor.

3.3 IEEE Standard 519

ANSI/IEEE Standard 519, IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters, was published in 1981. It recommended maximum levels of total-harmonic-voltage-distortion (THDV) at the point that the

utility connects to different types of users (point of common coupling, or PCC), shown in Figure 2. Different maximum levels were provided for different types of buildings EEE-519 was revised in 1992 to provide recommendations on maximum allowable levels of harmonic current distortion (see Figure 6). The new standard also defined the maximum recommended contribution of any individual harmonic.

The amount of allowable distortion is based on a ratio of the short circuit current available to the distribution system (ISC –maximum short circuit current available at point of common coupling), and the maximum load current recognized by the distribution system (Il – the maximum load current at the point of common coupling).

Table 3.1: IEEE STD 519 for voltage distortion limits.

Bus voltage V at PCC	**Individual harmonic (%)**	**Total harmonic distortion THD (%)**
V ≤ 1.0 kV	5.0	8.0
1 KV < V ≤ 69 kV	3.0	5.0
69 KV < V ≤ 161 KV	1.5	2.5
161 KV < V	1.0	1.5

Table 3.2: Current distortion limits for system rated 120 V through 69 kV.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
<20	4.0	2	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

CHAPTER FOUR

THE RESULTS

In previous chapter different type of harmonic reduction techniques used with AC drive were cleared-up, also equations used for designing different types of filters and reactors. Also presented a 6-pulse AC drive and explain its components.

In this Chapter practical design of different types of harmonic reduction techniques will be presented, And the calculations of components of mitigation techniques will be established, finally simulation will be done by MATLAB/Simulink program and the results will be extracted and analyzed for each method.

The following figure represents the model of VFD used in MATLAB/Simulink program.

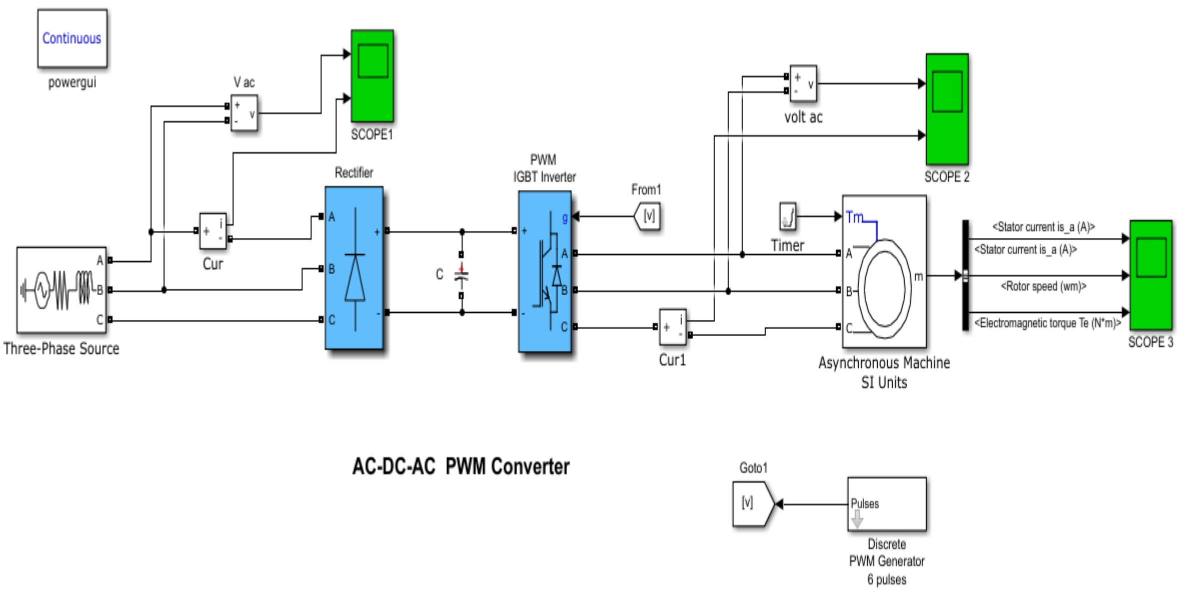

Fig 4.1: Model of VFD using MATLAB/Simulink program

Fig (4.2) below shows voltage and current waveforms of 6-Pulse drive with no mitigation technique.

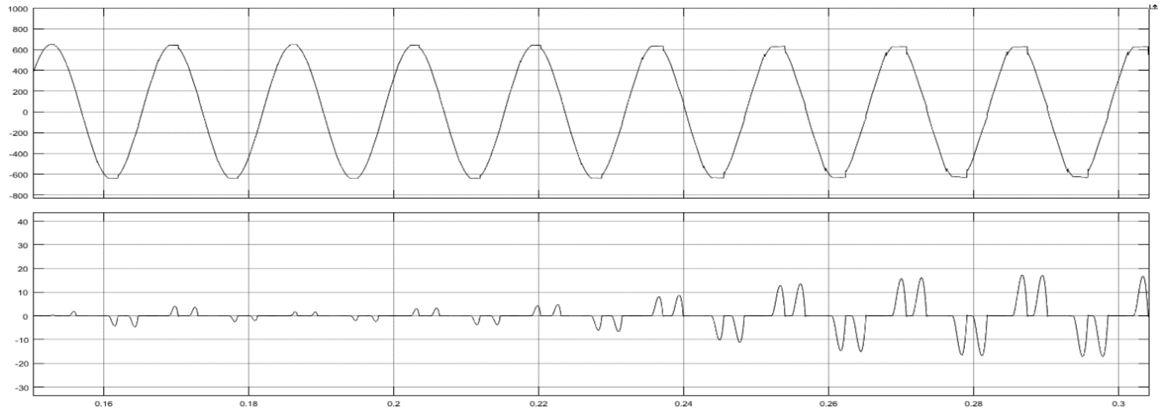

Fig 4.2: Voltage and current waveforms of supply side for 6 pulses VFD

In Fig (4.3) below it can be noticed that the value of THDI is high (95.53%) and that proves that AC drive is one of the largest harmonic sources in the electrical network. From the harmonic spectrum of Fig (4.3) it is clearly that the 5th, 7th, 11th and 13th are the dominant harmonics.

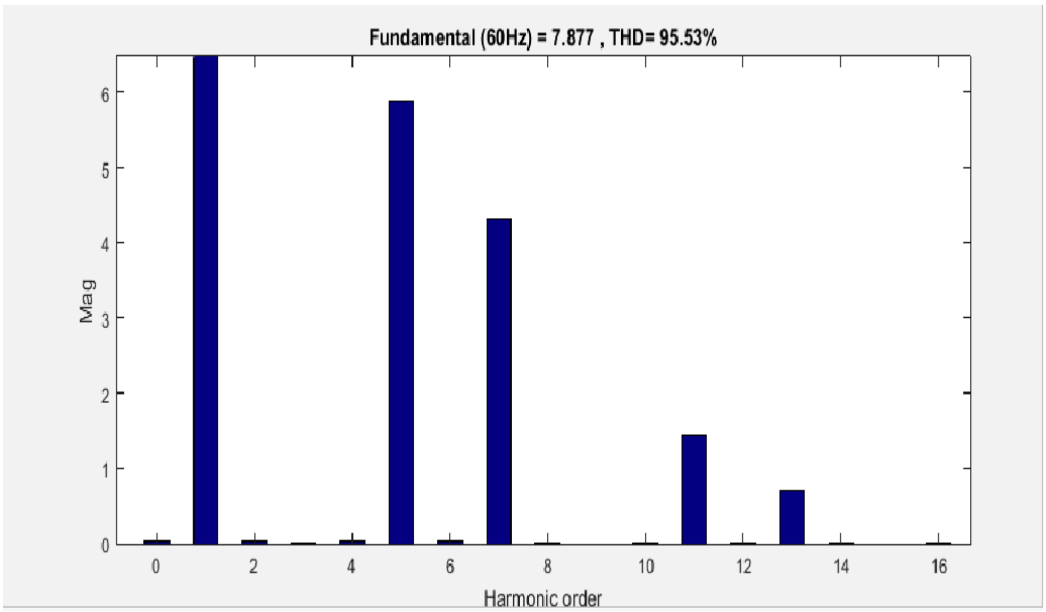

Fig 4.3: Harmonic spectrum for current of supply side of VFD

The reason for this large value of THD is the present of two harmonic generating non-linear loads (Rectifier and inverter). These two devices draw high non-linear current which distorts the source's current waveform.

In Fig (4.4) below it is noted that the value of THDV is low (small) and the reason for that is the source Impedance, the voltage distortion is mainly caused by the non-linear drop in voltage at the source impedance. And because the source impedance is small that in return makes the THDV small.

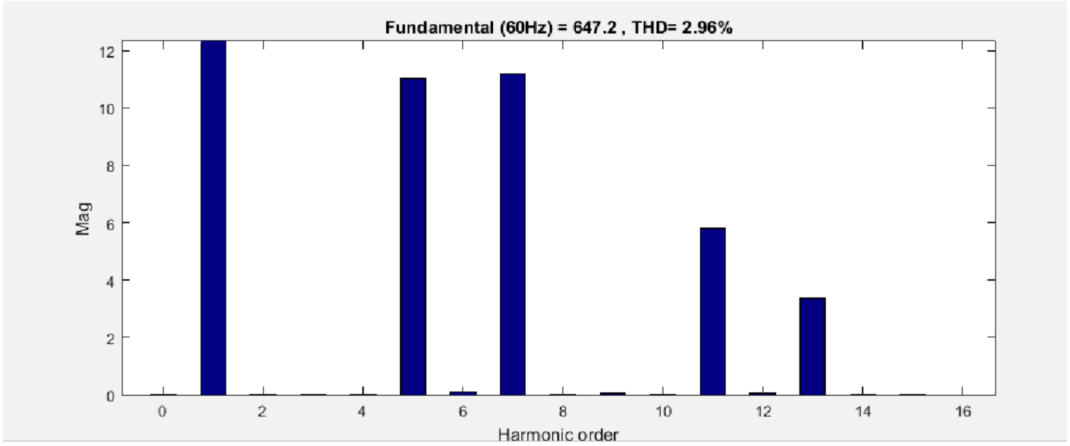

Fig 4.4: Harmonic spectrum for voltage of supply side of VFD

This small value of THDV meets the IEEE 519 standard (2014) but the value of the current distortion does not meet the standard, because of this high distortion harmonic mitigation techniques have to be implemented to solve this problem.

As shown in Fig (4.5) below the voltage waveform is basically constructed of pulses generated by high switching inverter using SPWM technique which is the reason for this high level of voltage distortion.

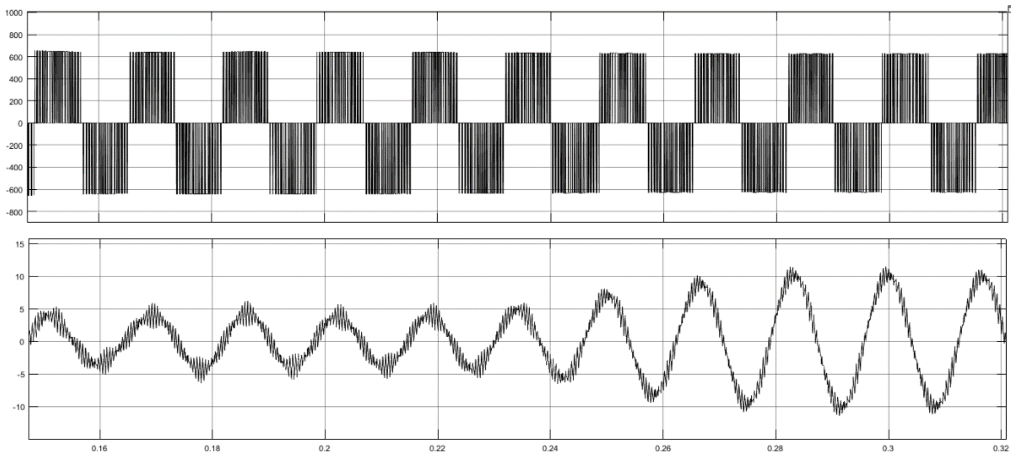

Fig 4.5: Voltage and current waveforms of motor side for 6 Pulse VFD

At the motor side it can be seen clearly from Fig (4.6) that the voltage distortion at the motor side is very high (68.19%), this high value of voltage distortion is very dangerous to the motor and could lead to insulation breakdown and motor failure because of high dv/dt Raito.

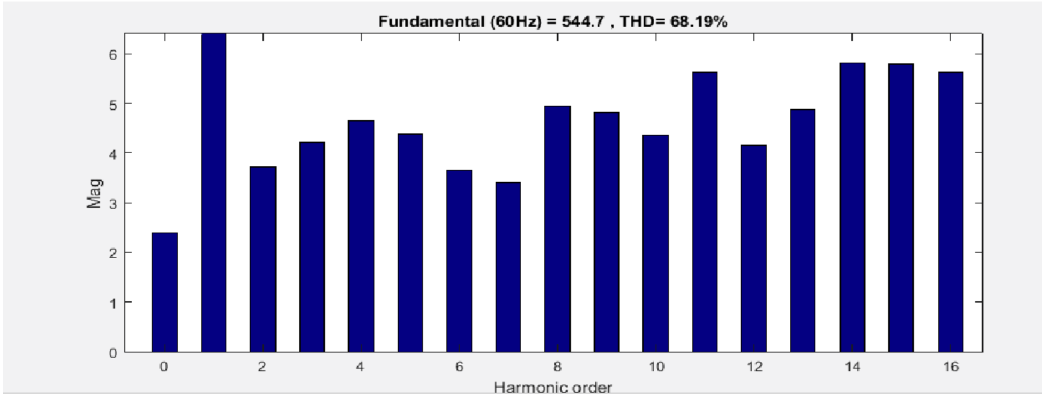

Fig 4.6: Harmonic spectrum for voltage of motor side

In Fig (4.7) which is showing the current distortion on the motor side, the current distortion is low if it has been compared with the supply side current distortion, the reason for that is the use of high switching inverter as described is section (4.2.3).

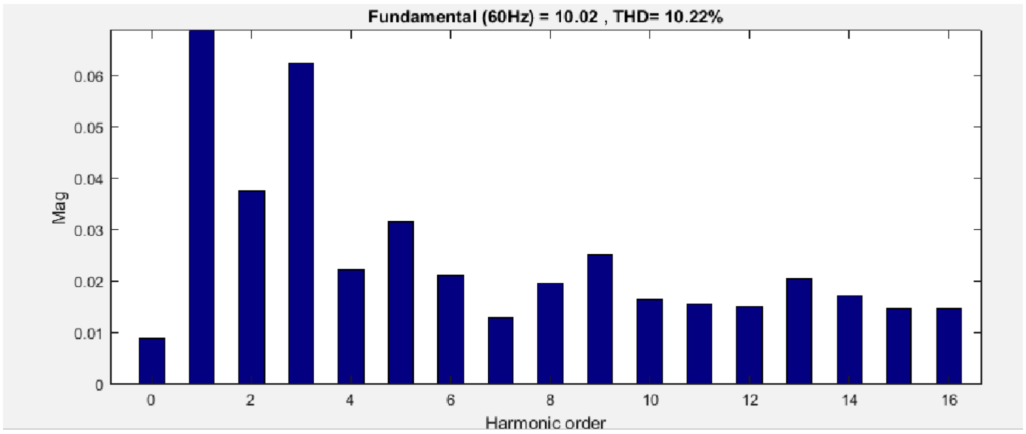

Fig 4.7: Harmonic spectrum for one phase current of motor

-As it has been described in the previous chapters, the AC drive has two parts which are causing harmonic these parts are the supply side and the load or motor side, in this section we will present different types of harmonic reduction techniques according to this two parts.

