Study on the variable frequency drive of an induction motor to reduce harmonics

Kassaw Eneyew Mekcha

A Thesis Submitted to

The Department of Electrical Power and Control Engineering
School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of
Master's in Electrical Power and Control Engineering (power)

Office of Graduate Studies
Adama Science and Technology University

September, 2022
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DECLARATION

I hereby declare that this Master Thesis entitled “A Study on the variable frequency drive of an induction motor to reduce harmonics” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Kassaw Eneyew Mekcha September, 2022

Name of the student Signature Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled "A Study on the variable frequency drive of an induction motor to reduce harmonics" prepared under our guidance by **Kassaw Eneyew Mekcha** submitted in partial fulfillment of the requirements for the degree of Master's of Science in power Engineering. Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

____________________________	________________________	________________
Major Advisor	Signature	Date

APPROVAL SHEET

We, the advisors of the thesis entitled "A Study on the variable frequency drive of an induction motor to reduce harmonics" and developed by **Kassaw Eneyew Mekcha**, here by certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Kassaw Eneyew Mekcha have read and evaluated the thesis entitled "A Study on the variable frequency drive of an induction motor to reduce harmonics" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in power Engineering.

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Contents

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Lists of Acronyms

VFD	Variable Frequency Drive
AC	Alternative Current
DC	Direct Current
PWM	Pulse Width Modulation
VSD	Variable speed drive
SPWM	Sinusoidal Pulse Width Modulation
DOL	Direct On Line
ASD	Adjustable Speed Drive
CSI	Current Source Invertors
VSI	Voltage Source Invertors
NS	Synchronous Speed
NB	Base speed
NM	Newton-Meter
FLA	Full load ampere
PC	Personal computer
PF	Power factor
THD	Total Harmonics Distortion
MOSFET	Metal Oxide Field Effect Transistor
IGBT	Insulated gate bipolar transistor
GTO	Gate turns off thyristor
BW	Band Width
FSF	Frequency Scaling Factor
ISF	Impedance Scaling Factor
VCVS	Voltage Control Voltage Source
THD	Total harmonics distortion
MAT-LAB	Matrix laboratory
IEEE	Institute of Electrical and Electronics Engineers

PCC	Point of Common Coupling
HCS	Harmonic Current Source
HVS	Harmonics Voltage Source

Lists of symbols

V	Linear Velocity
N	Rotational Speed
ω	Angular velocity
a	Linear acceleration
I	Current
V	Voltage
R	Resistance
Tr	Transistor
Rn	Normal Resistance
Cn	Normal Capacitance
Fc	Cut Off Frequency
HZ	Hertz

ABSTRACT

This thesis presents a method of designing and specify low voltage harmonics filters for variable frequency drives. The proposed method is used to measure the harmonics generated by VFD drive using harmonics analyzer and calculating then analyzing it to design active filter. The Variable Frequency Drive (VFD) is an electronics device to change utility power source to variable frequency to control AC motor in variable speed operation. It can be varies as per the load requirement. So, speed must be change as per increasing or decreasing the load. If supply voltage decreased, motor torques is also decreased. Motor speed is directly proportional to supply frequency, Hence, to maintain the speed supply voltage and frequency must be vary accordingly but during the switching sequence of the variable frequency drive generates harmonics. This thesis is intended to provide a basic understanding of Variable Frequency Drive (VFD) and reducing the VFD drive generated harmonics of the system by designing the active high pass filter in kessem sugar factory pump motor drives. This is done by using matlab Simulink software to show the effectiveness of the active filter. The reduced total harmonics distortion values in current and voltage are THD_I=0.064% and THD_V=0.017% respectively This makes reducing harmonics and as a result the VFD drives itself, the motor, the cable, total systems becomes protected from unwanted signals/harmonics and their life time will be increase if it is implemented. Output of the Simulink model with filter and without filter are shown, their out puts are compared and discussed based on results.

CHAPTER ONE

INTRODUCTION

1.1 Back ground of variable frequency drive/variable speed drive

It is known that the VFD drive converts the 50Hz fixed frequency and fixed voltage AC power supply to variable frequency and voltage using an integrated rectifier. Integrated power electronics then inverts the DC power supply in to a simulated PWM sinusoidal output with continuously variable frequency and voltage which is used to drive motor depending on the requirements of the operation. Converter changes AC power to DC power while inverter changes DC power to AC power. Therefore, there are many and diverse reasons for using variable speed drives in the factory. Some applications, such as paper making machines cannot run without them while others, such as centrifugal pumps, can benefit from energy savings (Dave Galbraith, 2018)

In general, variable speed drives are used to:

- ✓ Match the torque of a drive to the process requirements
- ✓ Match the speed of a drive to the process requirements
- ✓ Save energy and improve efficiency
- ✓ Controlling the Process
- ✓ Have Low inrush starting (soft starting method)
- ✓ Have the Overload protection
- ✓ Have Multi-motor operation
- ✓ Increasing Power Factor and low loss of power
- ✓ Make suitable Phase converting
- ✓ Control Over-speeding
- ✓ Critical speed rejection which is unwanted

The needs for speed and torque control are usually fairly obvious. Modern electrical VSDs can be used to accurately maintain the speed of a driven machine to within ±0.1%, independent of load, compared to the speed regulation possible with a conventional fixed speed squirrel cage induction motor, where the speed can vary by as much as 3% from no load to full load. The benefits of energy savings are not always fully appreciated by many users. These savings are particularly apparent with centrifugal pumps and fans. Substantial cost savings can be achieved in some applications. An everyday example, which illustrates the benefits of variable speed control, is the motor car. It has become such an integral part of our lives that we seldom think about the technology that it represents or that it is simply a variable speed platform. It is used here to illustrate how variable speed drives are used to improve the speed, torque and energy performance of a machine. It is intuitively obvious that the speed of a motorcar must continuously be controlled by the driver (the operator) to match the traffic conditions on the road (the process). In a city, it is necessary to obey speed limits, avoid collisions and to start, accelerate, decelerate and stop when required. On the open road, the main objective is to get to a destination safely in the shortest time without exceeding the speed limit. The two main controls that Practical Variable Speed Drives and Power Electronics are used to control the speed are the accelerator, which controls the driving torque, and the brake, which adjusts the load torque. A motorcar could not be safely operated in city traffic or on the open road without these two controls. The driver must continuously adjust the fuel input to the engine (the drive) to maintain a constant speed in spite of the changes in the load, such as an uphill, downhill or strong wind conditions. On other occasions he may have to use the brake to adjust the load and slow the vehicle down to standstill. Another important issue for most drivers is the cost of fuel or the cost of energy consumption. The speed is controlled via the accelerator that controls the fuel input to the engine. By adjusting the accelerator position, the energy consumption is kept to a minimum and is matched to the speed and load conditions. Imagine the high fuel consumption of a diesel generator using a fixed speed setting and controlling the speed by means of the drive of the load.

The paper focuses on problem lies with system harmonics generates by VFD drive which adjusts the speed of induction motor. The irregularities in the sine wave are called harmonics. In an ideal power circuit world, these harmonics should not exist. They do nothing but cause problems. Fortunately, there are a number of ways to mitigate harmonics. To reduce this harmonics, active filters are better to reduce harmonics because due to this harmonics equipment in the system and the drive itself damaged as I have seen in factories, therefore the aim of the research is to reduce this problem to make operation smooth and to make the factory profitable (United States Department of Agricalture,2010).

Fundamental principles of operation: the following are some of the fundamental principles associated with variable speed drive applications.

a. Forward direction: this refers to motion in one particular direction, which is chosen by the user or designer as being the forward direction. The forward direction is designated by positive (+ve). For example, the forward direction for a motor car is intuitively obvious from the design of the vehicle. Conveyor belts and pumps also usually have a clearly identifiable forward direction.
b. Reverse direction: this refers to motion in the opposite direction. The reverse direction is designated as being negative (-ve).for example, the reverse direction for a motor car is occasionally used for special situation s such as parking or up-parking the vehicle.
c. Force: motion is the result of applying one or more forces to an object. Motion takes place in the direction in which the resultant force is applied.so force is a combination of both magnitude and direction. a force can be positive or negative if it is applied in the reverse direction.in SI units, force is measured in Newtons.
d. Linear velocity (v) or speed (n): Linear velocity is the measure of the linear distance that a moving object covers in a unit of time.it is the result of linear force being applied to the object. In SI units, this is usually measured in meters per second (m/sec).kilometers per hour (km/hr) are also a common unit of measurement. For motion in the forward direction, velocity is designated as positive and for motion in the reverse direction, velocity is designated as negative.
e. Angular velocity (ω) or rotational speed (n): Although a force is directional and results in linear motion, many industrial applications are based on rotary motion. The rotational force associated with rotating equipment is known as torque. Angular velocity is the result of the application of torque and is the angular rotation that a moving object covers in the unit of time.in SI units; this is usually measured in radians per second (rad/sec) or revolutions per second (rev/sec). Torque: Torque is the product of the tangential force F, at the circumference of the wheel, and the radius r to the center of the wheel.in SI units, torque is measured in Neuton meter (Nm).a torque can be positive (+ve) or negative (-ve) depending on the direction in which it is applied. A torque is said to be +ve if it is applied in the forward direction of rotation and negative if it is applied in the reverse direction of rotation.
f. Linear acceleration(α): Linear acceleration is the rotary of change of linear velocity usually in meter per second square (m/sec2)

Linear acceleration

$\alpha = \frac{dv}{dt} m/sec2$, where linear acceleration is the increase in velocity in either direction linear deceleration or braking is the decrease in velocity in either direction.

g. Rotational acceleration (α): Rotational acceleration is the rate of change of rotational velocity, usually in rad/sec2.rotational acceleration

$\alpha = \frac{dw}{dt} rad/sec2$, rotational acceleration is the increase in velocity in either direction. Rotational deceleration or braking is the decrease in velocity in either direction.