4.1 Harmonic Reduction in Supply Side:

The methods used are:

1. Passive filters.

2. Connecting reactors in ac line or in dc link side.

3. The use of multi-pulse convertor (12 pulse is used here).

4.1.1 Passive filters:

In this section we will analyze the performance of this filter at different tuning frequencies and show methods of designing this type of filters. The different filters used are:

1. Single tuned 5^{th} harmonic filter.

2. Double tuned harmonic filter (tuned to the 5^{th} and 7^{th}).

First discrete three phase positive sequence power measurement is used to measure the real and reactive power when the motor is running at full load and torque of (20 N.m) applied to its Tm input, and then these values are used to calculate the apparent power, after that this value is used to calculate the filter's different components.

Q_{old}=4379 VAR P=6131 W S=7534 VA

Where:

P is the real power, Q_{old} is the Reactive power and S is the apparent power.

4.1.1.1 Single tuned 5th harmonic filter:

Calculations for 5thharmonic single tuned filter:

The steps for calculating the 5th harmonic filter components are presented at section (3.2.1.1) the calculation is done below:

Q_{old}=4379 VAR   P=6131 W   S=7534 VA

So calculating the P.f of the system is carried out as follows:

$$P.f_{old} = \frac{P}{S} \qquad (4.1)$$

$P.f_{old}$= 0.814

In this calculation the desired P.f ($P.f_{new}$) is 0.95, from this new desired P.f a new value of Q will calculated as shown below:

$$Q_{new} = S * \sin(\cos^{-1}(P.f_{new}))$$

$$Q_{new} = 7534 * \sin(\cos^{-1}(0.95))$$

Q_{new} = 2352.49 KVAR

$$Q_c = Q_{old} - Q_{new}$$

Q_c = 4379-2352 = 2026.51 VAR

From Eq (3.3) to Eq (3.8)

X_{cap} = 108.77 Ω, C =24.387 µF, X_L =4.351 Ω , L =11.54 mH,

R_{coil}= 0.10612 Ω, R_t = 0.04351 Ω, $R_{external}$ =0.0626 Ω.

Substituting these values in an RLC series branch and simulating, the following results are shown below:

In Fig (4.8) and Fig (4.10) below, it is clear that the current waveform shape has improved and it's THD value had reduced from 95.48% to 58.62% as a result of adding 5th filter, and from Fig (4.9) it is seen that THDV decreased from 2.96% to 2.55%, when the harmonic current decrease. The THDV will decrease.

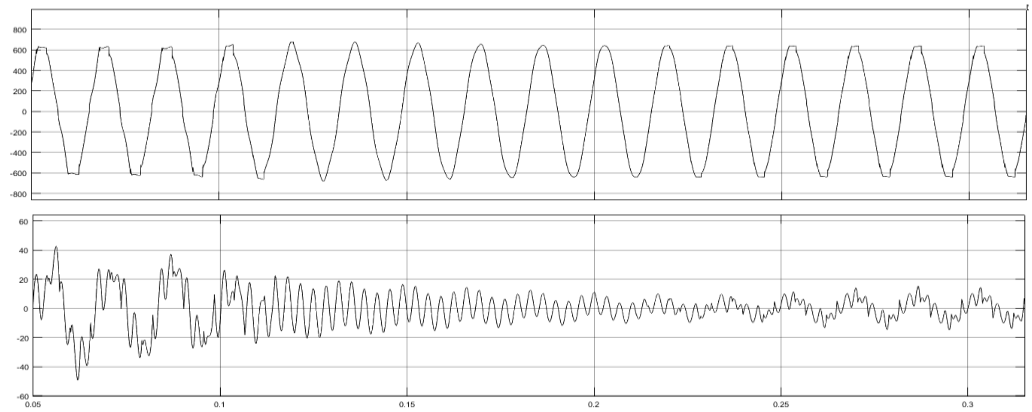

Fig 4.8: Voltage, current waveforms for supply side When 5th harmonic filter is installed

In Fig (4.9) below it is seen that the value of voltage distortion has decrease from 2.96 to 2.55 and the reason for that is the decrease in current distortion, also the voltage distortion at the 5th harmonic had decrease from 10.71 % to 1.58 % and the reason for that is the drop in the 5th harmonic current.

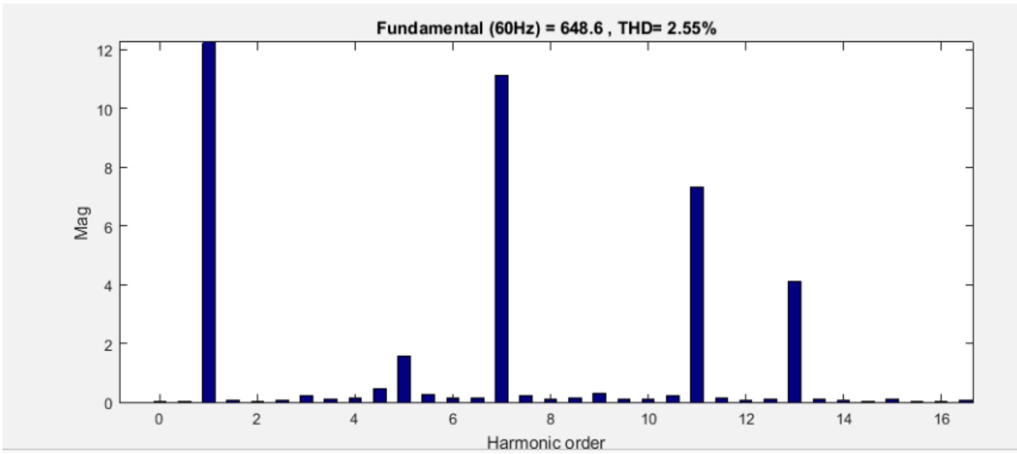

Fig 4.9: Harmonic spectrum for voltage of supply side when a 5th harmonic filter is installed

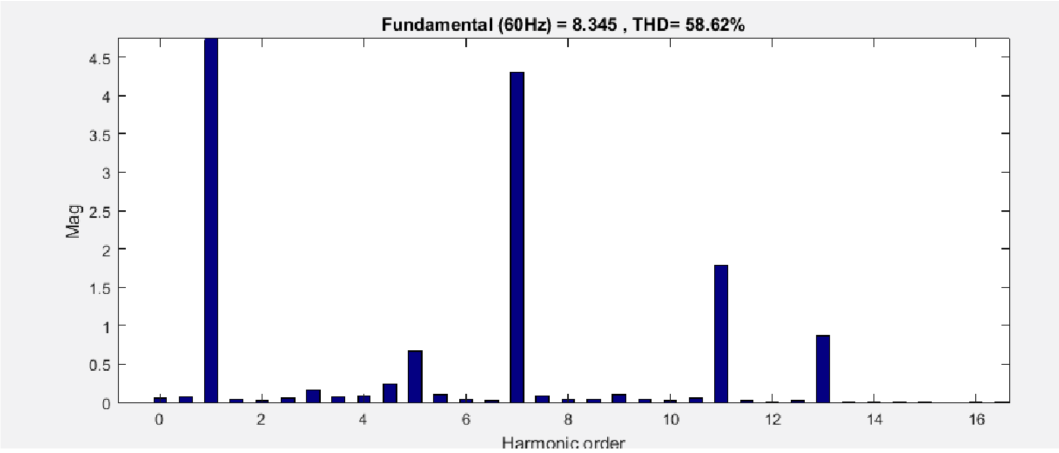

Fig 4.10: Harmonic spectrum for current of supply side when a 5th harmonic filter is installed

To compare the effect of adding the filter with the case of AC drive without any mitigation, values of these two cases are plotted in Fig (4.11), this plot is drawn on the base that the fundamental, 5th, 7th, 11th and 13th harmonics are the dominant harmonic orders so their values are of effective and the other harmonic orders are small so they are neglected.

Fig (4.11) below had been drawn from the data taken from the harmonic spectrum when the filter is not used and the case when the filter is installed.

In Fig (4.11) below it is obvious that the filter is working well on filtering the 5th harmonic order because the value drops from 5.9 A to 0.67 A, it is noted also that the values of other harmonic orders are not largely affected just a small increase at the 11th and 13th harmonic orders.

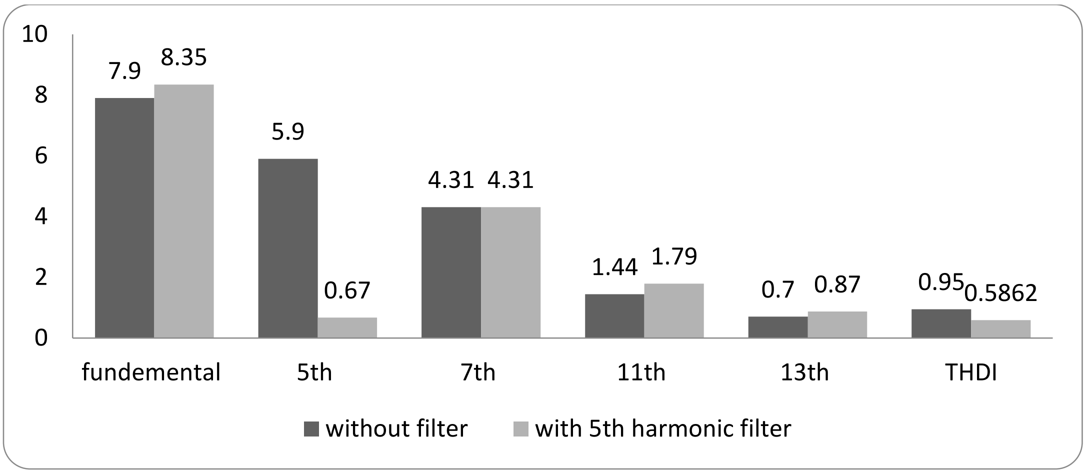

Fig 4.11: Comparison between current harmonic orders with and without 5th harmonic filter

4.1.1.2 Double-tuned filter:

In this section double-tuned filter is going to be designed which is tuned to the 5th and 7th Harmonics:

The double-tuned filter is basically constructed of two single tuned filters which are tuned to the desired harmonic orders that needs to be filtered, then the components of double-tuned filter can be calculated from two filters components as will be shown below:

Values of component of multiple arm filters are:

C_a=0.3411 µF, R_a=0.0447 Ω, L_a=8.25 mH

C_b=0.1897 µF, R_b=0.041 Ω, L_b=7.57 mH

From Eq (3.9) to Eq (3.16) and by neglecting R1 the components of the filter are:

C1=0.5307 µF, C2=0.0453µF, L1=3.95mH L_2=0.426mH a=1.798, x=0.7145 R_2 = 4.283 mΩ R_3 = 0.56409 mΩ

The double-tuned filter waveform is shown in the MATLAB/Simulink model below:

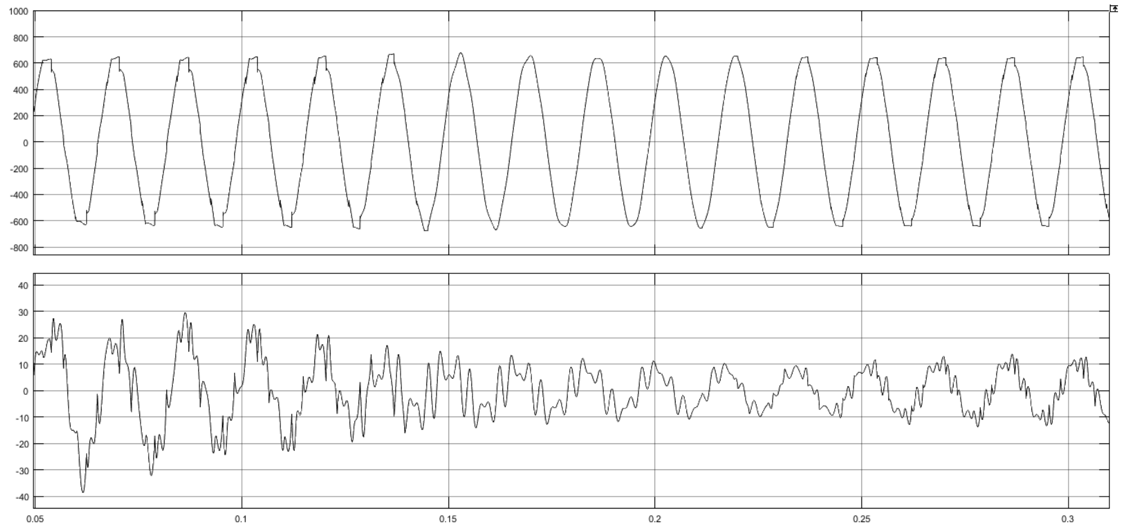

Fig 4.12: Voltage, Current waveform for supply side When a double-tuned harmonic filter is installed

In Fig (4.13) below it is clear the current waveform had improved if it is compared with the waveform of Fig (4.2) for the VFD without any filter, Fig (4.14) below had been drawn from the data taken from the harmonic spectrum when the filter is not used and in the case when the filter is installed.

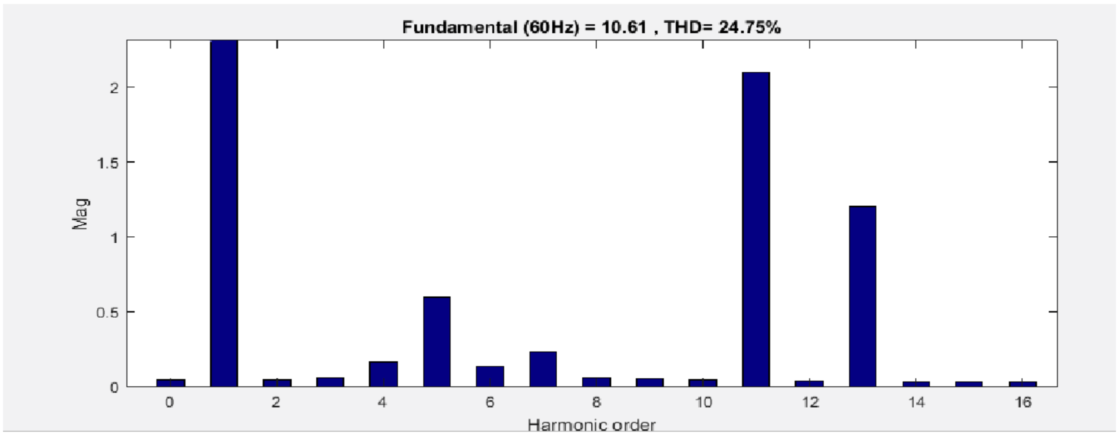

Fig 4.13: Harmonic spectrum for current of supply side when a double tuned harmonic filter is installed

In Fig (4.14) below it is clear that the filter is working good on filtering both the 5th and7th harmonic because the value of 5th harmonic current drops from 5.9 A to 0.59 A, and also 7th harmonic current has decreased from 4.33 to 0.23, it is noted that the values of others harmonic orders are also affected with a small increase at the at the 11th and 13th.

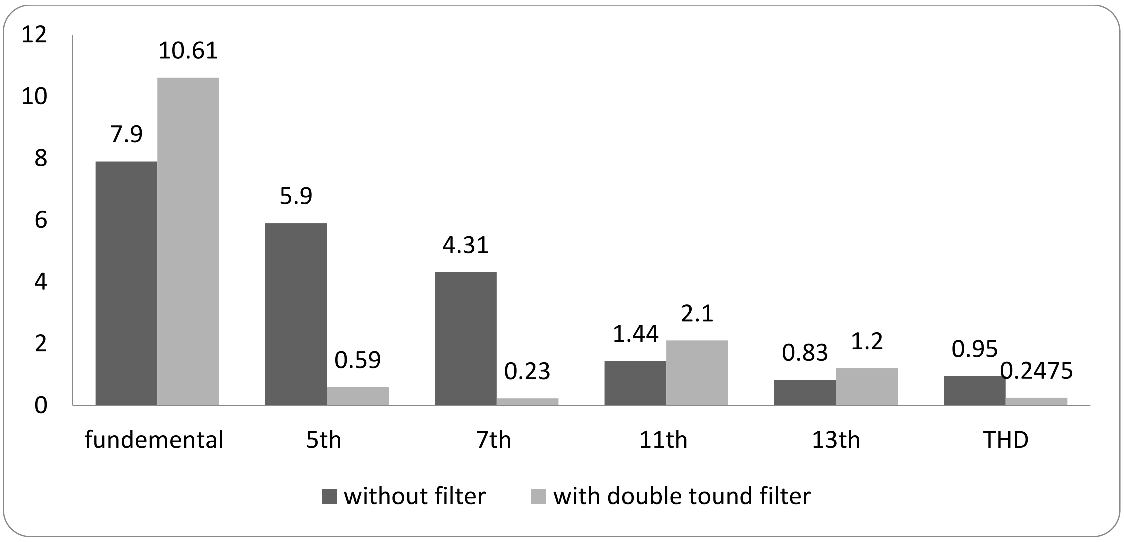

Fig 4.14: Comparison between current harmonic orders with and without double tuned harmonic filter

The main advantage of the double-tuned filter is using less number of inductors subjected to the line which means it costs less, that is why it is preferred more than multi-arm single tuned filter.

4.1.2 Harmonic reduction using reactors:

In this section design of AC line reactor and dc link reactor will be discussed, the values of components will be calculated and the results of installing them will be analyzed.

4.1.2.1 Line side reactor:

As a general rule, the total AC reactor should not exceed 5%. This is sufficient to meet the harmonic levels required by international standard IEC-61000-3-12 for a balanced 3 phase rectifier. [33]

Computation the inductance of the reactor from Eq (3.17)

Where : %Z=5, $V_{\emptyset}$=460 V, f =60Hz, I_{ac}=5.57 .

So $L_{ac} = 0.05 * \frac{460}{\sqrt{3} * 2\pi * 60 * 5.57}$ =6.324 mH .

The following results were extracted after simulation.

In Fig (4.15) and Fig (4.16) below, current waveform is similar to waveform of Fig (4.2) of VFD without any mitigation, %THD is noticeably decreased, this happens because the reactor works on blocking most of the harmonic current frequencies by appearing as a high impendence which reduces their effect in the system. Reactor's attenuates all harmonic orders in the drive, that can be observed from Fig (4.17) below not like passive filters which attenuate only the resonance harmonic order.

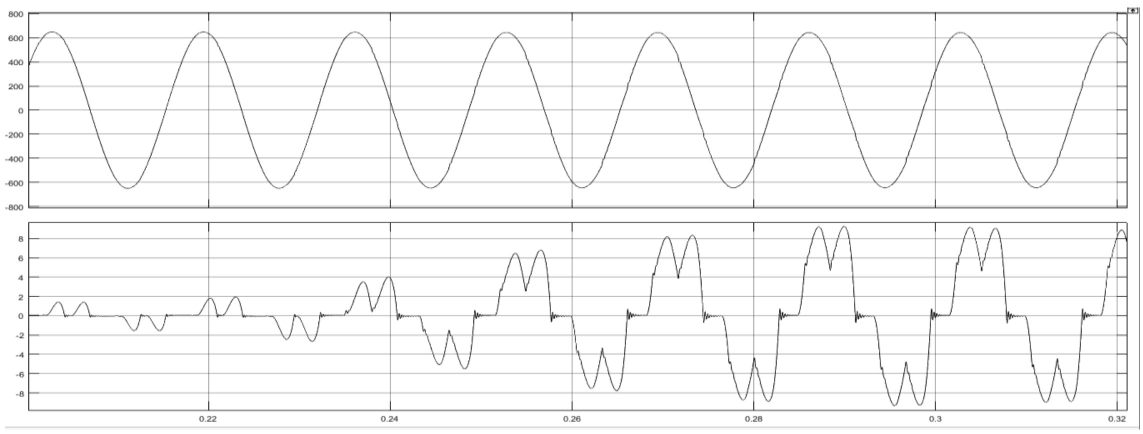

Fig 4.15: Voltage, Current waveforms for supply side when an AC Reactor is used

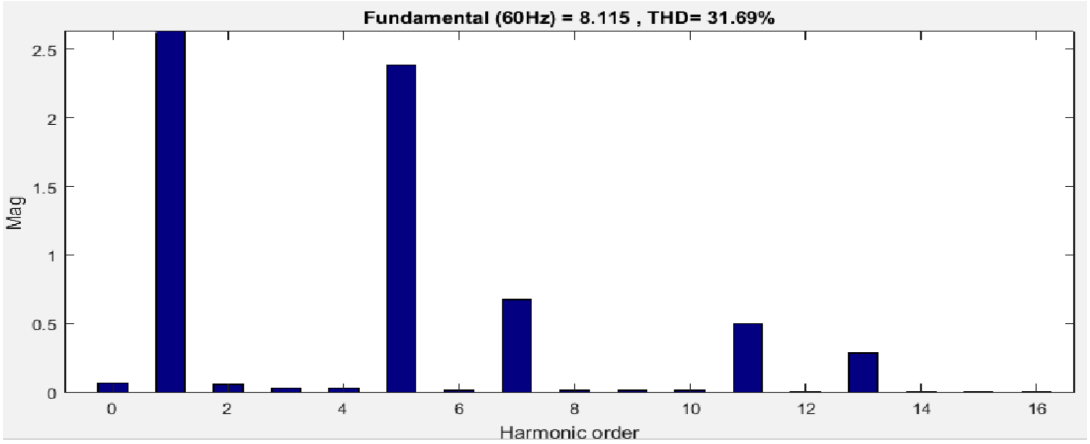

Fig 4.16: Harmonic spectrum for current of supply side when an AC Reactor is used

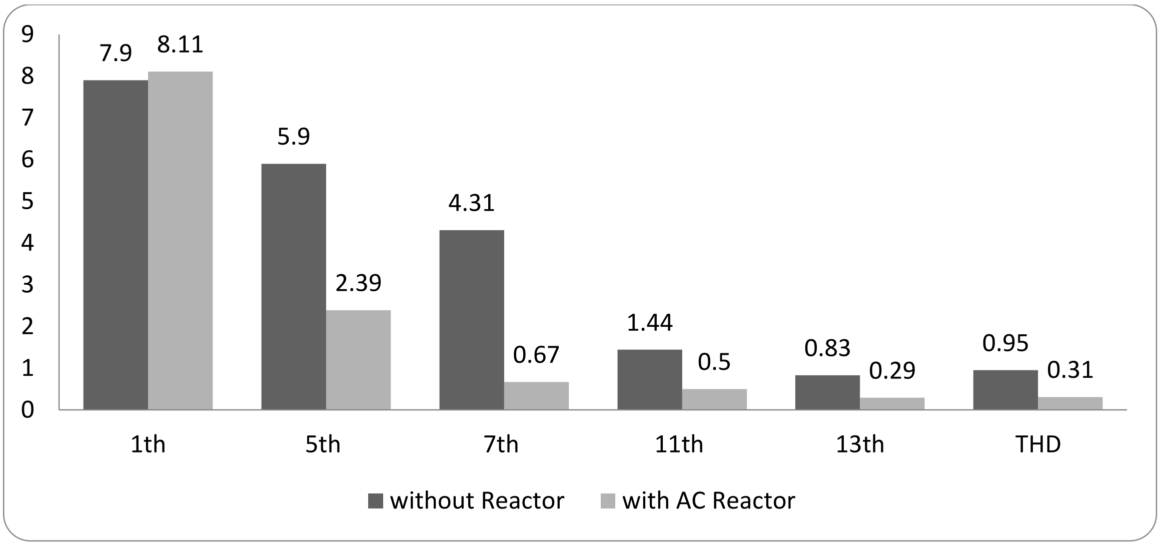

Fig 4.17: Comparison between current harmonic orders with and without a AC Reactor

4.1.2.2 Dc link reactor:

A value of 5% reactor will be calculated as shown below and this reactor is placed on both the positive and negative bus bars of the dc link.

The dc bus voltage and current are 623 V and 10.17 A.

From Eq (3.18) :

$$L_{dc} = Z\% * \frac{V_{\emptyset}}{\sqrt{3}*2\pi*f*I_{dc}} = L_{dc} = 0.05 * \frac{623}{\sqrt{3}*2\pi*60*10.17} = 8.125 \text{ mH}.$$

The following results were extracted after simulation

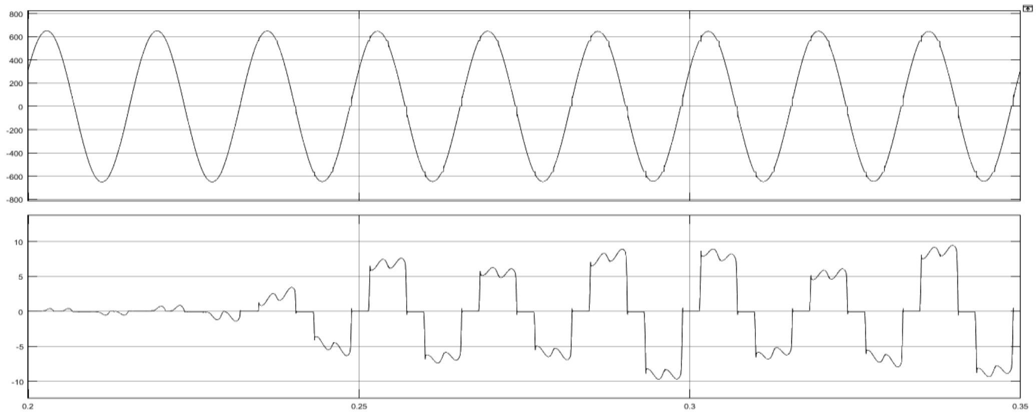

Fig 4.18: Voltage, Current waveforms for supply side when DC Reactor is used

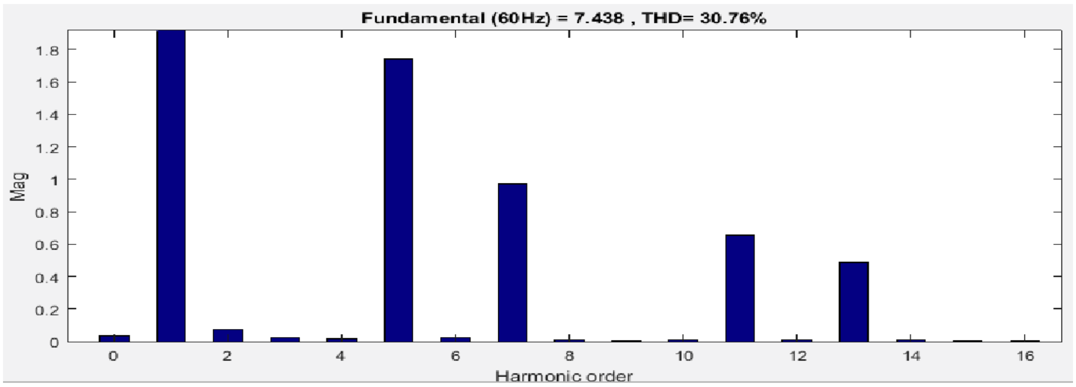

Fig 4.19: Harmonic spectrum for current of supply side when DC Reactor is used

In Fig (4.20) below it is obvious that DC reactor effect in attenuation of harmonic orders is similar to AC reactor effect but DC reactor has better effect because THD is reduced to 0.3, also the voltage waveform will improve as a result of the decrease in THDI.

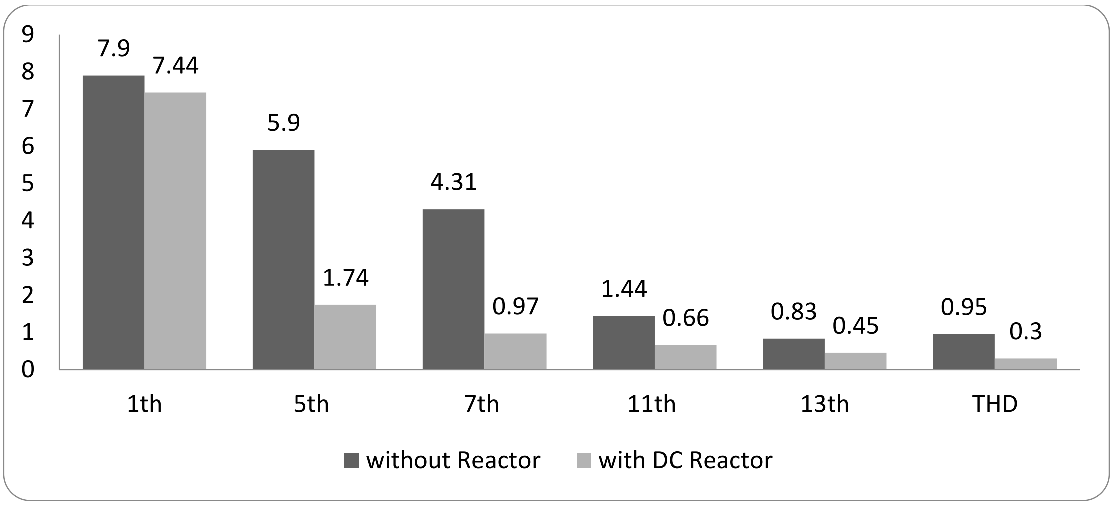

Fig 4.20: Comparison between current harmonic orders with and without DC Reactor

4.1.2.3 Double-tuned with dc reactor:

Since most modern drives have DC reactor build in the section a DC link, chock was added to the double tuned filter presented at section (4.1.1.4). Performance of this new combination were presented were analyzed below.

Values of DC link voltage and current were measured

V_{dc}=640.5 V I_{dc} = 6.81 A

From Eq (3.18)

$L_{dc} = 2 * Z\% * \frac{V_{\emptyset}}{\sqrt{3}*2\pi*f*I_{dc}}$ so $L_{dc} = 2 * 0.05 * \frac{460.5}{\sqrt{3}*2\pi*60*6.81}$ =12.47 mH

The following results have been extracted after simulation:

In Fig (4.21) below it is noted that the shape of the current waveform is improved, that indicate a reduction in the harmonic because the new waveform nearly sinusoidal with some notches appearing at its surface.