1.2 Types of variable speed drive

The most common types of variable speed drives are used today in many industries.

The main types of variable speed drives for industrial applications are as follow:

a. Typical mechanical VSD with an AC motor as a prime mover
b. Typical hydraulic VSD with an AC motor as a prime mover
c. Typical electrical VSD with a DC motor and DC voltage converter
d. Typical electrical VSD with an AC motor and AC frequency converter

1.2.1 Proposed VFD drive with filter for induction motor speed control

This study focuses on searching on the analysis of the drive converter and inverter parts and it is expected to get better power saving, increasing production through tighter process control and extend equipment life and reduce maintenance by reducing the harmonics which is the common problems of VFD and In addition, comparing with other convectional types of drives.

A filter is a circuit that is designed to pass a specified band of frequencies while attenuating all signals outside this band. Filter networks may be either active or passive. Passive filter networks contain only resistors, inductors, and capacitors. Active filters, which are the only type covered in this paper, employ operational amplifiers (op-amps) as well as resistors and capacitors (Dave Galbraith, 2018).

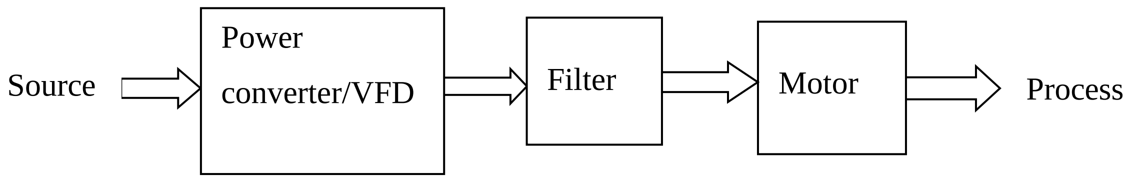

Figure1.1 Block diagrams of VFD drive with filter

As filters are defined by their frequency-domain effects on signals, it makes sense that the most useful analytical and graphical descriptions of filters also fall under the frequency domain. Thus, curves of gain versus frequency and phase versus frequency are commonly used to illustrate filter characteristics, and most widely used mathematical tools are based on the frequency domain. The frequency-domain behavior of a filter is described mathematically in terms of its transfer function or network function. This is the ratio of the Laplace transforms of its output and input signals. The voltage transfer function of a filter can therefore be written as

$$H(s) = \frac{Vo(s)}{Vi(s)}$$

Where s is the complex frequency variable

The Laplace transform approach to the filter analysis allows the designer to work with algebraic equations in the frequency domain. These are relatively easy to interpret by observation. In contrast, a time-domain approach to filter mathematics results in complex differential equations that are usually far more difficult to manipulate and interpret. The transfer function defines the filter's response to any arbitrary input signals, but we are most often concerned with its effect on continuous sine waves, especially the magnitude of the transfer function to signals at various frequencies. Knowing the transfer function magnitude (or gain) at each frequency allows us to determine how well the filter can distinguish between signals at different frequencies (United States Department of Agriculture, 2010).

1.3 Statement of the problem

The demand for VFD drives of the induction motor has increased in many industrial applications. Because, the main advantages of these machines which use VFD drives includes high efficiency and reliability, reduce noise, long life time, and better speed versus torque characteristics.

Currently the main problems in industries are the starting methods because many starting methods like star delta, direct on-line and others have high starting current. During starting high inrush current flows through the winding of the machine (above 4-7 times of its rating), it causes disturbance in the system, shortening the life times of the machine, transient currents will occur, low starting torque. These and other additional problems causes the voltage collapse and interruption of the system, over flow of inrush currents causes temperatures on the lines(cables).these causes failure of insulators of the conductor and also these in sequence cause short circuit between line to line. The short circuit damages the machines and causes interruption in the network even there is a probability of voltage collapse. VFD drives are the most preferable when compared with the other starting method but harmonics is the major problems of the drive, so this thesis focuses on improving or reducing the harmonics because it causes many failure on the system and failure on drive, this causes high expense on the factory to purchase the failed VFD drive and causes high down time to re start the operation. Due to this the profitability of the factory will be reduced. Therefore, we have to avoid or reduce the harmonics which is generated from the VFD drive.

The research focuses to answer the following questions:

- ✓ How to select the induction machine rating with its drive?
- ✓ How to reduce the current harmonics?
- ✓ How to model the current and speed controllers of the system of VFD free from harmonics?
- ✓ How to drive the induction motor with better efficiency and performance with reduced harmonics?
- ✓ How to model the entire equipment of VFD using Matlab/simulink with active filter
- ✓ How the outputs of the model of VFD simulink differ with filter and without filter

1.4 Objectives of thesis

1.4.1 General objective

The general objective of the thesis is to reduce harmonics which is generated by VFD drive on pump system and to control the speed by varying frequency of the signal depending on operation. This extends the equipment life time, reducing the harmonics of VFD drive and supplying harmonic free power for induction motor to make it more available for a long time for the required operation, pumping operation and making the factory more profitable.

1.4.2 Specific objectives

The main aim of this thesis is to reduced harmonics in the pump systems of the factory to avoid failure of equipment like drive, motor, cable, the whole system in the factory

The objectives are:-

- ✓ To controlling the speed of induction motors using improved (reduced harmonics)
- ✓ To improve time response parameters for induction motor speed response(overshot, settling time, rise time) without harmonics disturbance
- ✓ To improve frequency response for induction motor speed response by using active power filters in the pump system
- ✓ Performing analysis of the system by comparing VFD with filter, and without filter in addition with the other types of drives soft starter, star-delta, DOL

1.5 Scope of the study

The study mainly focuses on reduction of harmonics in the pump drive systems, variable frequency drive (VFD) both on converter and inverter to control the current flow through the system, voltage drop and speed of the induction motor with free of harmonics since harmonics is the main problems of electronics drive. Reducing the harmonics of VFD is the main target of this thesis using the active power filter. The study simulates the drive circuit with filter and without filter and comparing the output then concludes the advantages of the active power filter function in the reduction of harmonics in the VFD drive system. Due to the materials scarcity practical is not done.

1.6 Area of the study

This research is done on the pump drive systems in Kessem sugar factory for controlling the speed of the pump depending on the operation by reducing the harmonics which is generated by VFD because harmonics is the main problem on VFD drives in the factory. To extend the life the machine and to reduce cost of the operation we have to use the proposed active filter to reduce harmonics of VFD drive in kessem sugar factor pump systems

CHAPTER TWO

LITERATURE REVIEW

2.1 variable frequency drive fundamentals

In Variable Speed application, voltage Source Inverter is commonly used to supply a variable frequency variable voltage to a three phase induction motor. In this PWM drives are more efficient and typically provide higher levels of performance. A suitable Pulse Width Modulation technique is employed to obtain the required output voltage of the inverter. The most common AC drives today are based on sinusoidal pulse-width modulation SPWM. Induction motor is rugged, reliable, and single-fed machine; it can directly absorb the reactive power from the utility with this device, we can get two advantages: one is that we can get a low start current; the other is that we can change the motor speed conveniently by controlling the output frequency of the ASD (Jay Bradford, 2010).