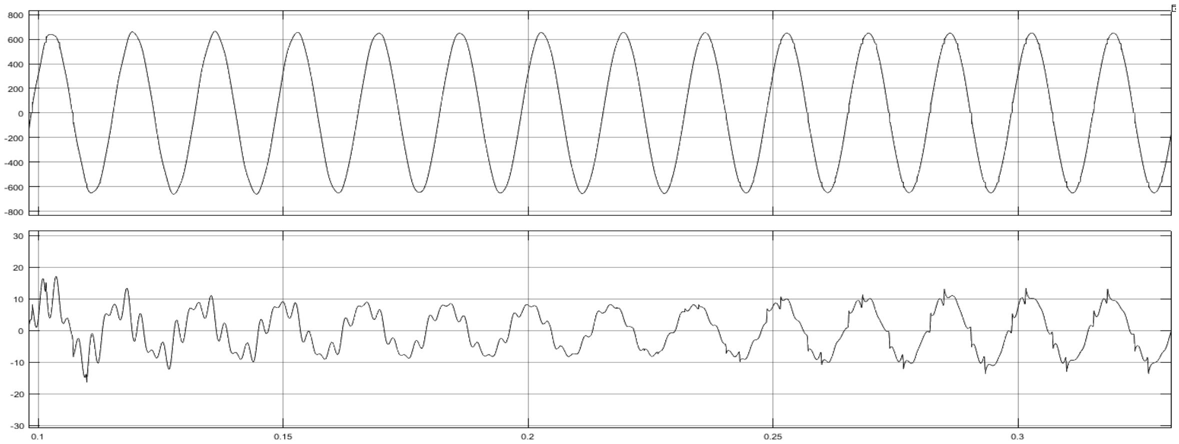

Fig 4.21: Current waveform when DC reactor and double-tuned filter are used

From Fig (4.22) below the following data is extracted and redrawn in form of chart

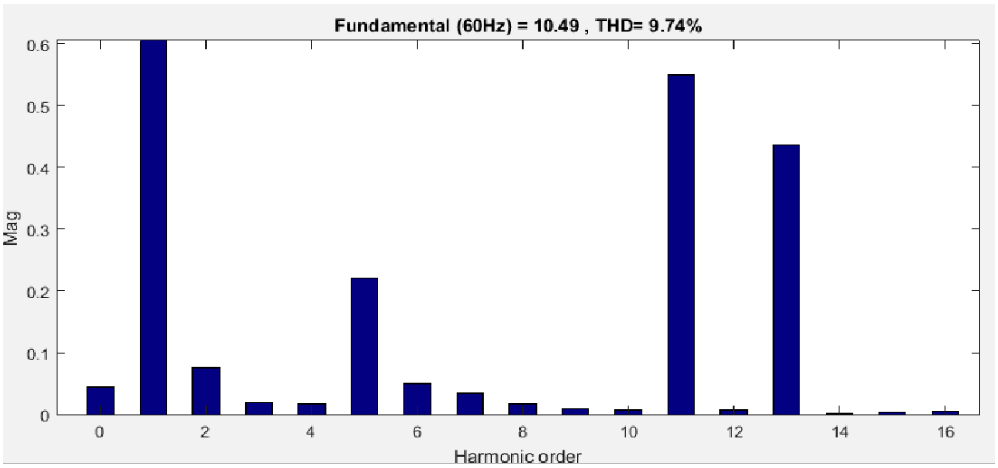

Fig 4.22: Harmonic spectrum for current when a dc reactor and a double tuned filter are used.

In Fig (4.23) below it is obvious that the value of 5th,7th harmonic currents significantly drop from 5.9 A to 0.22 A, 4.33 A to 0.04 respectively it is also clear that the 11th had decreased from 1.44 A to 0.55 and 13th drops from 0.83 A to 0.44 which proves the significant effect of this combination.

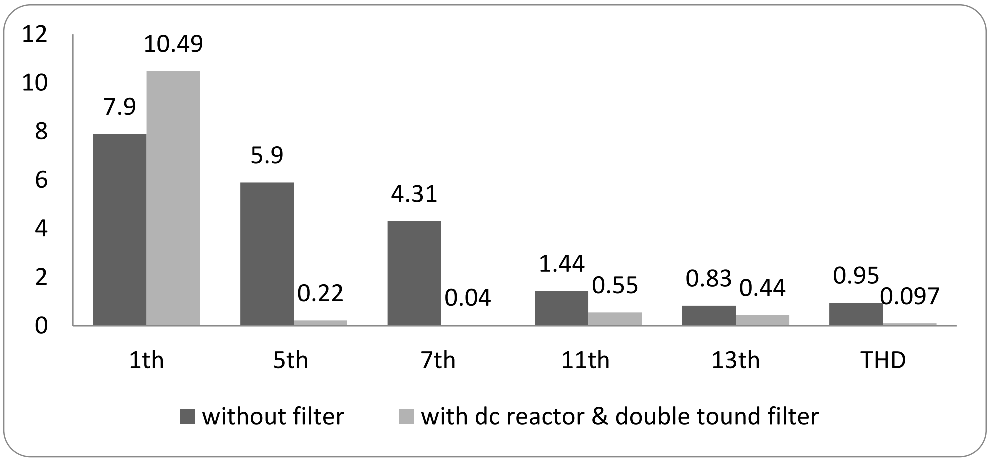

Fig 4.23: Comparison between current harmonic orders with and without a dc reactor and a double tuned harmonic filter

4.1.3 Harmonic reduction using 12-Pulse Drive:

An additional method of mitigating harmonics is using of 12-pulse drives. These drives contain multiple rectifiers as well as an expensive transformer with one primary and multiple secondary. These configurations act to cancel some of the lower harmonic orders, higher amplitude harmonic currents. [33]

it requires either a DELTA-DELTA and DELTA-WYE transformers, “Zig-Zag” transformer or an autotransformer to accomplish the 30° phase shifting necessary for the proper operation of 12-pulse configuration. [17]

4.1.3.1 Three phase isolation transformer:

Three phase three winding transformer is chosen from the library of (simpower system) at MATLAB/Simulink to construct the 12-pulse drive, the parameters of three phase three winding transformer had been modified to give the required 30^0 phase shift by choosing a transformer with a vector group of (D11) on the secondary, also the primary and secondary voltages had been modified to a value of 460 V to make the transformer work as isolation transformer.

In Fig (4.24) and Fig (4.25) below it is seen that the current waveform had improved because 5th and 7th harmonic orders which are the dominating harmonics had been significantly reduced. also 11th and 13th harmonic had been affected and their values had been decreased.

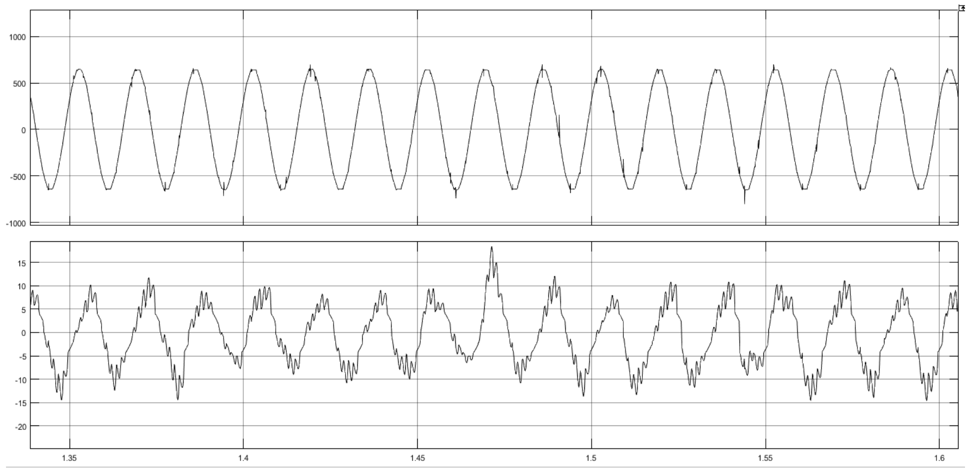

Fig 4.24: Voltage, Current waveforms for 12 pulse drive with isolation transformer

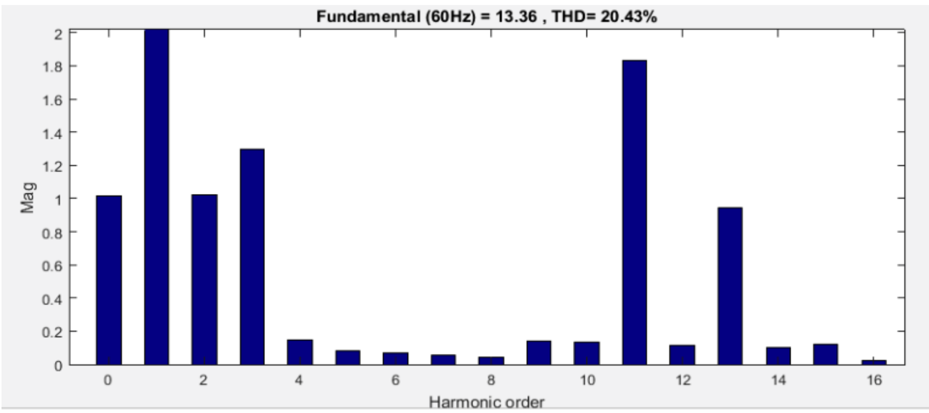

Fig 4.25: Harmonic spectrum for current of supply side for 12-pulse drive with isolation transformer.

In Fig (4.26) below, it could be seen that the fundamental current component had increased, and 5th and 7th harmonic orders had decreased to a very low values. Total harmonic distortion had decreased to low a value but this value doesn't pass the IEEE STD 519 which is 20%.

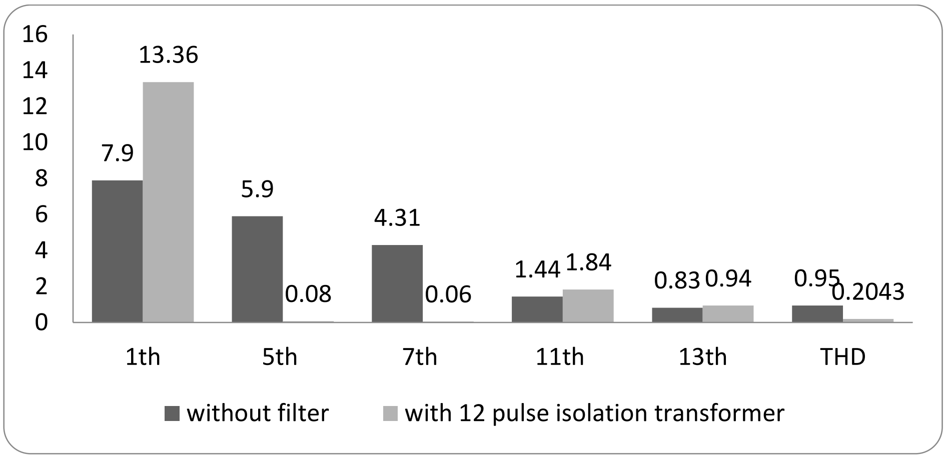

Fig 4.26: Comparison between current harmonic orders with and without 12 pulse isolation transformer

4.1.3.2 Three phase ZigZag shifting transformer:

As seen in Fig (4.27) below the phase shifting done by the zigzag transformer had worked as expected to cancel lower order harmonics which is seen in better shape of current waveform.

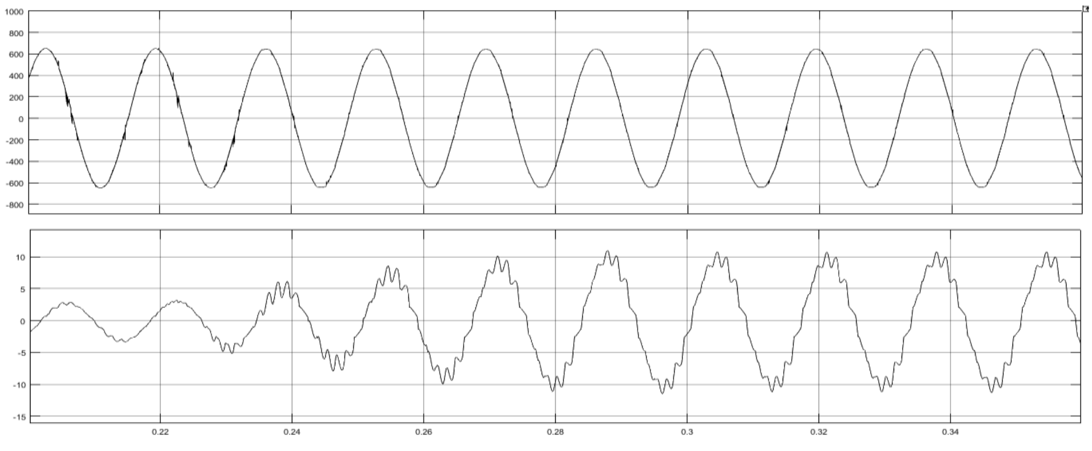

Fig 4.27: Voltage, Current waveforms for 12 pulse drive with a zigzag transformer

From Fig (4.3) and Fig (4.28) below, THDI's value dropped from 95% to 9.75%, 5^{th} and 7^{th} harmonic orders had been eliminated, now the dominant harmonics are the 11^{th} and 13^{th} harmonic, this technique work by shifting the positive and negative harmonic again stand opposite to each other and zero sequence harmonics against each other which work on canceling a considerable amount of harmonic orders.

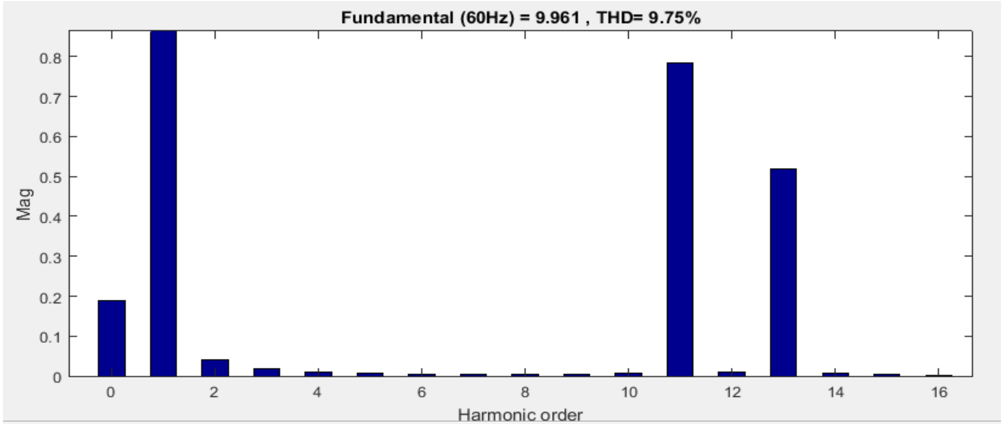

Fig 4.28: Harmonic spectrum for current of supply side when a 12 pulse drive with a zigzag transformer is used.

Fig (4.29) below illustrates that the 5th and 7th harmonics have been eliminated by the effect of phase shifting, this type of mitigation had given the best performance of all mitigation techniques because it passes the (IEEE STD 519) without the need for additional equipment such as reactors which had been used with the isolation transformer type of 12-pulse.

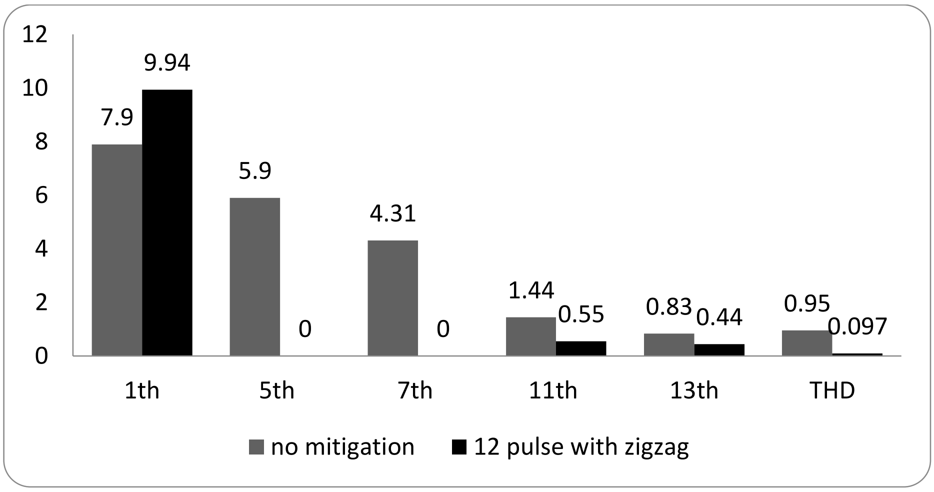

Fig 4.29: Comparison between current harmonic orders with and without 12-pulse zigzag transformer being used

4.1.3.3 Three phase isolation transformer with a DC reactor:

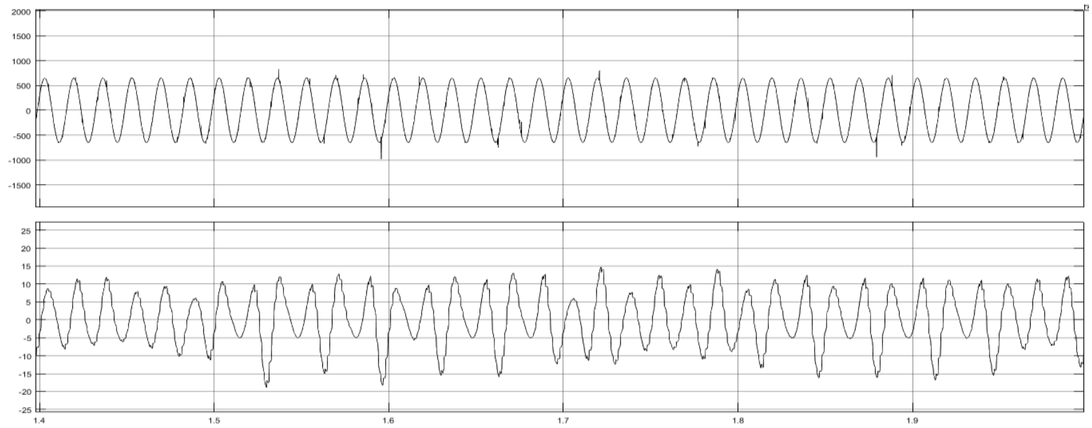

Fig 4.30: Voltage, Current waveforms for 12 pulse drive with isolation transformer and a DC reactor

In Fig (4.31) below, the THDI had decreased from a value of 95% to a value of 9.51%, the reason for this is 5th and 7th harmonic orders had been eliminated by the 12-Pulse system while other harmonics had been reduced to a value below (1A) by the dc link reactor which works in smoothing the dc link voltage and reducing current non linearity.

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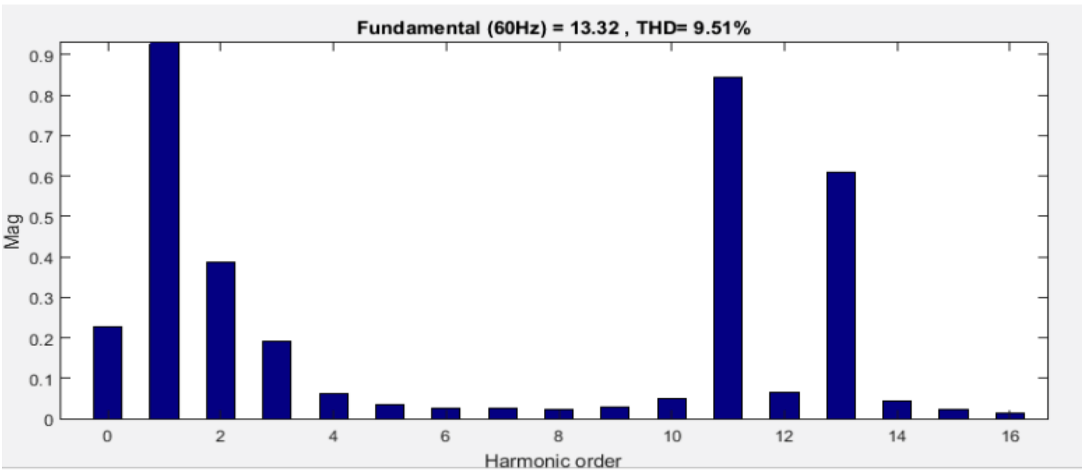

Fig 4.31: Harmonic spectrum for current of supply side when a 12 pulse drive with an isolation transformer and a dc reactor is used

In Fig (4.32) below, it is noticeable that the values of 5th and 7th harmonic orders had been reduced, 11th and 13th harmonic orders had also been reduced, the value of THDI had been reduced to a value of 9.51% which passes the (IEEE STD 519).

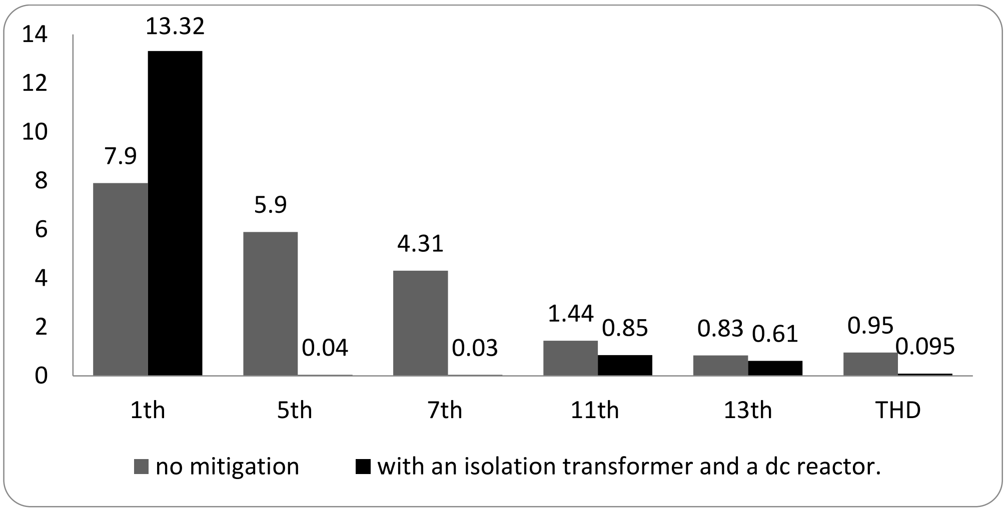

Fig 4.32: Comparison between current harmonic orders with and without a 12 pulse drive by an isolation transformer and a dc reactor been used.

4.2 Harmonic Mitigation on Motor Side:

The use of (PWM) introduces undesirable harmonics that may disturb other sensitive loads/equipment on the grid, also result in extra power losses and will generate noises in the motor, in the following section solutions will be presented and how to design them in order to reduce the voltage and current noises to the levels required.

4.2.1 Dv/dt reactor (output reactor):

dv/dt reactors protects the motor coils insulation from premature aging and destruction and increases significantly the service life of electric motors. Value of inductance of reactor would be calculated as shown below:

The following values are taking directly from simulation

$f_{out} = 60$ Hz $f_{sw} = 2$ kHz $V_{\emptyset} = 385.1$ V $I_{ac} = 7.07$ A

Note: the voltage and current values used are RMS values.

From Eq (3.17) L_{ac} = 7.224 mH.

In Fig (4.33) The shape of voltage waveform changes to nearly sine wave and the current wave doesn't change much because current waveform is already similar to sine wave as a result of using fast switching.

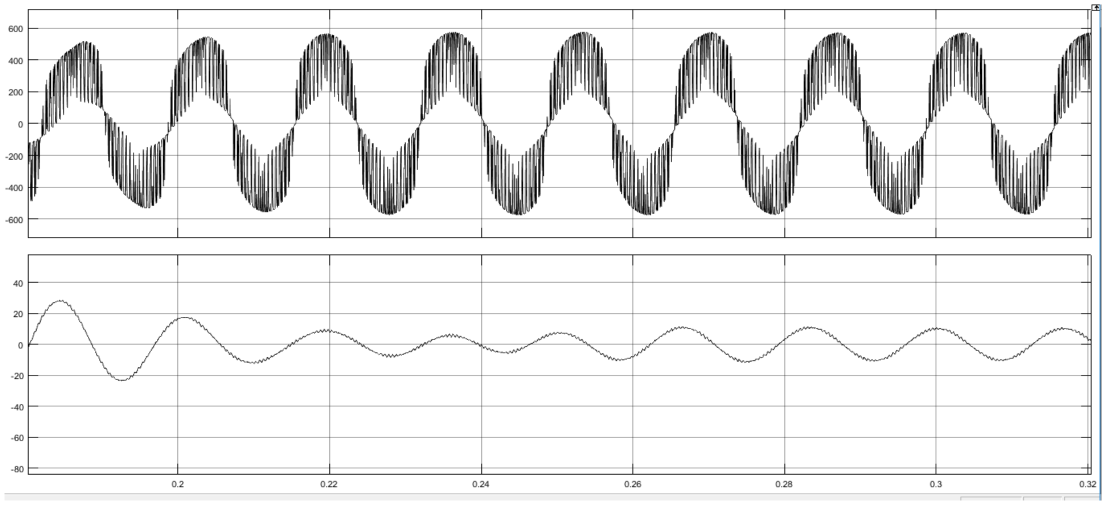

Fig 4.33: Voltage and current waveforms after installation of dv/dt reactor

In Fig (4.34) it is seen that total harmonic distortion is reduced from 68.19% to 33.47% and there's a voltage drop as a result of installing 5% dv/dt reactor.

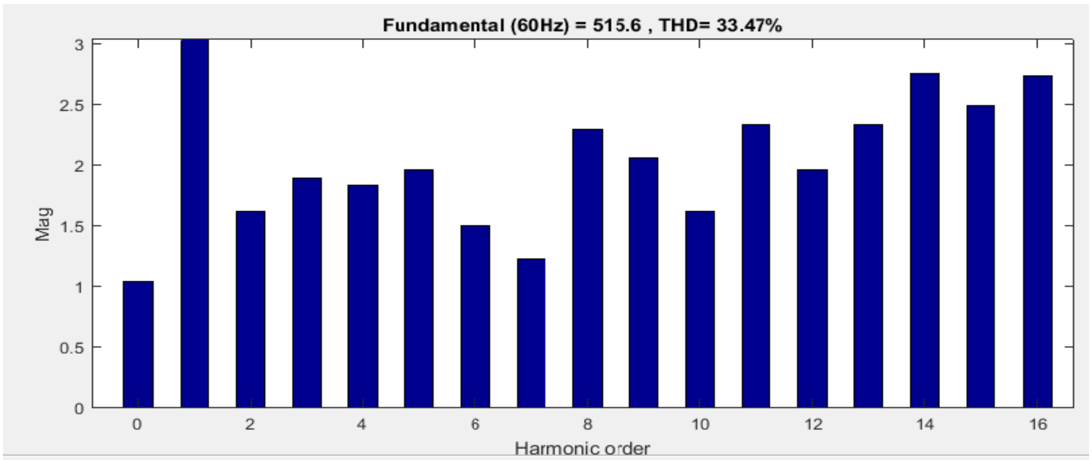

Fig 4.34: Harmonic spectrum for voltage after installation of dv/dt reactor on motor side

In Fig (4.35) total harmonic distortion THDI is reduced from 10.22% to 5.70%. It is already low as a result of fast switching.

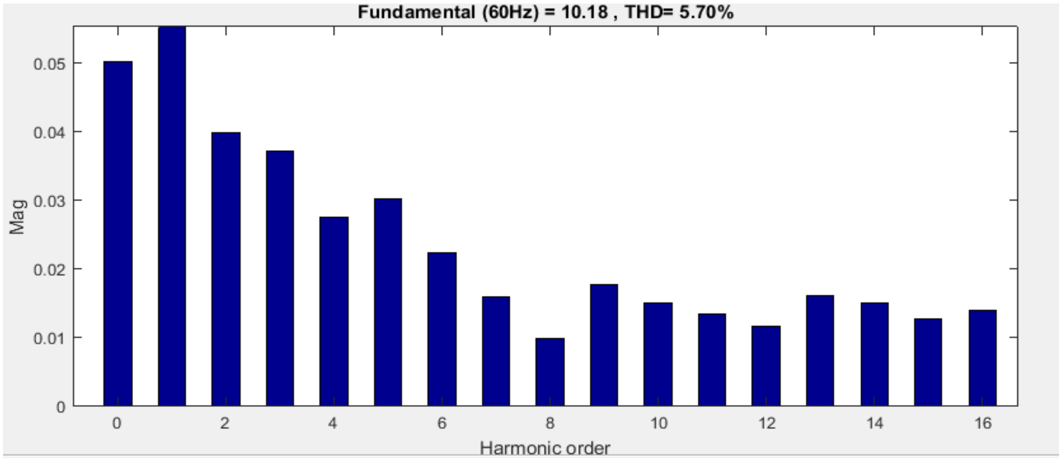

Fig 4.35: Harmonic spectrum for current after installation of dv/dt reactor on motor side

4.2.2 Motor filter (Sine filter):

The calculation of the filter's inductance L_1 is similar to the previously explained AC line reactor. the same values used to calculate dv/dt reactor will be used here even the value of inductance so L_1=7.224 mH .

From Eq (3.19) f_{res} = 700 Hz .

From Eq (3.20) C_1 = 7.155 μF.

The effect of sine filter is obtained from waveform in Fig (4.36) below:

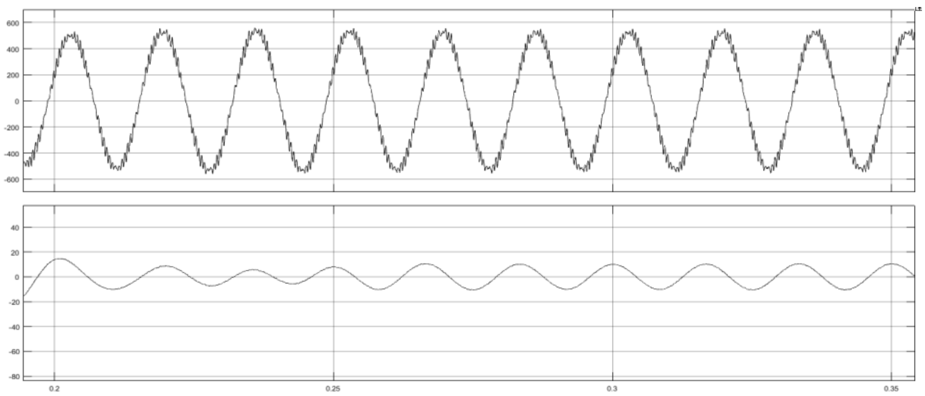

Fig 4.36: Voltage and current waveforms after installation of sine filter

It is observed that voltage waveform took a sine wave shape as result of installing sine filter.

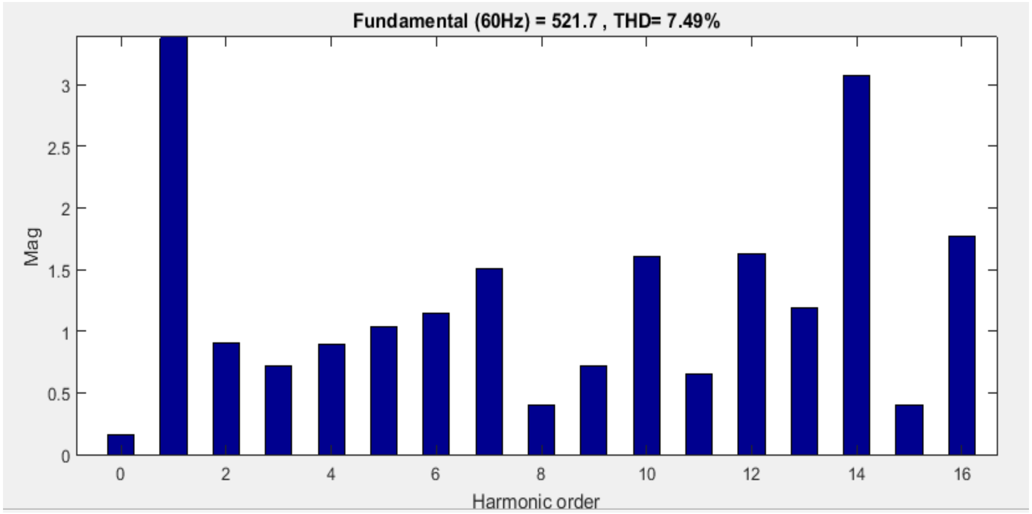

Fig 4.37: Harmonic spectrum after installation of sine filter

Total harmonic distortion is reduced from 68.19% to 7.49%, this proves that sine filter is more effective when compared to dv/dt reactor.