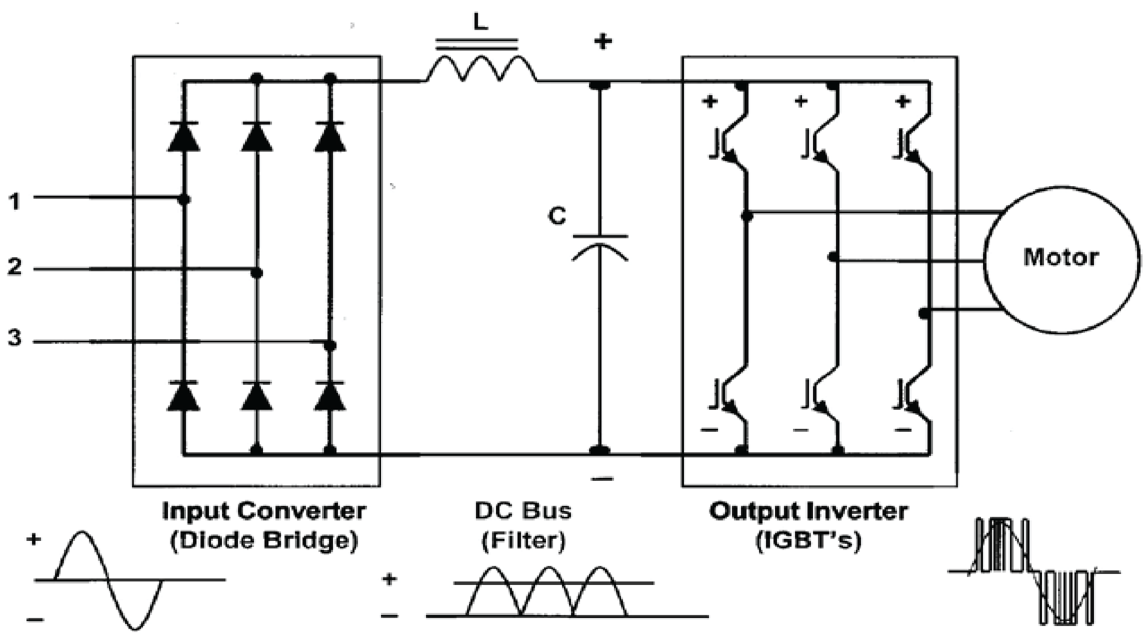

Figure 2.1 Basic PWM Drive Components with induction motor without filter

Two basic types of inverters exist in general. Current source inverter (CSI), employing a dc link inductance across the inverter and this provides a switched current waveform at the motor output terminals. CSI are robust in operation and reliable due to the insensitivity to short circuits and noisy environment. Voltage Source Inverter (VSI), employing a dc link capacitor and providing a switched voltage waveform and they are commonly used when compared to Current Source Inverter since the use of Pulse Width Modulation (PWM) in them allows efficient and smooth operation, which is free from torque pulsations and cogging. Furthermore, the frequency range of VSI is higher and they are usually more in expensive when compared to CSI drives of the same rating. Both Voltage Source Inverters and Current Source Inverters are used in adjustable speed AC drives. However, Voltage Source Inverters with constant Volts/Hertz (V/f) are more popular, where the need of high accuracy of speed control is not crucial and for the applications without position control requirements. we can divide the world of electronic motor drives into two categories: AC and DC. AC motor drive controls the speed, torque, direction and resulting horsepower of a motor. A DC drive typically controls a shunt wound DC motor, which has separate armature and field circuits. AC drives control AC induction motors, and-like their DC counterparts-control speed, torque, and horsepower. A drive can control two main elements of a 3-phase induction motor: speed and torque. To understand how a drive controls these two elements, we will take a short review of AC induction motors(Hydro-Quuebec,2008).The two basic parts of the motor, the rotor and stator, work through magnetic interaction. A motor contains pole pairs. These are iron pieces in the stator, wound in a specific pattern to provide a north to south magnetic field. With one pole pair isolated in a motor, the rotor (shaft) rotates at a specific speed, the base speed. The number of poles and the frequency applied determine this speed. This formula includes an effect called slip. Slip is the difference between the rotor speed and the rotating magnetic field in the stator. When a magnetic field passes through the conductors of the rotor, the rotor takes on magnetic fields of its own. These rotor magnetic fields will try to catch up to the rotating fields of the stator. However, it never does this difference is slip. Think of slip as the distance between the greyhounds and the hare they are chasing around the track. As long as they don’t catch up to the hare, they will continue to revolve around the track. Slip is what allows a motor to turn (United States Department of Agriculture, 2008).

The speed of an Alternating Current (AC) motor depends on three principle variables:

- The fixed number of winding sets (known as poles) built into the motor, which determines the motor's base speed.
- The frequency of the AC line voltage. Variable speed drives change this frequency to change the speed of the motor.

- The third variable is the amount of torque loading on the motor, which causes slip. Because slippage occurs, the actual motor speed is somewhat lower than the nameplate value for the motor.

2.1.1 Motor speed and slip:

The synchronous speed of an AC motor is determined by the frequency of the source and the number of poles. The RPM is calculated by multiplying the frequency times 60 and dividing by the number of pairs of poles. Actual speed of the induction motor will be less than the synchronous speed. The reason for this is if the armature turns exactly at synchronous speed, then the magnetic field of the stator windings no longer cuts the rotor windings. Under this condition, no current would be induced to the rotor windings. With no current flow in the armature, no magnetic field will be developed.

Synchronous speed= $120 \times \frac{\text{frequency}}{\text{number of poles}}$,

$$\%\ \text{slip} = \frac{\text{NS} - \text{NB}}{\text{NS}} \times 100$$

Where f is frequency in Hz applied to the motor and p is pole number of motor

NS-synchronous speed, NB-base/motor speed in rpm

Normal electric power in the Ethiopia is supplied at 50 cycles per second, or 50 hertz (Hz). Common motor rotational speeds (rpm) at this frequency are 3,000 rpm, 1,500 rpm, 1,000 rpm, or 750 rpm, depending on how the motors are wound (number of poles). Once the motor is fabricated, the only variable that can change in the synchronous speed equation is the frequency (Hz) of the power supply. The motor speed is directly proportional to the frequency. Rather than supplying the electric motor with a constant frequency of 50 Hz, the VFD takes the electrical supply from the utility and changes the frequency of the electric current which results in a change of motor speed also increasing the frequency above 50 hertz makes the motor run faster but it generates several concerns (ABB, 2018).

1. Is the motor or load design to increase in speed? Some motors are designed to operate at higher than normal speeds at frequencies above 50 Hz. However, most motors and devices are not mechanically balanced to operate without vibration and mechanical safety concerns at higher than design speeds.

2. VFD’s control both frequency and voltage simultaneously to keep a constant ratio of volts and hertz so that the motor sees a constant current flow similar to full speed conditions. VFD’s are not capable of increasing voltage so as the frequency increases the torque starts to decrease. At

some point as the speed increases there will not be enough torque to drive the load, and the motor will slow even with increased frequency.

VFD changing the frequency of the power supply is one way of controlling the pump speed; VFD’s are a subset of VSD’s. VFD’s are electronic systems that convert AC to DC and then simulate AC with a changed frequency thereby changing the speed of the motor. There are three basic designs for variable frequency AC motor controls: Six Step Inverter (variable voltage source), Current Source Inverter, and Pulse Width Modulated Inverter (PWM; constant voltage source). Each type possesses unique electrical characteristics which must be considered in the application for load requirements, motor selection, system operating efficiency, and power factor. Pulse Width Modulated (PWM) is the most prevalent. The PWM creates a series of pulses of fixed voltage and adjustable time duration (width). The sum of widths of the pulses and intermediate off cycles determine the resultant frequency of the wave. The sum of the pulse areas equals the effective voltage of the true alternating current (AC) sine wave. By varying the width of the pulses different wave lengths of alternating current can be simulated to emulate variable frequencies and the motor speed is controlled (ABB, 2018).

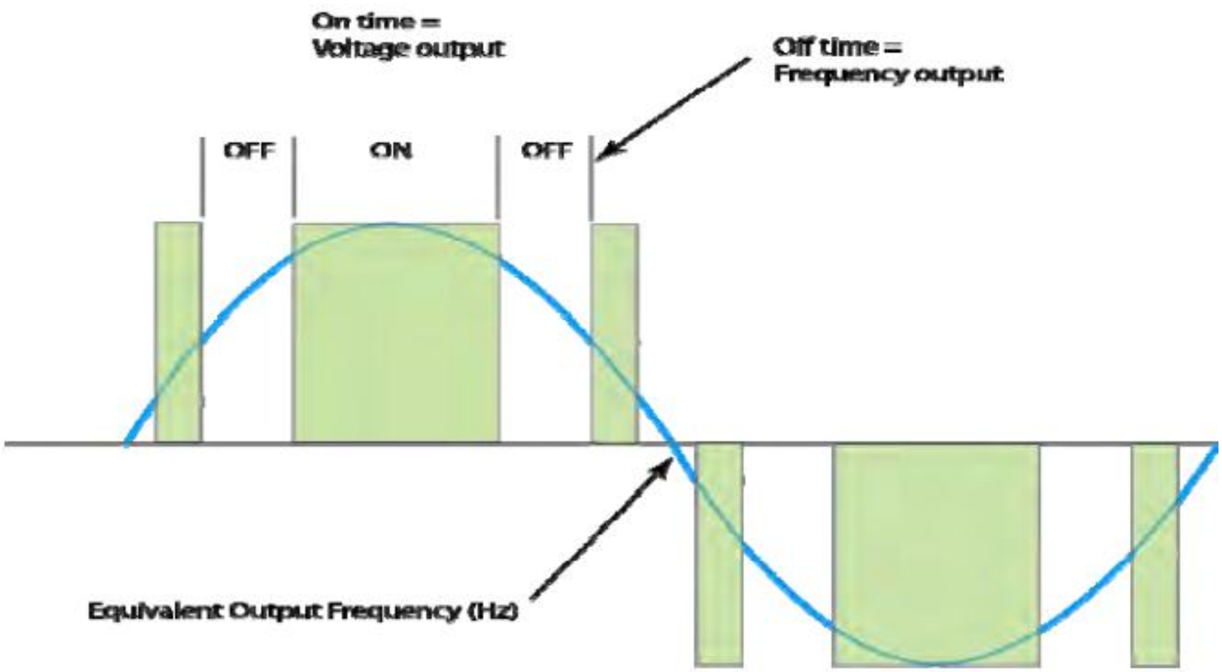

Figure 2.2 Pulse Width Modulation Wave form (United States department of agriculture, 2010)