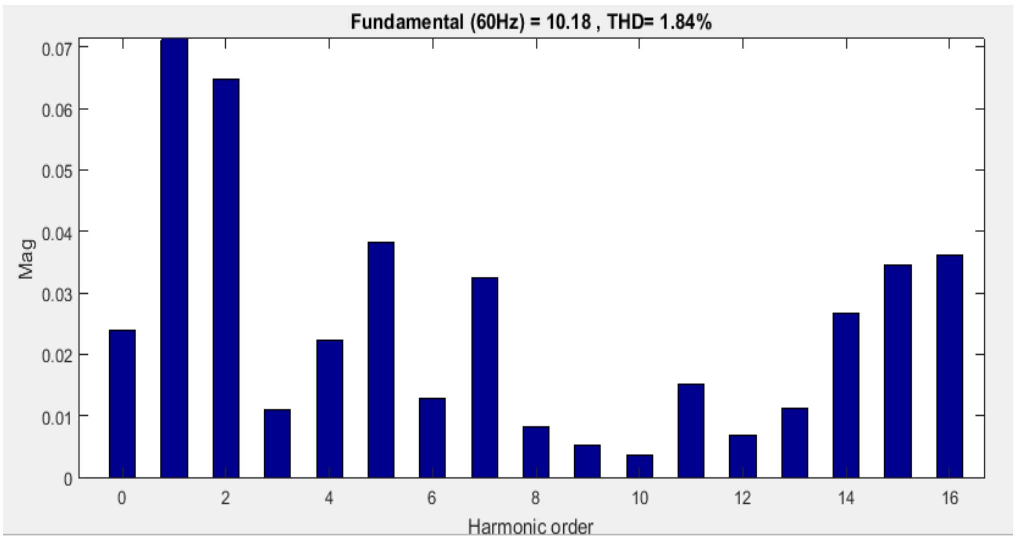

Fig 4.38: Harmonic spectrum for current after installation of sine filter

THDI is reduced to a value below the standard limit which is 2%.

Fig (4.39) below represents a comparison of the effect of installing dv/dt reactor and sine filter to harmonic orders of voltage.

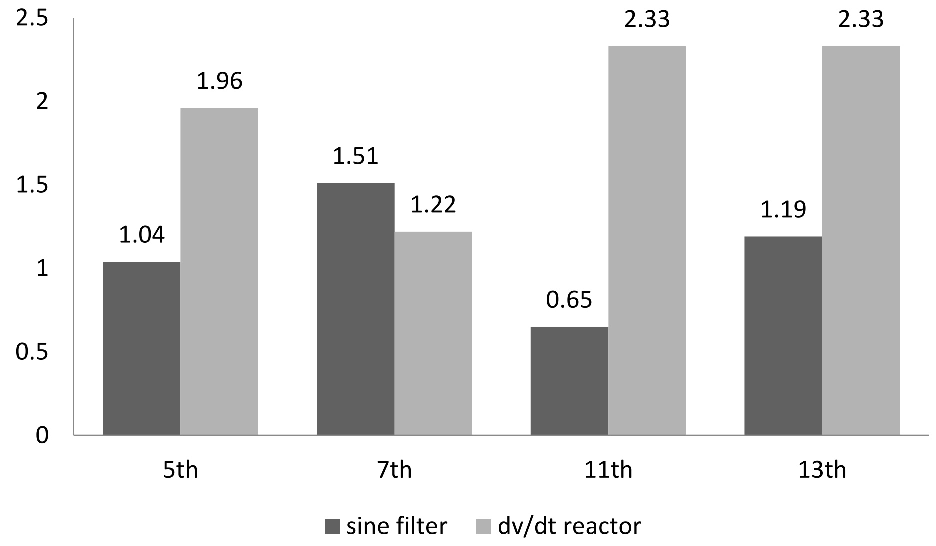

Fig 4.39: Comparison between effect dv/dt reactor and sine filter to harmonic orders of THDV

Fig (4.40) below represent a comparison to effects of dv/dt reactor and sine filter to harmonic orders of current.

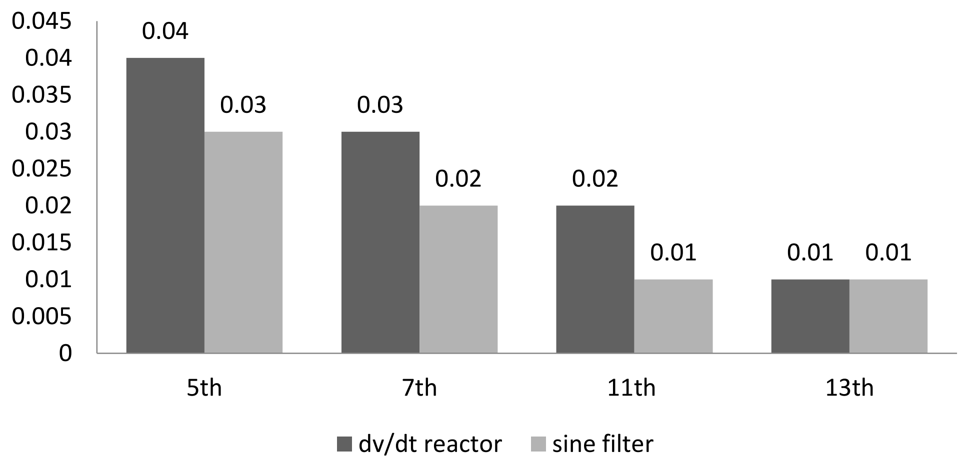

Fig 4.40: Comparison between effect dv/dt reactor and sine filter to harmonic orders of THD of current

4.2.3 Switching frequency:

Pulse width modulated *(*PWM*)* inverters, need high frequency switching to provide a smooth output current waveform. Consequently, power MOSFETs were used in VSD applications in the 300–600volt range. The main advantages of a power MOSFET are high speed switching capability (10 nsec to 100 nsec) and they can be used at switching frequencies from 30kHz up to 1GHz. Another power electronic device which is suitable for switching is insulated gate bipolar transistor (IGBTs), they are suitable for 3-phase AC VSDs rated up to about 500 kW at 380 V/415 V/480 V. They can be used at switching frequencies up to 100kHz. [8]

power MOSFET has larger range of switching frequency than IGBT, but (IGBT) is preferred from these two choices because it has good power handling capabilities and high speed switching capability.

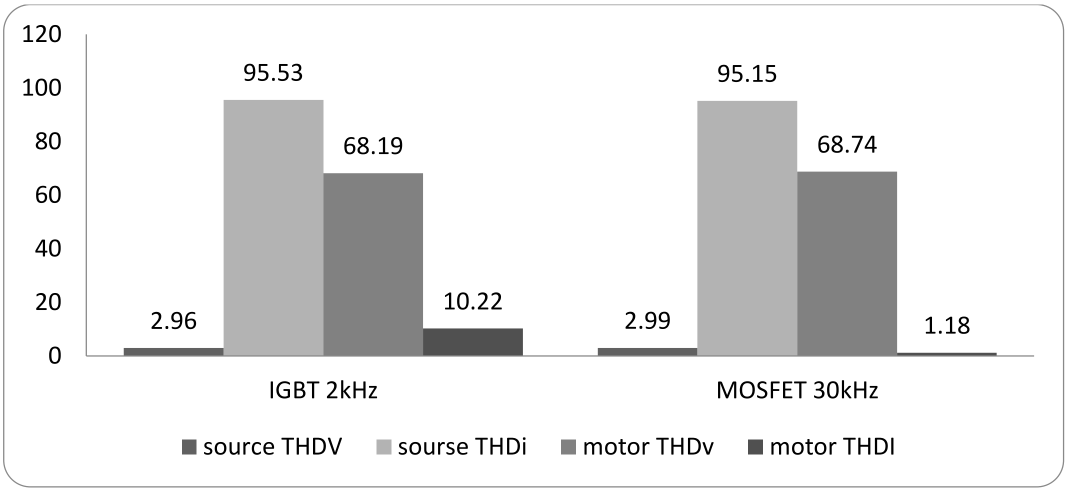

Fig 4.41: Comparison between MOSFET and IGBT and the effect of their switching frequency range on THD of voltage and current

Increasing switching frequency has obvious effect on decreasing THDI of motor.

4.3 Total Comparison:

The following tables summarizes the previous analysis of all mitigation techniques used in this project report.

Table (4.1): Represent dominate current harmonic orders along with their THD values of all mitigation techniques

	Fundame ntal	5th	7th	11th	13th	THD
Without mitigation	7.9	5.9	4.31	1.44	0.7	%95
5th filter	8.35	0.67	4.31	1.79	0.87	%58.62
Double tuned filter	10.61	0.59	0.23	2.1	1.2	%24.75
Ac reactor	8.11	2.39	0.67	0.5	0.29	%31
Dc reactor	7.44	1.74	0.97	0.66	0.45	%30
Double tuned filter with dc reactor	10.49	0.22	0.04	0.55	0.44	%9.7
12 pulse	13.36	0.08	0.06	1.84	0.94	%20.43
12 pulse with dc reactor	13.32	0.04	0.03	0.85	0.61	%9.5
12 pulse zigzag	9.94	0	0	0.55	0.44	%9.7

Using the values of table (4.1) the following chart had been drawn.

In Fig (4.42) as shown below 5^{th} or7^{th} single tuned passive filters don't pass the IEEE STD 519, and give poor performance, also it could lead to resonance to the system. but if its extended to multi harmonic orders (typically the 5^{th} ,7^{th} ,11^{th} and 13^{th}) the passive filters will perform good in absorbing the tuning harmonics, it also has the advantage of the mitigating harmonic for several drives connected to the same bus bar (as it will be shown later using ETAP software).

Also as seen at Fig (4.42) below, the 12-pulse drive with an isolation transformer reduces harmonic current distortion to low values but a DC link reactor have to be used to give the best performers which is a drawback because of the additional cost.

The best harmonic reduction had been obtained with the use of 12-pulse drive phase shifted with a zigzag transformer the THDI had been reduced from 95% to 9.7%.

As seen in the Fig (4.42) 12-pulse drives have the best harmonic reduction performance from technical view but from an economical view this type of system is very expensive because the need for a special type of phase shifting transformer along with the additional 6-pulse 3 phase rectifier, which increases the cost even more , because of that this type of drives are best suited for high power applications another disadvantage of the 12-pulse drive is bad harmonic reduction when the system suffers from voltage unbalance which is the case for most industrial applications.

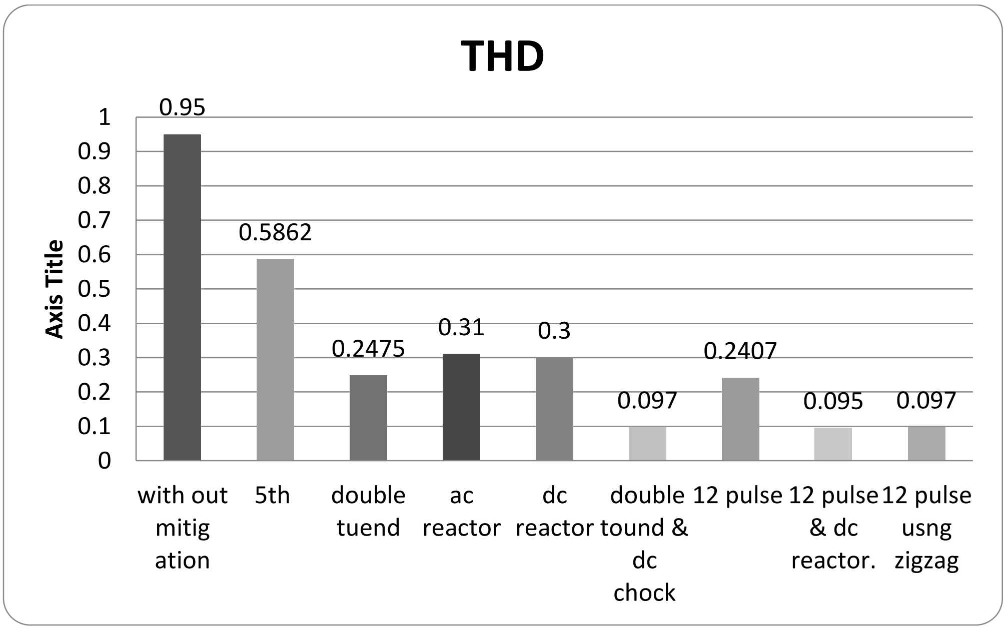

Fig 4.42: Comparison between THDI values of all mitigation techniques

Also it is seen that the AC and DC reactors have medium performance (30-35)% and a capably to reduce multi harmonics of different orders, AC reactor would cause voltage drop so DC reactor is preferred , DC link reactor is built in most drives, so they are better than single tuned 5th harmonic filter which had a THDI of(58%) ,but reactors cannot made VFD pass the (IEEE 519 standard) which is 20% , but if multi-tuned harmonic filters were combined with a DC reactor the THDI will comply to the (IEEE STD 519) ,which it has been illustrated in this project using multi-arm passive harmonic filter tuned to the 5th and 7th orders with a DC reactor , the THDI had been reduced to (9%).

AC and DC reactors are considered the cheapest solution for harmonic problems, because of the simple construction and easy installation, and sometimes are provided by the manufacturer as built in component.

Passive filters have three main components, a 3 phase capacitor which is subjected to full line voltage, a 3 phase reactor and 3 phase resistance these components lead to increase in the overall cost of the filter so it is considered more expensive than ac and dc reactors.

Double-tuned filters are considered cheaper than single-tuned filters because they have the advantage that the reactors L1 and L2 are not subjected to line of supply as it has been demonstrated on the methodology section.

Based on previous comparison the following chart had been drawn to summarize the economical differences between different mitigation techniques.

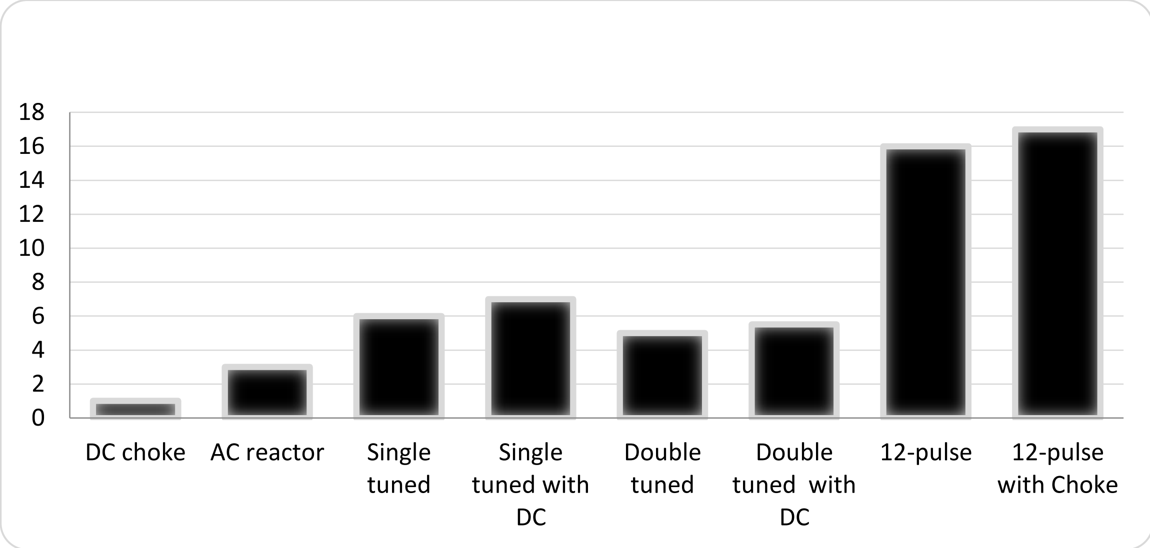

Fig 4.43: Comparison of typical cost of each mitigation techniques

4.4 Results Validation Using ETAP Software:

ETAP software used for confirmation of results obtained by MATLAB/Simulink.