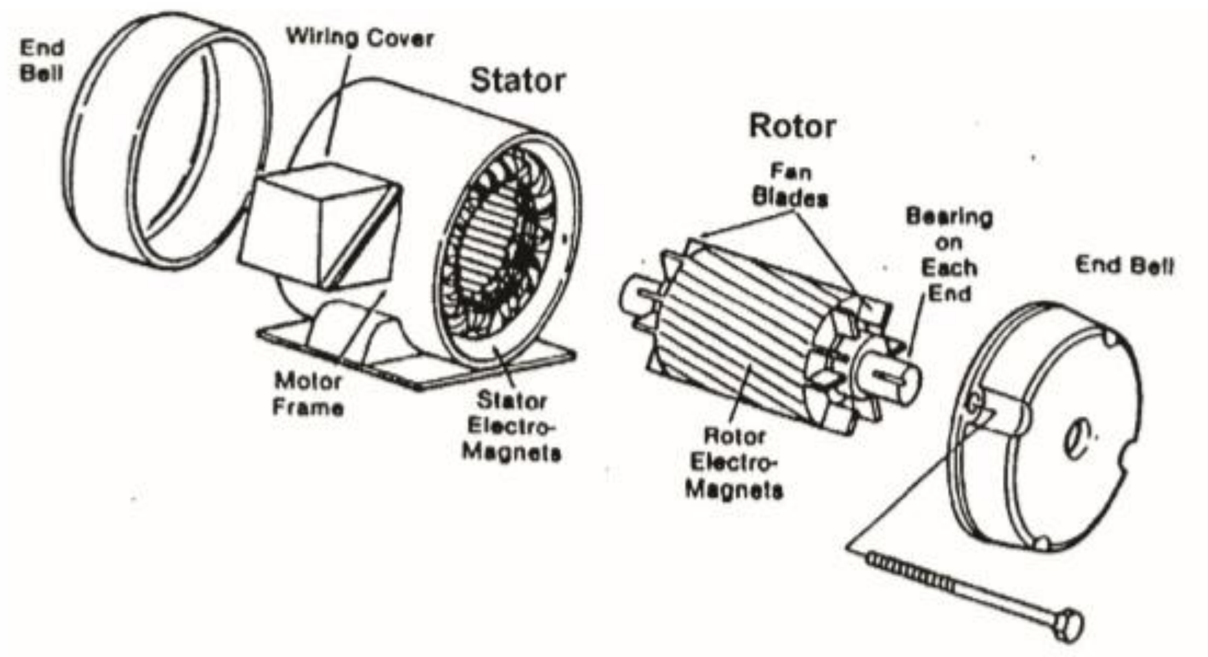

Figure 2.3 Basic Induction Motor Constructions (ABB, 2018)

VFDs run at a high power factor. Any class of induction motors usually has a low power factor at half and three-quarters load (0.75 to 0.85). This is actually decreases the life of the motor, because the unnecessary increase in current overheating the winding insulation. VFDs bypass this problem by running the load at a frequency below the fundamental.

The most obvious reason to procure a VFD is speed control. This is usually done for process, operation, and economic benefits. One economic benefit comes from the reduction of maintenance when using a VFD, especially not having to deal with the DC motor carbon brushes or mechanical speed-control gearboxes (transmissions). The most obvious economic benefits of VFDs occur with fans and pumps. The power that a pump or fan consumes is directly proportional to the cube of the velocity. This means if an operator can run a fan at 80% of full speed; it theoretically uses 51% of full load power.

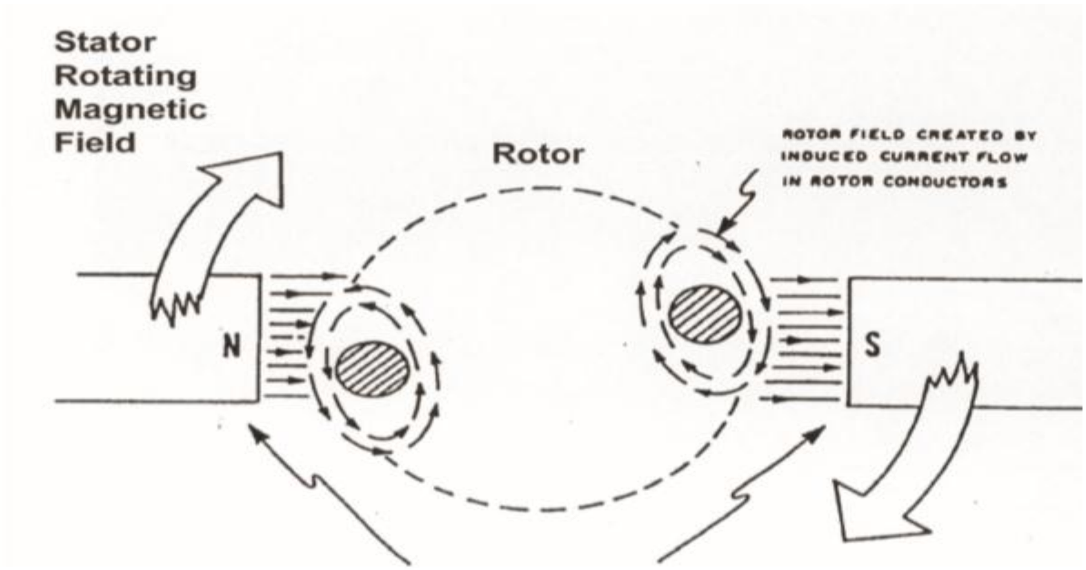

Figure 2.4 Operating Principles of Induction Motor (ABB, 2018)

We can conveniently adjust the speed of a motor by changing the frequency applied to the motor and by adjusting the number of poles, but this is a physical change to the motor. It would require rewinding, and result in a step change to the speed. So, for convenience, cost-efficiency, and precision, we change the frequency.

VFDs also optimize motor starting characteristics. VFDs bring motors up to full speed quickly and by drawing only 100% to 150% of full load amps (FLAs). This ability to start at normal FLA is very important if the power supply cannot withstand the normally six times FLA across-the-line starting draw, or even the 350% FLA soft-start device current. VFDs do this by managing the magnetic flux of an induction motor. Magnetic flux is directly proportional to the voltage and inversely proportional to the frequency. By keeping the flux constant, the inrush current does not exceed the FLA rating of the motor, and full torque is maintained. This is a significant improvement on a soft-start, which has significant voltage drop problems and cannot start under full load but the harmonics is the series problems of VFD, the research will reduce this problems by using the active filters in the system and reducing the harmonics to make VFD most preferable and harmonic free.

2.1.2 Torque Equation of Induction Motor

Full load torque expression

$T=KsE_2^2R2/(R_2^2+(SX_2)^2)$

Where $K=\frac{3}{2\pi NS}$

NS is the synchronous speed in revolution per minute

X2 is Rotor reactance at stand still

E2 is induced EMF in rotor at standstill

R2 is rotor resistance

S is slip

Starting Torque Equation of Induction Motor: The starting torque of a motor is that torque which is produce by it at start. It is denoted by T_{st} and corresponds to s = 1. So by substituting s = 1 in above expression, we get the expression for starting torque. Therefore starting torque formula for induction motor is as follows:
Starting Torque Expression

$T_{st} = KE_2^2R2/(R_2^2+(X_2)^2)$

Where $K=\frac{3}{2\pi NS}$

NS is the synchronous speed in revolution per minute

X2 is Rotor reactance at stand still

E2 is induced EMF in rotor at standstill

R2 is rotor resistance

Maximum Torque at Start: The condition for maximum torque is

S=R2/X2 OR R2=SX2,

R2=X2(since at start s=1)

Thus to obtain maximum torque at the start, the value of rotor resistance must be equal to the rotor reactance at standstill.
However, the normal rotor resistance is quite small as compared to the reactance, otherwise, the rotor losses will be high and the efficiency of the motor will be low.
Hence to obtain maximum (higher) at the start some external resistance is added in the rotor circuit which is only possible in the case of slip ring induction motors. Once motor picks up speed this external resistance is reduced to zero and slip rings are short-circuited.

2.2 Harmonics

Harmonics are undesirable components in the sinusoidal waveform of the AC Power supply. Harmonics occur as integral multiples of the fundamental frequency.

That is, the third order harmonic will have a frequency of 3 times the fundamental frequency; 150 Hz which is 3 times the fundamental 50 Hz frequency. Harmonics affect power quality and efficiency. It is therefore necessary that Harmonics in any power system be monitored (Anderzej pietkiewcz, 2008).

The harmonics can arise in three ways:

- ✓ Through the application of a non-sinusoidal driving voltage to a circuit containing nonlinear impedance.
- ✓ Through the application of a sinusoidal driving voltage to a circuit containing nonlinear impedance.
- ✓ Through the application of a non-sinusoidal driving voltage to a circuit containing linear impedance.

Harmonics can rectify by using suitable methods such as filters. Using a mathematical technique known as Fast Fourier Transforms, the distorted AC waveform can be resolved into its component waveforms. Of the measured harmonics, the even harmonics(harmonics whose frequency are the fundamental frequency multiplied by even numbers such as 100Hz(2 *50) or 200Hz(4*50) get cancelled out and have no effect. For the study and management of Harmonics, only the odd harmonics are considered (Y. Hsiao, 2001)

The harmonics content must be reduced due to the following reasons

- ➢ Equipment Failure and misoperation
- ➢ Notching (electronic control malfunctioning, regulator misoperation)
- ➢ Overheating/Failure (transformers, motors, cables/neutral)
- ➢ Nuisance Operation (fuses, breakers, PC lock-ups)
- ➢ Insulation deterioration – Capacitor resonance / failure
- ➢ Economic Considerations
- ➢ Over sizing neutrals, transformers, generators
- ➢ Losses/Inefficiencies/PF Penalties – Inconsistent meter reading
- ➢ Performance of loading device fed through inverter is affected by harmonics.
- ➢ Harmonics cause additional losses.

- Added efficiency losses to the system composed by electrical installation and equipment.
- Unexpected resonances.
- Disturbances in electronic equipment, causing “logical” faults in digital circuits
- Malfunctions of motors and generators.
- Unwanted Circuit Breakers tripping or Fuses blowing.
- Harmonics cause additional losses.