4.4.1 Model illustrated using ETAP software:

In the section ETAP software will be used for the validation of the results obtained by MATLAB/Simulink model.

On this system motor rating is 5 HP had been used with 0.46 KV grid voltage,the short circuit 1 MVA had been used , this value are similar to the value on the MATLAB/Simulink model. At harmonic page of the VFD , THOSHIBA harmonic library had been chosen.

The Fig (4.44) below shows the harmonic distortion of both the voltage and current, as seen the value THDI obtained by this drive is bigger than what had been found on the MATLAB/Simulink model the reason for that is ETAP has different libraries provided by the manufacture according to their drive harmonics, so by using different libraries a different harmonic distortion will be present.

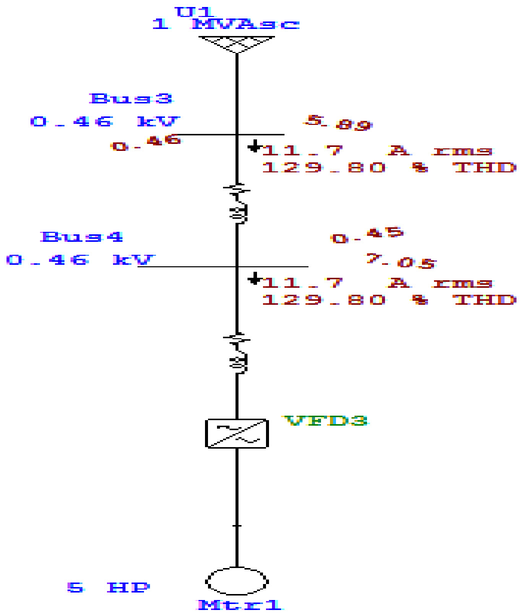

Fig 4.44: VFD connected to a 5 HP motor with the load flow of the system

Fig (4.45) below, as seen the current waveform look simler to that obtained by the MATLAB/Simulink.

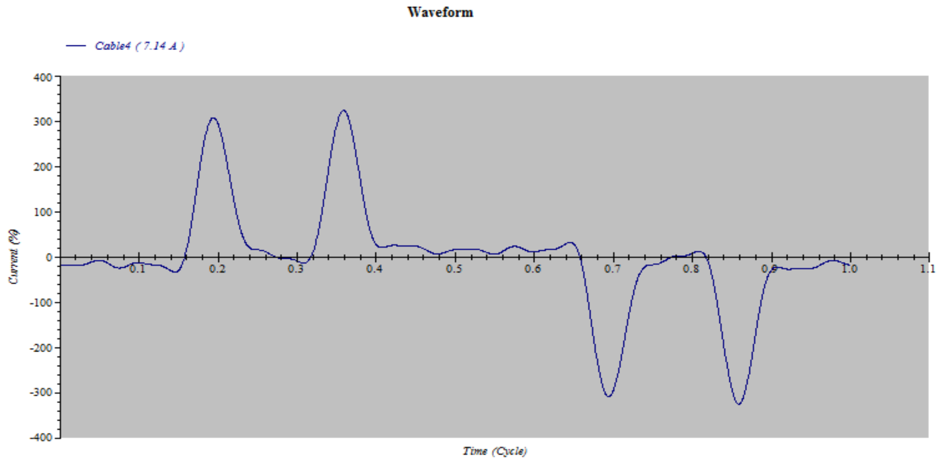

Fig 4.45: Current waveforme on cable 4

Fig (4.46) below shows the harmonic spectrum of the current, as in case of the 6-pulse VFD, the dominating harmonic orders are the 5th and 7th harmonics.

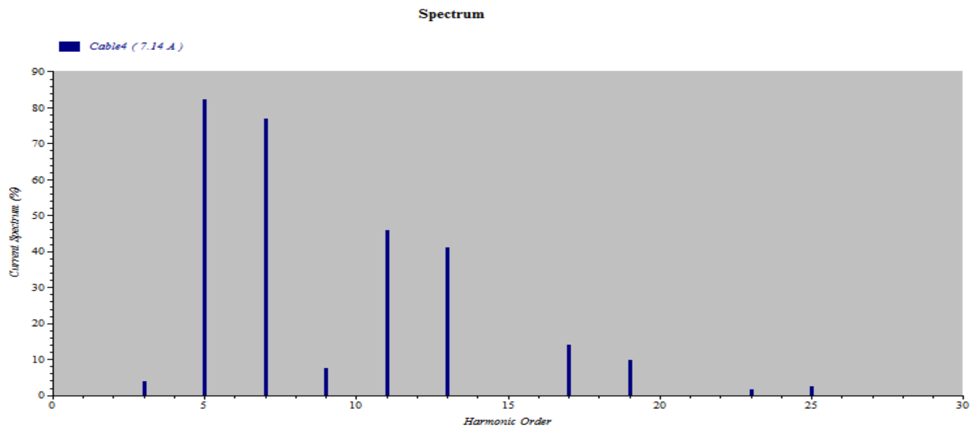

Fig 4.46: Harmonic spectrum for current on cable 4

From Fig (4.47) below, the effect of having a VFD in the system is very clear, the harmonics are spreading in the system causing voltage distortion at different bus bars of the system. This value of voltage distortion doesn't comply with (IEEE STD 519).

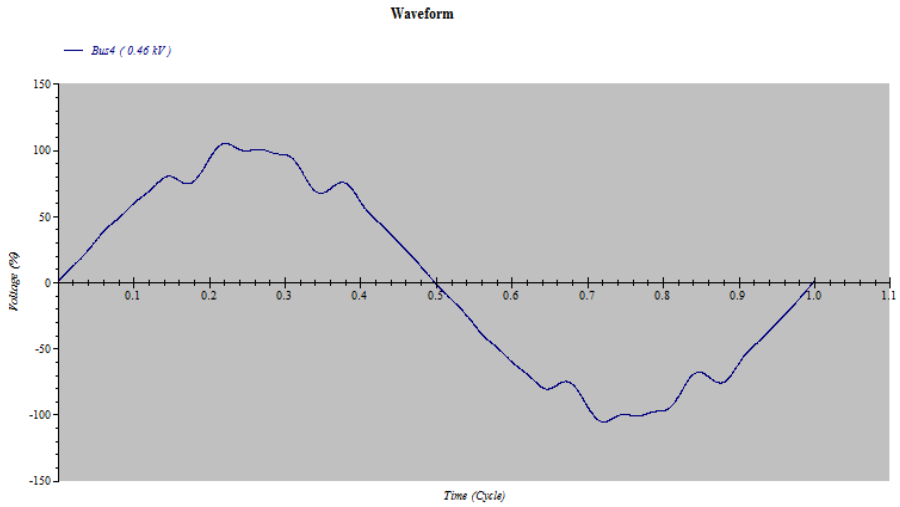

Fig 4.47: Voltage waveform at bus bar 4

4.4.2 Harmonic reduction using ETAP software:

Analysis of harmonic distortion on a system containing more than one VFD had been performed.

The model consists of 10 motors controlled by 10 VFDs, the system has two transformers, a utility transformer which steps down the incoming voltage from 33KV to 11KV, the second transformer is the user transformer which steps down the voltage from 11KV to 0.46KV. The point of common coupling will be at T1 which is the utility transformer, so the harmonic distortion at that point must not exceed the (IEEE STD 519) limit. The proposed model had been designed using ETAP software and a harmonic analysis had been performed, the following result had been obtained on Fig (4.48) below.

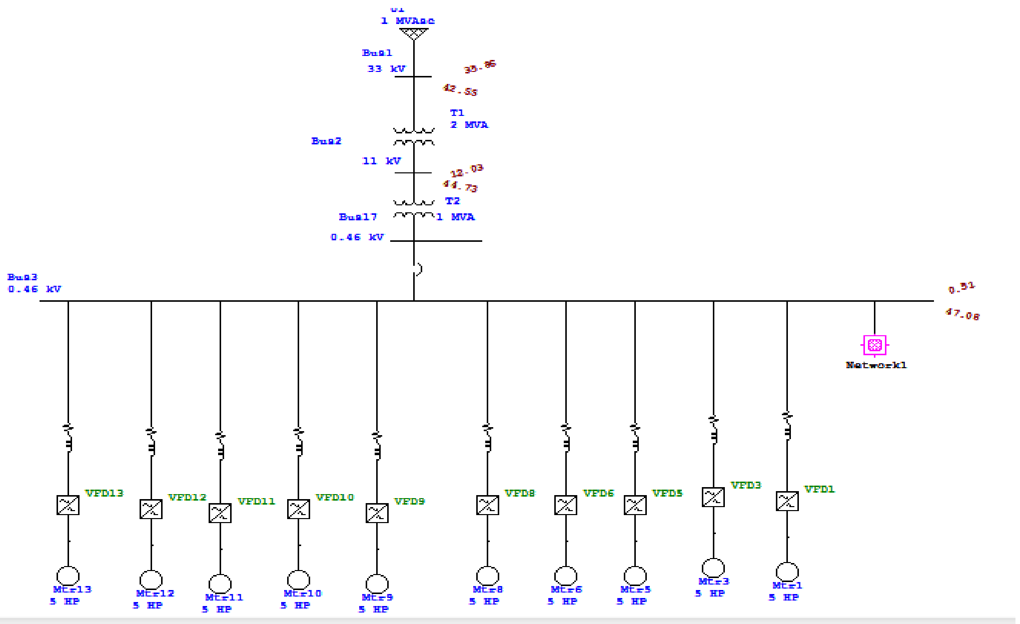

Fig 4.48: ETAP model of the proposed 10 motors system

From the harmonic analysis the following table is filled representing the voltage distortion at each bus bar

Table (4.2) the voltage distortion of different bus bars in the system

Bus bar	Voltage distortion
Bus 3	47.08%
Bus 17	47.08%
Bus 2	44.73%
Bus 1	42.55%

From Fig (4.54) to Fig (4.56) it is clear that the system harmonics are (5^{th},7^{th}, 11^{th},13^{th},17^{th},19^{th}) The system reactive power demand is 61 KVAR, total current of 77.2 A at bus 3 and the power factor of 85.2%, the 12-pulse system is not a practical solution for this system because of the high cost, and because of the high reactive demand of the system the multi-arm passive filter is preferred to compensate for that reactive power and improving the power factor. So a multi-arm passive filter is used for the mitigation of harmonic. Using ETAP filter design tool, the filters had been designed, the reactive power and harmonic current of each filter had been calculated using Eq (4.1).

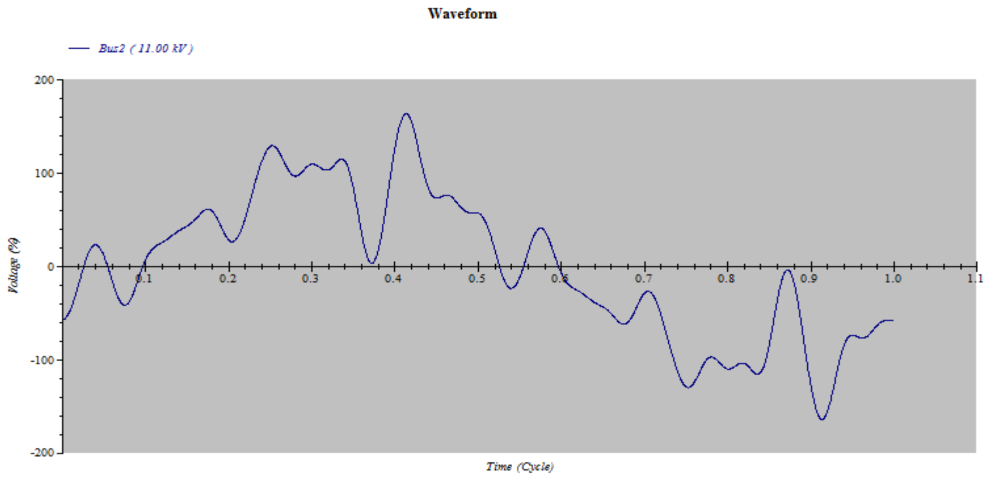

Fig 4.49: Voltage waveform on bus 2

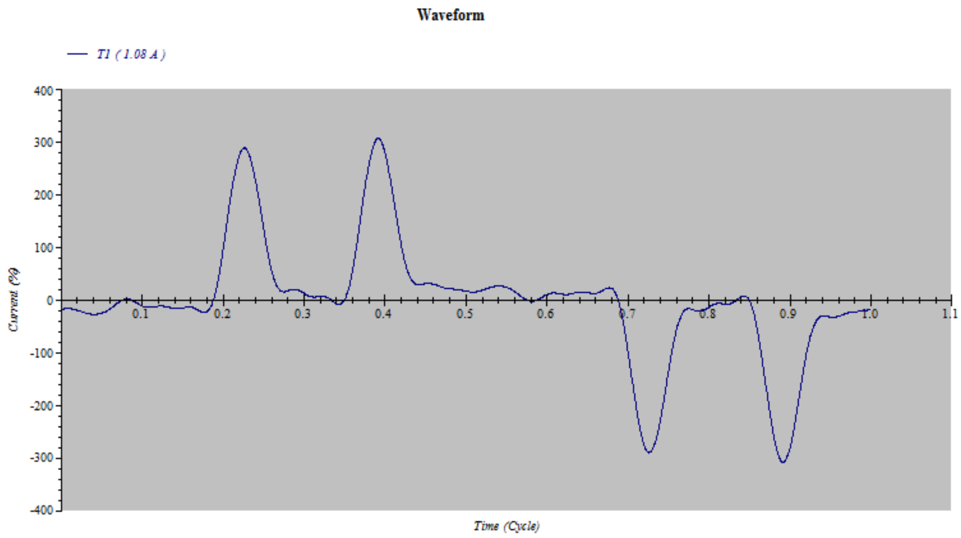

fig 4.50: Current waveform of the Utility transformer (T1)

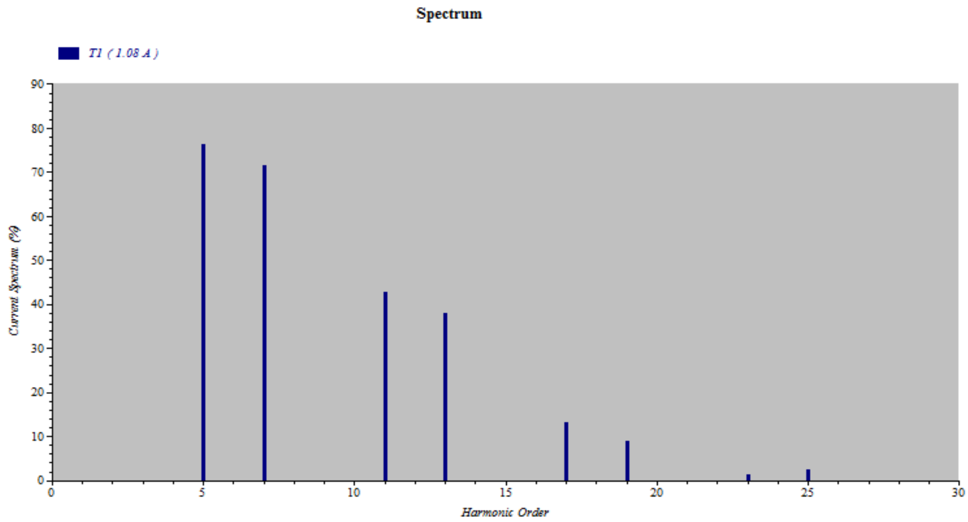

Fig 4.51: Harmonic spectrum for current at the Utility transformer

The following results had been obtained for each filter and put together in the following table.

Table (4.3) calculated values for the multiple arm passive filter

Harmonic order	XL(Ω)	C(μF)
5^{th}	0.8982	118.1
7^{th}	0.5062	106.9
11^{th}	0.3497	62.68
13^{th}	0.2773	56.61
17^{th}	0.4881	18.81
19^{th}	0.5861	12.54

The following results had been obtained after the installation of the multiple arm filter

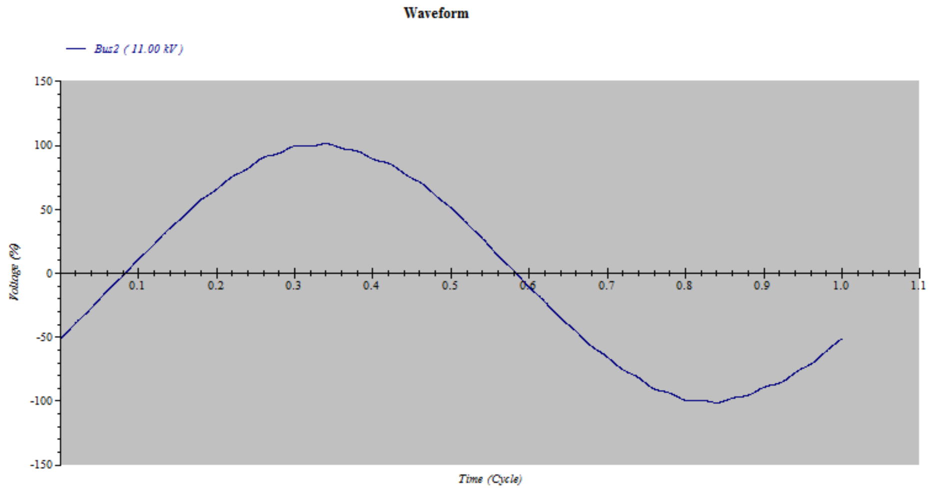

Fig 4.52: Voltage waveform at bus 2 when filters are used

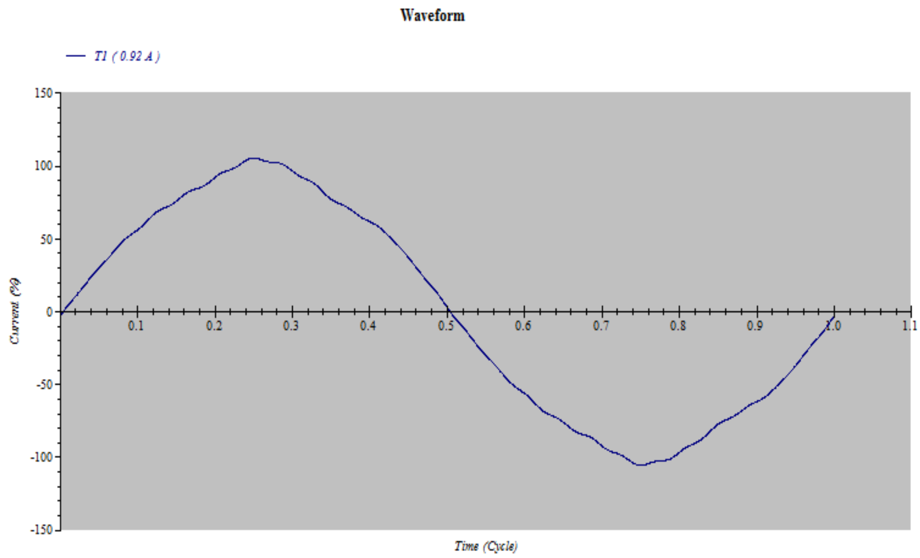

Fig 4.53: Current waveform at the Utility transformer (T1) when filters are used

In Fig (4.54) below, the reduction on harmonic current on the system can be noted, the THDI had dropped from 120 % to 3.78% which comply with (IEEE STD 519), because the short circuit current at bus 2 is 0.017 KA (obtain by performing a S.C test at bus 2) and the full load current is 77.2, by dividing this two values we will get (60) .so from Table (3.1&3.2) of (IEEE STD 519), it is seen that minimum current distortion allowed is 8%.

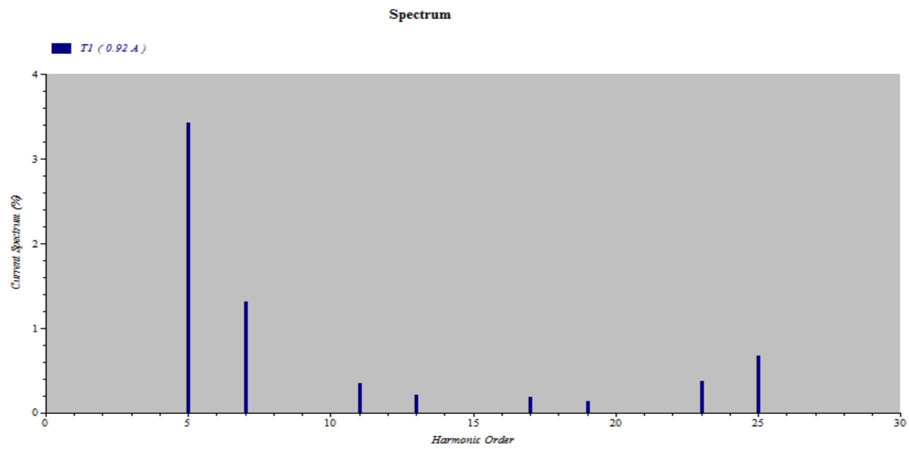

Fig 4.54: Harmonic spectrum for current at the Utility transformer when filters are used

4.5 Effect of rating of motor on harmonics:

To study the size of motor on harmonic, another motor with different rating have to be examined and simulated with MATLAB/Simulink, in this case 100 HP motor was selected to be examined.

FFT analysis had been used to present total harmonic distortion of both voltage and current, Fig (4.55) below represent harmonic spectrum of current of 100 HP motor.

In Fig (4.55) It is seen that the values of harmonic currents are higher than the case of 5 HP motor, because motor draws more nonlinear current from the supply. And it is obvious that the total harmonic distortion of this motor is lower than the total harmonic distortion of 5 HP motor, because the total harmonic distortion is obtained by the Eq (4.2) below, and the fundamental value of current is very high when compared to other harmonics order currents, it is just a mathematical matter when denominator is high the result going to be low.

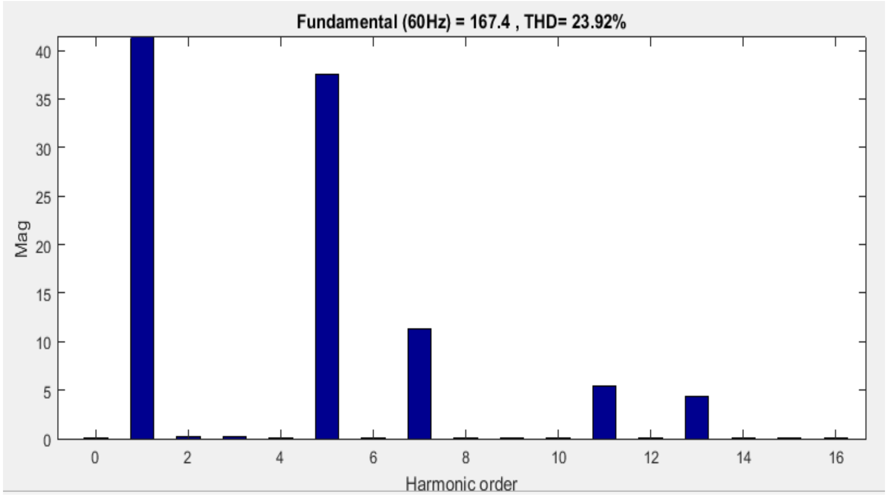

Fig 4.55: Harmonic spectrum of current to 100 HP motor.

$$I_{thd} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_n^2}}{I_1} \times 100\% \qquad (4.2)$$

From Fig (4.56) below the THDV is 15.5% this value is higher than the THDV to 5 HP, the reason for this is harmonic currents had increased and voltage distortion is caused when the harmonic currents interact with the system impedances to produce voltage drop at each individual harmonic frequency.

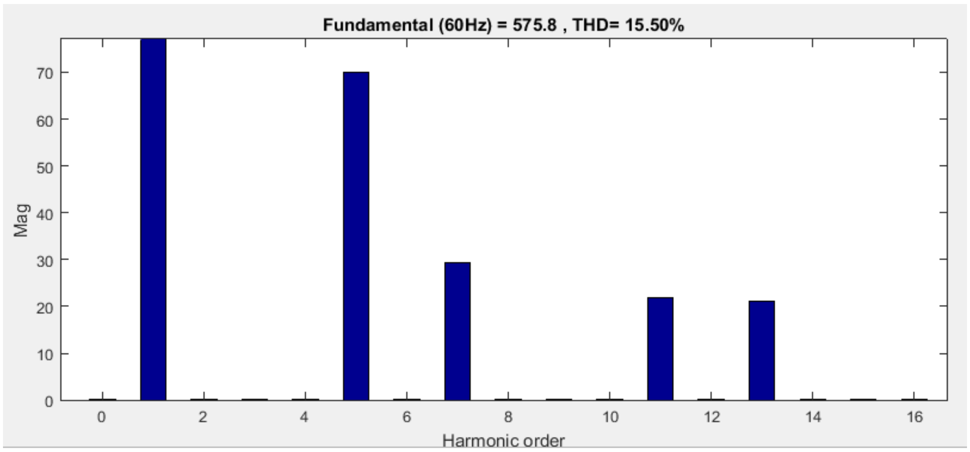

Fig 4.56: Harmonic spectrum of voltage to 100 HP motor.

In Fig (4.57) it’s clear that voltage waveform is less sinusoidal in shape because THDV is increased when compared to THDV of 5 HP motor, and current waveform improved when compared to current waveform of 5 HP motor the reason for that is THDI is reduced from 95.53% to 23.93%.

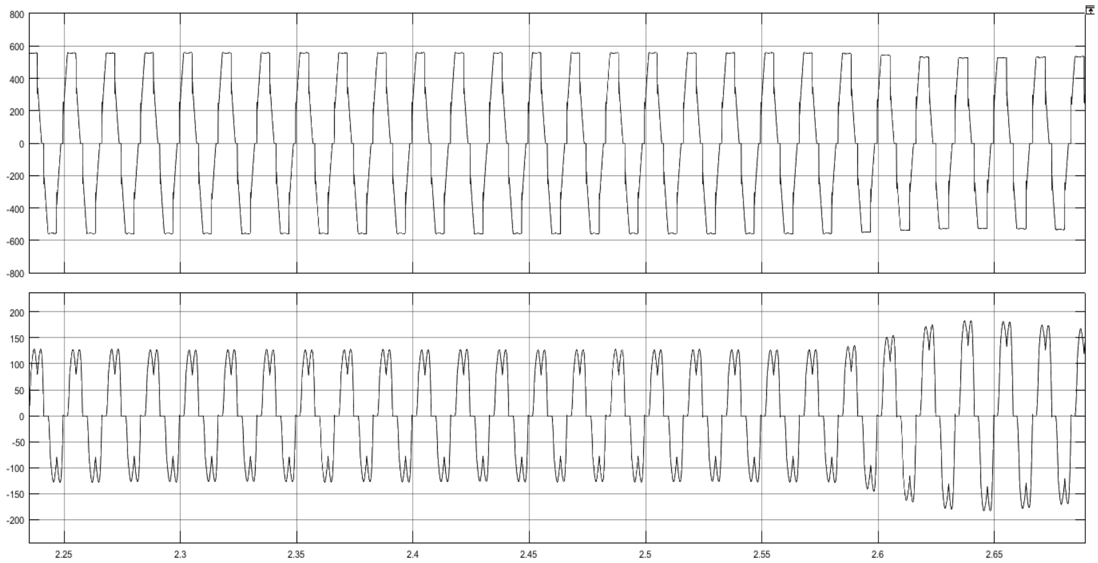

Fig 4.57: Voltage and current waveforms of 100 HP motor

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion:

Six Pulse VFDs are widely used in speed control in industrial and domestic applications but these devices generate harmonics at both of its sides because it uses a rectifier and an inverter to control the speed.

The higher the motor loading (current drawing) the lower the total current harmonic distortion THD.

The larger the system impedance (transformers, cables,) the larger the voltage distortion because the distorted current will cause more distorted voltage drops which increases the THDV.

Harmonic voltages and currents at the primary of the transformer are less than that of the secondary, because the transformer impedance will work to reduce the distortion.

The higher the short circuit capacity of supply, the lower the voltage harmonics.

The best method of harmonic mitigation in this project is the 12-pulse system, but it will have a poor performance with voltage unbalance (more than 1%).

The most economical harmonic mitigation technique is the AC or DC reactor, but it will not reduce harmonic distortion to a level that complies with (IEEE STD 519).

Single-tuned Passive filters can decrease a single harmonic order to a low value but this is not enough to make the drive comply with the standard unless it is combined with another single-tuned filter and a reactor.

The higher the motor's rating the lower the total harmonic distortion in current.

5.2 Recommendations:

In this project, not all of the mitigation techniques were used, we hope that more researches will continue the work that we began, the following methods of mitigation techniques may by a good start:

- SVPWM: VFD is a two-stage power converter that transforms first the grid AC to DC and then DC to AC. PWM and the control of the Power Electronic DC-AC converter has attracted much attention in the last three decades. It is recommended to use space vector PWM (SVPWM) rather than sinusoidal PWM (SPWM) because the achievable output in the case of SVPWM is higher when compared to the SPWM. And the main aim of the modulation techniques is to attain the maximum voltage with the lowest Total Harmonic Distortion (THD) in the output voltages. [30]

-Active filters: It is recommended to use active filter. It can be applied either as a standalone harmonics filter or by incorporating the technology into the rectifier stage of a drive. It will monitor the load current. It filters out the fundamental frequency current and analyse the frequency and magnitude content of the remaining current. Then, it injects the appropriate inverse currents to cancel the individual harmonics.

-18-pulse drive: For mitigation of harmonics It is recommended to use18-pulse drive. It involves a special type of rectifier and transformer configuration, transformers three, respectively, separate secondary windings. This configuration act to cancel some of the lower level, higher amplitude harmonic currents. The degree of phase shift between each secondary is 20^{o}.

Current distortion at the input terminals is approximately 5% for 18-pulse drives.

-Active Interphase Transformer for 12-Pulse Rectifier System: By incorporating active interphase transformer in 12-pulse rectifier system, a suitable method of harmonic reduction in utility line currents can be achieved. This system provides clean input power. A triangular shaped current of (300 Hz frequency) is injected into the auxiliary winding of active interphase transformer yields near sinusoidal utility line currents The utility line current THD is measured around (2.8% - 4.9 %). It gives superior performance under varying load condition with reduced kVA component. [34]

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