2.2.1 Types of harmonic mitigation

While most modern electrical equipment generates some level of harmonic pollution, Variable Frequency Drives (VFDs) tend to be the primary cause of harmonic pollution of power systems. For this reason, this paper will focus primarily on harmonic mitigation of Variable Frequencies Drives (Steve Rossiter, 2015).

6-pulse VFDS with & without reactors

Since the modern VFD (drive) typically uses 6 diodes in the converter section, a “pulse” of current is generated each time one of these diodes commutates. Thus, these drives are typically referred to as 6-pulse drives. The drives have a capacitor on the dc bus. Each time a diode turns on; there is a large pulse of current that flows from the power system to charge the capacitor.

A typical waveform is shown in the following figure:

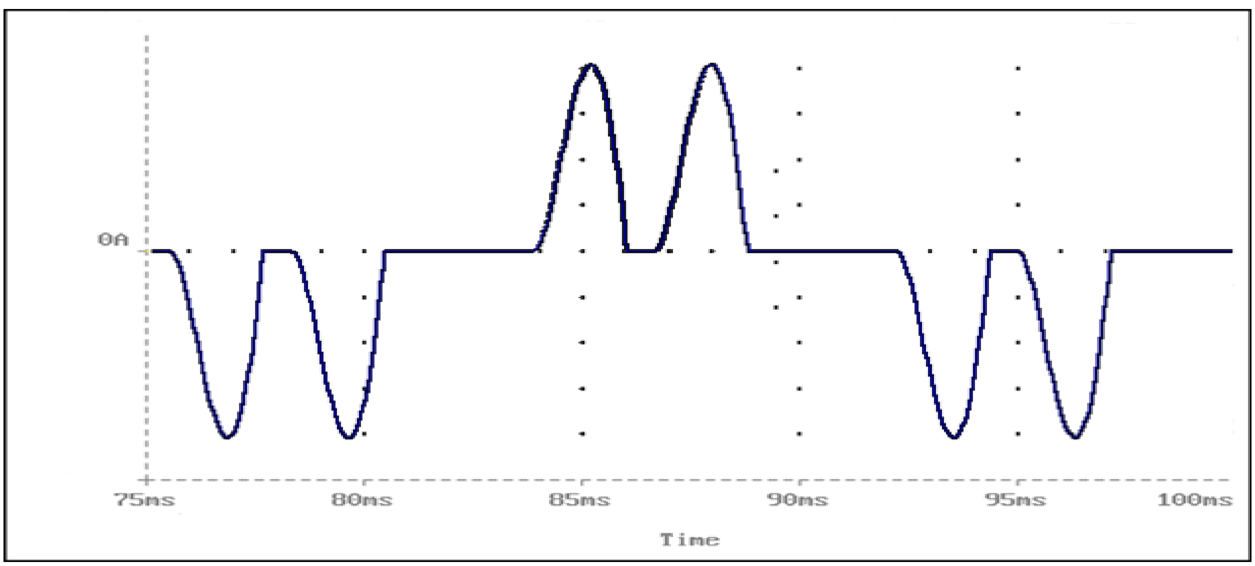

Figure 2.5 Current Wave form without Reactors

Since this VFD has a 3-phase power supply, the typical camel hump shape is due to the current between the phase being monitored and the commutation between the other 2 phases. This wave shape can have in excess of 100% Total Harmonic Current Distortion (THID).This can be thought of as generating one amp of high frequency noise distortion into the power distribution system for every amp of current used to drive the motor! This is irresponsible design, to say the least. The addition of reactors (Fig. 2.6) eliminates two thirds of the current harmonics resulting in the waveform shown in Fig. 2.7. AC Reactors can also protect the drive from power system transients and surges, resulting in longer life and improved reliability .Line reactors should be specified with a minimum of 3% impedance (Z). This will result in a THID at full load of approximately 35%. Using high impedance (5% Z) reactors will improve performance resulting in THID at full load of approximately 30%. While ac line and dc link reactors of equivalent impedance will result in similar harmonic levels, ac reactors are preferred for the following reasons.

1. Protection from ac line voltage transients and surges.
2. Improves performance of external active harmonic filters.

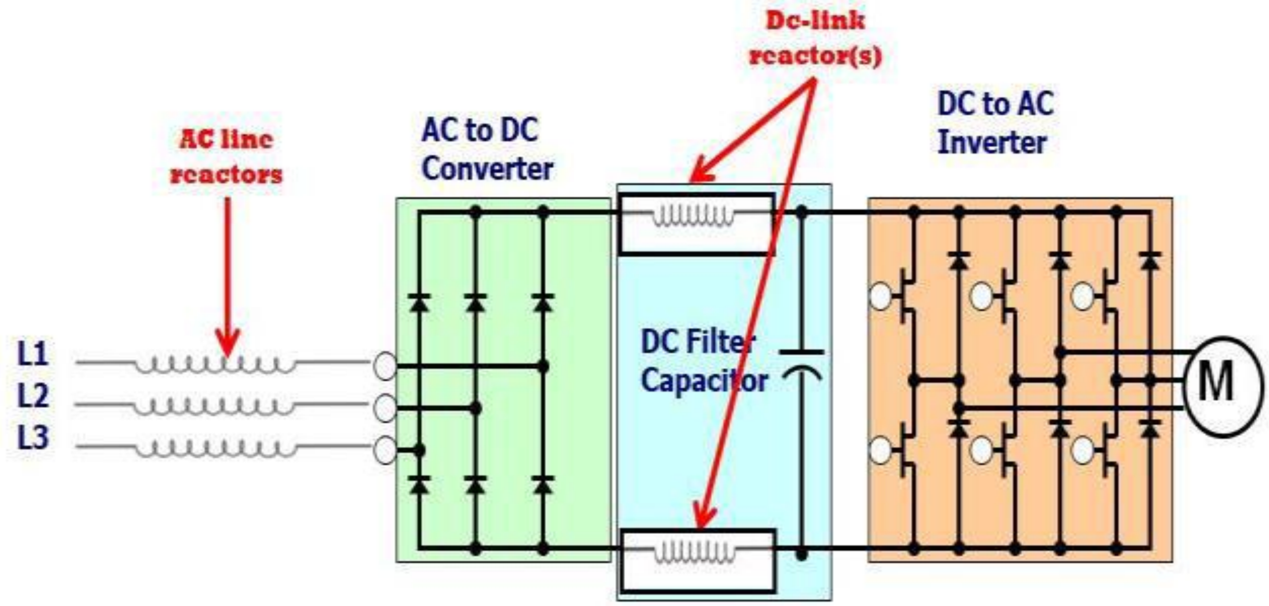

Figure 2.6 VFD with AC and DC-link Reactors (Steve Rossiter, 2015)

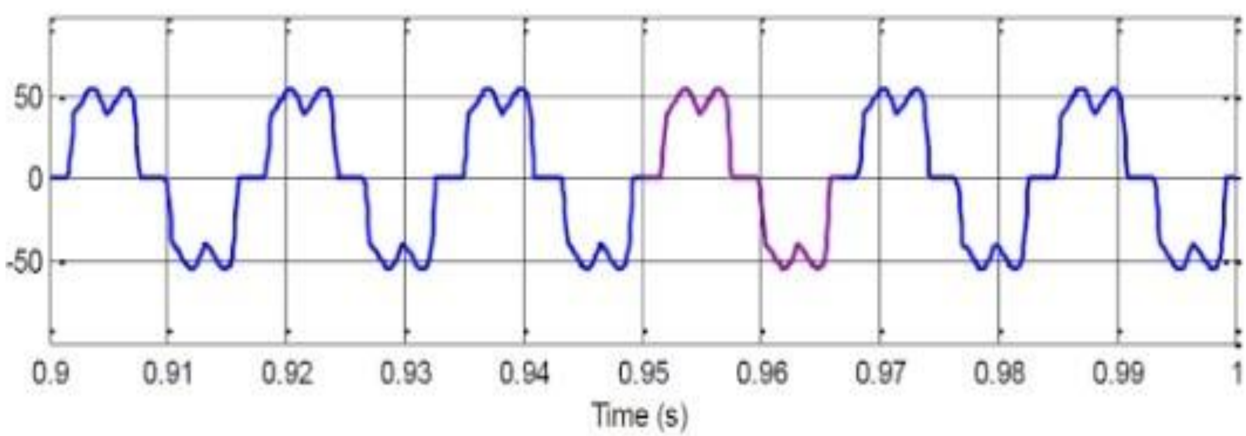

Figure 2.7 Current Waveform with Reactors

12-pulse VFDS

12-pulse VFDs use two separate 6-pulse bridges, for a total of 12 diodes, in the input converter of the VFD. In order to function properly they need two 3-phase inputs, with one input shifted by 30 electrical degrees. Since the two bridges are in parallel, the voltage, phase angle, and impedance of the two power inputs must be very carefully matched. Otherwise the bridges will not balance, and poor performance will result.

This type of VFD is generally a poor choice since the high cost of magnetic is not rewarded by equivalent performance improvements. While a carefully balanced 12-pulse drive can have approximately 11% THID, this is seldom seen in actual installations, which have THID in the high teens. Also, because of the necessity to balance the two bridges, this type of drive is very sensitive to voltage imbalance. Performance also degrades at low load levels.

18-pulse VFDS

18-pulse VFDs use three separate 6-pulse bridges, for a total of 18 diodes, in the input converter of the VFD. In order to function properly they need three 3-phase inputs, phase shifted by 20 electrical degrees. The three inputs are generally provided by a phase-shifting transformer located within the VFD itself. These drives are a significant improvement over the 12-pulse drives due to the higher number of pulses and the integral transformer that provides better balancing between the 3 bridges. While 18-pulse drives can provide THID less than 5%, this is seldom seen in practice. Measurements of 18-pulse drives in most power systems results in THID of approximately 7-8%.

Because 18-pulse low-voltage drives use parallel bridges, they are sensitive to voltage imbalance on the power line as well as degraded performance at low load levels. Medium voltage VFDs (over 1,000 volts) commonly use multi-pulse technology, but are able to put the bridges in series rather than in parallel. This results in much better harmonic performance. Medium voltage drives of 24-pulse and higher are quite common and will consistently deliver THID values of less than 5%.

Hybrid filters

Hybrid filters typically use a tuned circuit to mitigate the 5th harmonic (the highest harmonic in a 6-pulse drive) and additional reactors to mitigate higher order harmonics. Due to differences in the actual configuration of different manufacturer's passive filters, performance may vary. Be aware that many manufacturers' filters require the user to install an additional reactor on the drive for the filter to function effectively. Many users are unaware of the "small print" and neglect to install this additional reactor, resulting in poor performance.

Hybrid filters often advertise THID values of less than 5%. But, this is rarely seen in actual installations. Actual THID measurements of 7-8% are common for quality filters. Note that these filters provide identical performance to an 18-pulse drive, but at a fraction of the cost. Since these filters are effectively “low-pass” filters, they also block high frequencies and provide extremely good protection from power line transients and surges (REF.JN, 2015).

Notice that the hybrid filter is better behaved at low load levels than multi-pulse technology. At very low load levels, its performance actually improves. It is also much less sensitive to power system voltage imbalance. One concern with hybrid filters is the capacitor used in the filter, which provides leading power factor at lower loads. This can lead to standby generator instability. The solution to this is virtually always quite simple and includes a capacitor cut-out contactor built into the filter. This contactor isolates the capacitor at low load levels.

High frequency harmonics can be reduced easily by low size filter. However, to reduce lower order harmonics, big size passive filter are required but it is advisable to use active filters to reduce such types of filters. The harmonics which happen or generated in the VFD drive are odd harmonics .harmonics from VFD and from other sources are shown in the following table 2.0.

Table 2.1 Harmonics of Different Sources

No.	Source	Type of harmonics
1	6 pulse drive/rectifier	3, 5,7,11,13,17,19…
2	12 pulse drive/rectifier	11,13,23,25…
3	18 pulse drive	17,19,35,37…
4	Switch mode power supply	3,5,7,11,13…
5	Fluorescent lights	3,5,7,11,13…
6	arcing devices	2, 3,4,5,7…
7	Transformer energization	2, 3, 4…

2.2.2 Types of Harmonics Sources

In the harmonic analysis of a power system, there are techniques that can be applied to linear circuits at steady state. These techniques vary depending on the required data, model complexity, the problem formulation and the computational algorithms in use. Nonlinear loads are considered as sources that inject harmonics into a linear network. Depending on the type of harmonics and their behavior in the system, the nonlinear loads can be considered as current source or voltage source type loads.

There are two types of Harmonic Sources:

1. Current-Source Type of Harmonic Sources
2. Voltage-Source Type of Harmonic Sources

2.2.2.1 Current-Source Type of Harmonic Sources

In the presence of nonlinear loads, there will be a load type whose input current is almost invariant to changes in the source impedance, so that it can be considered as a nonlinear load that generates harmonic current sources and it is named HCS (harmonic current source). The harmonic voltage distortion at the point of common coupling that produces this type of load is usually relatively low, typically less than 5%. Figure 2.8 shows a model for this type of load, which consists of an ideal current source, representing the harmonics injected by the load.

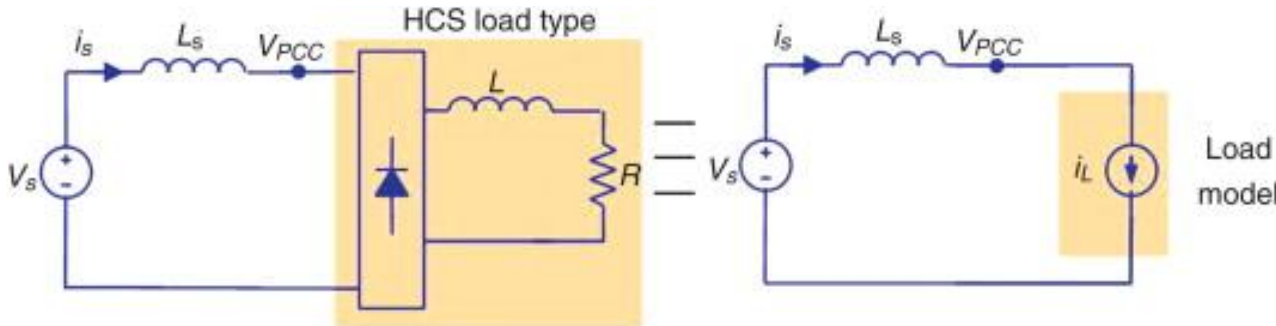

Figure 2.8 Current Source Harmonics Model

Example of load with this type of behavior is a rectifier with a high enough inductance to obtain a practically constant dc side current. This inductance is much larger than the source impedance, so that its variations do not significantly affect the load current. The Figure below shows the voltage and current for a load of this type. The figure shows how the harmonic distortion of the current is much higher than the voltage distortion at the load.

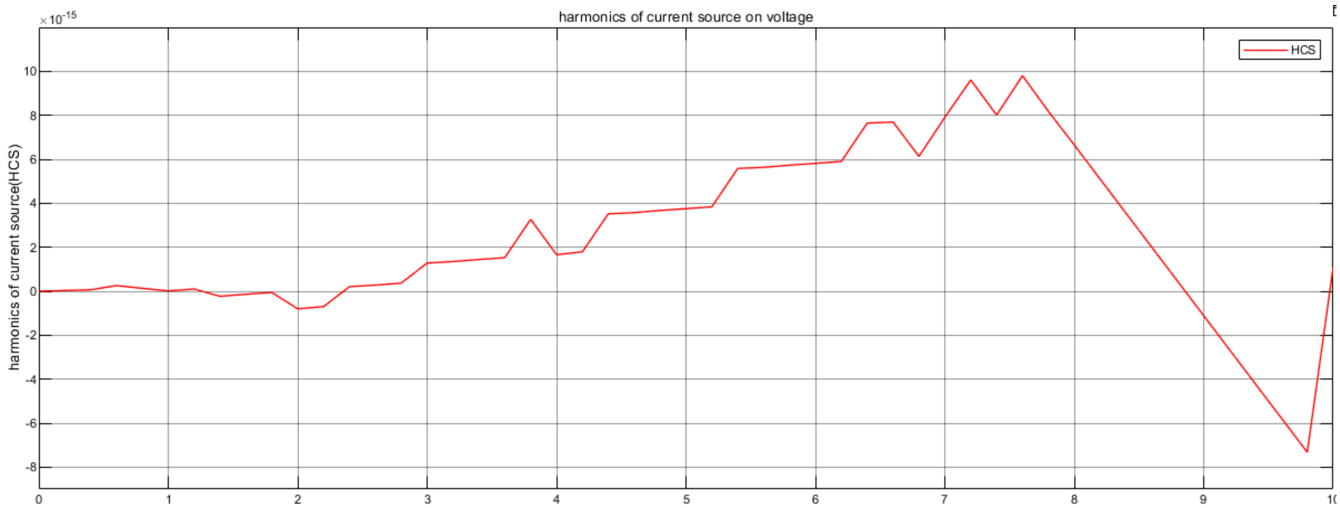

Figure 2.9 Wave forms of HCS load type voltage at the point of common coupling

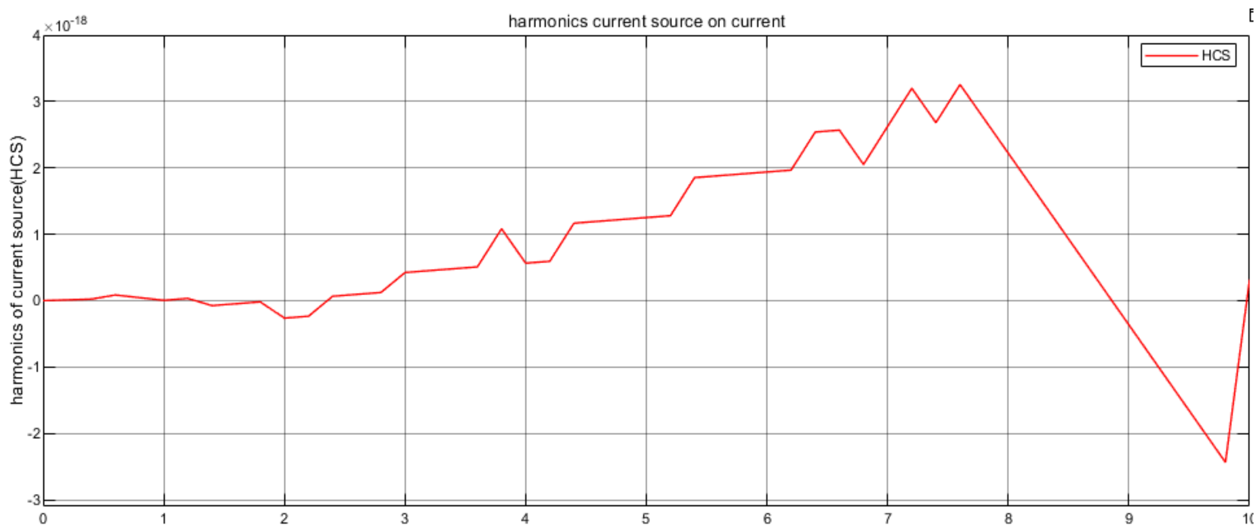

Figure 2.10 Wave forms of HCS load type load current

Voltage-Source Type of Harmonic Sources

There are others type of loads where the current drawn by them is strongly affected by the value of the source impedance. However, the voltage at the PCC remains virtually unchanged with reasonable changes in the impedance of the supply side. It can be considered that this load behaves like a harmonic voltage source (HVS) connected to the network.

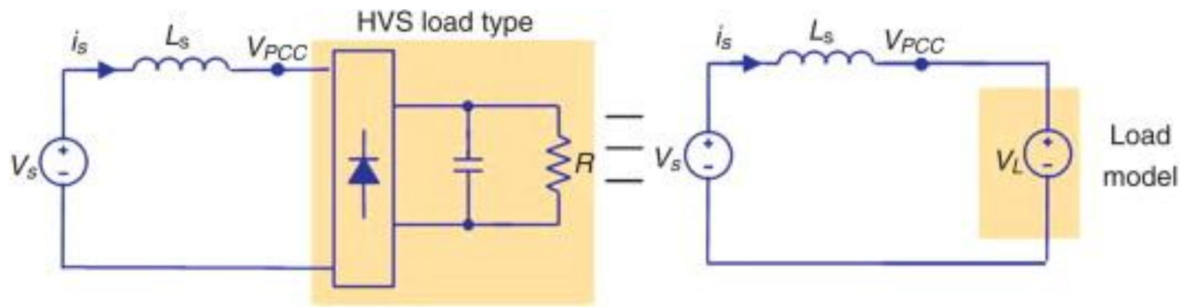

Figure 2.11 Voltage Source Harmonics Model

A typical example of a HVS load is a rectifier with a large capacitor to eliminate the ripple and to achieve a substantially constant voltage at the dc side. Figure 2.11 shows the current and voltage waveforms at the PCC for this rectifier type load. The current and voltage THD at the point of common coupling are 35.74% and 6.66%, respectively. Variations in the source impedance maintain the voltage at the PCC substantially constant, so in this case the ideal voltage source model in Figure below could be used

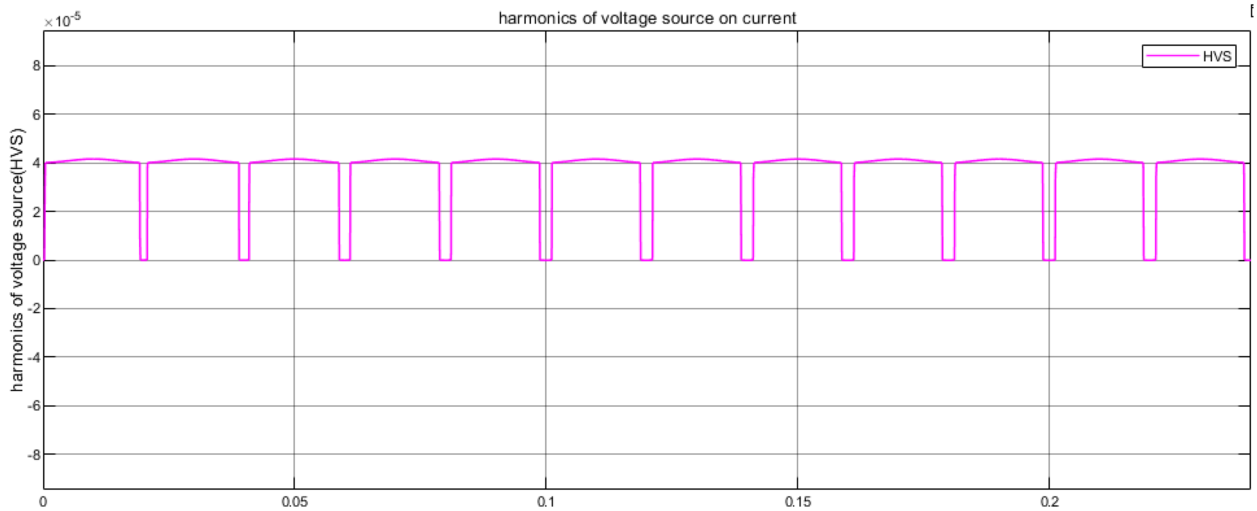

Figure 2.12 Wave forms of a HVS load type on current

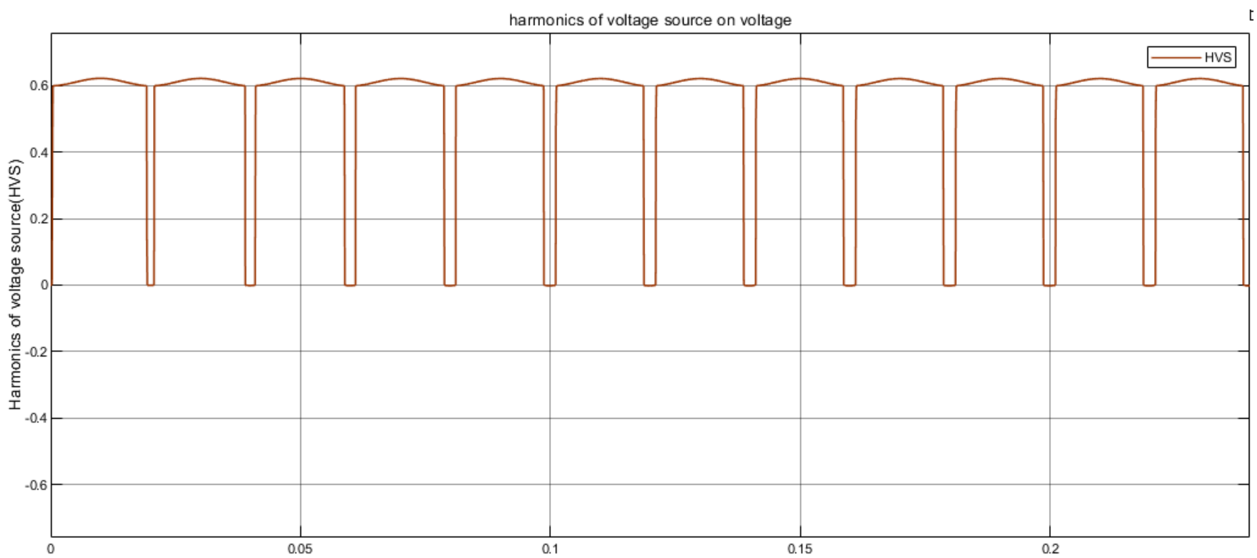

Figure 2.13 Wave forms of a HVS load type on voltage at the Point of Common Coupling

2.3 filters

Power electronics appliances are used widely in industrial, commercial, residential and military environment. These appliances generate harmonics and reactive power in the utility system. Power Electronics plays an important role in the control of generated electrical energy for today's industrial applications in various areas. The control of electrical power conversion from one form to another is necessary, and is achieved through power converters. The improvement of power quality by reducing harmonics has become an important issue now a day. The control strategy for power converters plays an important part in the harmonic generation and the output waveform distortion. Advancement of semiconductor technology has boosted the power electronic field due to the availability of power devices such as Power MOS Field Effect Transistors (Power MOSFETs), Insulated Gate Bipolar Transistors (IGBTs) and Gate Turn off Thyristors (GTO's) that have high power rating and good switching characteristics. These devices are widely used in the power converter circuits. However the output currents and voltages of static power converters are generally associated with low-order harmonics. The harmful effects of low-order harmonics produced by these devices can be reduced by incorporating the use of filters. Conventionally, passive LC filters have been used to eliminate line current harmonics and to improve the power factor. But the passive filters have many disadvantages, such as

- fixed compensation
- large size and
- Resonance problems.

To solve above mentioned problems, active power filters were introduced. Power quality can be defined as the interaction of electrical power with electrical equipment. If electrical equipment operates correctly and reliably without being damaged or stressed, we would say that the electrical power is of good quality free from harmonics which damages the equipment like motors, funs, lamp etc. On the other hand, if the electrical equipment malfunctions, is unreliable, or is damaged during normal usage, we would suspect that the power quality is poor. Power quality determines the fitness of electrical power to consumer devices. The presence of harmonic waveforms in power system is the main cause of power quality problems. Harmonics have a number of undesirable effects on the distribution system. It causes excessive voltage distortion, increased resistive losses or voltage stresses, reductions in ac motor efficiency and product quality etc. in the power system. With the wide spread use of harmonic generating devices, the control of harmonic currents to maintain a high level of power quality is becoming increasingly important. An effective way for harmonic suppression is the harmonic compensation by using active power filter. Active power filters are considered as a feasible solution for reducing current harmonics and reactive power due to their small size, no requirement for tuning and stable operation. The basic compensation principles of active filters were proposed around 1970. They act as harmonic current source to provide an effective result to eliminate the harmonic currents and also to compensate the reactive power (Mohamed EI-Hbrook, 2000).

Power system harmonics are integer multiples of the fundamental power system frequency. Power system harmonics are created by non-linear devices connected to the power system. Harmonics are voltage and current frequencies riding on top of the normal sinusoidal voltage and current waveforms. The presence of harmonics (both current and voltage) is viewed as `pollution' affecting the operation of power systems. The most common source of harmonic distortion is electronic equipment using switch-mode power supplies, such as computers, adjustable-speed drives, and high-efficiency electronic light ballasts. Harmonic waveforms are characterized by their amplitude and harmonic number. When a sinusoidal voltage is applied to a certain type of load, in which the load cause the current to vary disproportionately with the voltage during each cyclic period. These are classified as nonlinear loads, and the current taken by them will be a non-sinusoidal waveform. When there is significant impedance in the path from the power source to a nonlinear load, these current distortions will also produce distortions in the voltage waveform at the load. Waveform distortion can be mathematically analyzed to show that it is equivalent to superimposing additional frequency components onto a pure sine wave. These frequencies are harmonics (integer multiples) of the fundamental frequency, and can sometimes propagate outwards from nonlinear loads, causing problems elsewhere on the power system. The harmonics generated by the most common non-linear loads like VFD drive have the following properties (Mohamed EI-Hbrook, 2000):

- Lower order harmonics tend to dominate in amplitude if the waveform has half-wave symmetry there are no even harmonics
- Harmonic emissions from a large number of non-linear loads of the same type will be added

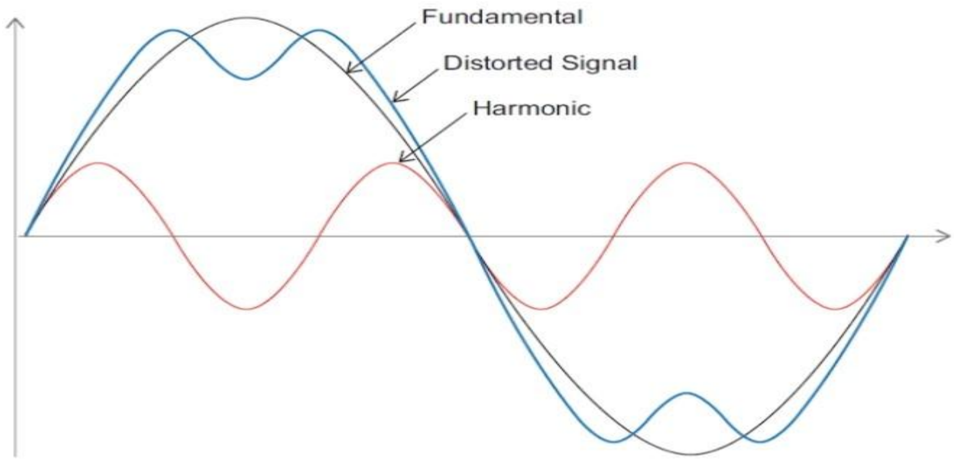

Figure 2.14 Effects of Harmonics on normal voltage and current wave form

The figure 2.14 shows the effect of harmonics on normal voltage or current waveform (William,A.B, 1981). Odd harmonics waveforms contribute more to power system instability. In the figure the combined waveform shows the result of adding the harmonics on to the fundamental. Harmonics in power systems can become the source of a variety of unwelcome effects. For example, harmonics can cause signal interference, over voltages, data loss, and circuit breaker failure, as well as equipment heating, malfunction, and damage. Any distribution circuit serving modern electronic devices will contain some degree of harmonic frequencies. The greater the power drawn by nonlinear loads, cause greater the level of voltage distortion. Potential problems (or symptoms of problems) attributed to harmonics include:

- ✓ Malfunction of sensitive equipment
- ✓ Random tripping of circuit breakers
- ✓ Flickering lights
- ✓ Very high neutral currents
- ✓ Overheated phase conductors, panels, and transformers
- ✓ Premature failure of transformers and uninterruptible power supplies (UPSs)
- ✓ Reduced power factor

Reduced system capacity (because harmonics create additional heat, transformers and other distribution equipment cannot carry full rated load) In addition, the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading. These harmonic currents can also cause interferences with telecommunication lines and errors in metering devices. Because of the adverse effects that harmonics have on power quality, Standard has been developed to define a reasonable framework for harmonic control. Harmonic distortion in power distribution systems can be suppressed using different approaches. One among them is the use of active power filters.

2.3.1 Working principles of active power filter

The Figure 2.15 below shows the components of a typical APF system and their connections. The compensation reference signal from the estimator drives the overall system controller. This in turn provides the control for the gating signal generator. The output of the gating signal generator controls the power circuit via a suitable interface

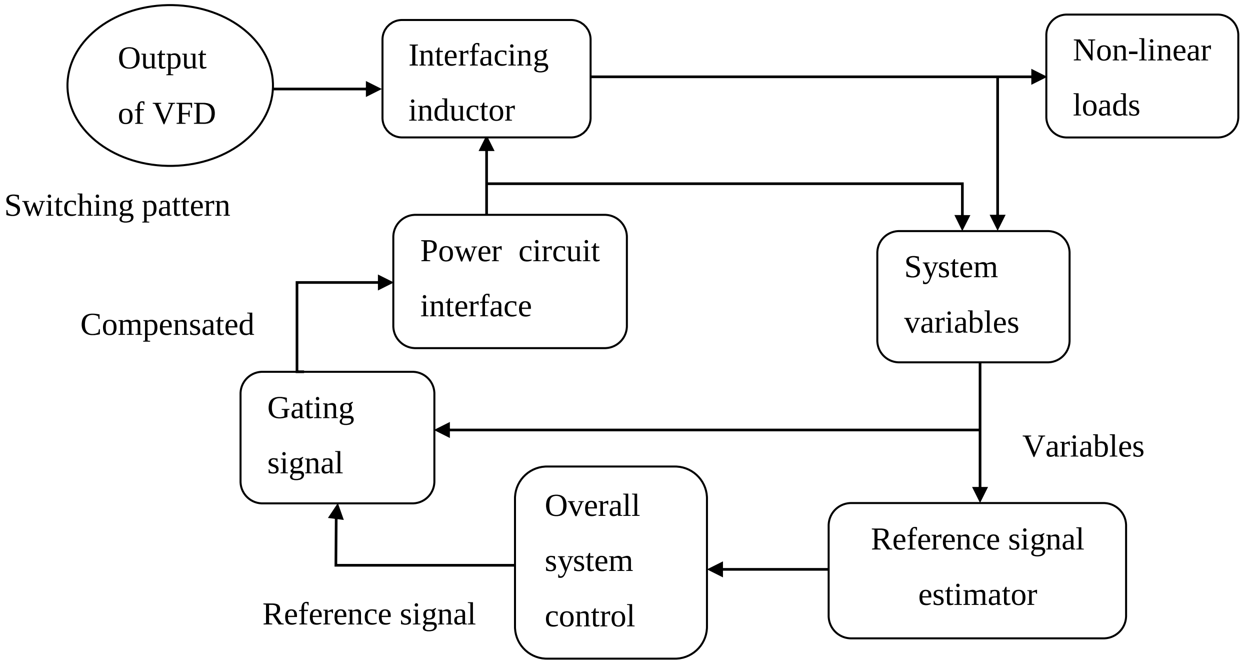

Figure 2.15 Basic block diagrams of APF

Finally, the power circuit in the generalized block diagram can be connected in parallel, series or parallel/series configurations depending on the interfacing inductor/transformer used. An unfavorable but inseparable feature of APF is the necessity of fast switching of high currents in the power circuit of the APF. An active power filter can be considered as a compensator for power system harmonics. The working of active power filter consists of mainly three stages. They are:

1. Signal conditioning
2. Derivation of compensating signal
3. Generation of gating signal

Signal conditioning refers to the detection or sensing of harmonics in the power distribution line. As shown in Figure 2.10, the reference signal to be processed by the controller is the key component that ensures the correct operation of APF. The reference signal estimation is initiated through the detection of essential voltage/current signals to gather accurate system variables information. The voltage and current variables in power system is sensed by using potential transformers, current transformers, isolation amplifiers etc. The voltage variables to be sensed are AC source voltage, DC-bus voltage of the APF, and voltage across interfacing transformer. Typical current variables are load current, AC source current, compensation current and DC-link current of the APF. Based on these system variables feedbacks, reference signals estimation in terms of voltage /current levels are estimated in frequency-domain or time-domain. The next stage is the derivation of compensating signal from the disrupted wave consists of both fundamental wave and the harmonic content. It can be done by two different methods-frequency domain approach and time domain approach. Frequency domain approach use Fourier transformation method for this purpose. While Time domain approach uses different methods like Instantaneous Reactive-Power Theorem, Synchronous-Reference-Frame Theorem, Synchronous Detection Theorem, Sine-Multiplication Theorem, notch filter method etc. The third stage is the generation of gating signal for harmonic suppression. So many control techniques like space Vector PWM, repetitive control, hysteresis current control, one-cycle control, dead-beat control, sliding mode control, fuzzy control and the artificial neural network method have been introduced and applied to various configurations of active power filters. Gating signal generator in the general block diagram of APF is used for this purpose (JamesW.Nilsson, 2010).

2.3.2 Types of filters based on passing behavior

There are four basic filter types which are described as follow:

1. **Low-pass filter (LPF**):- As might be expected, an LPF passes low-frequency signals, and rejects signals at frequencies above the filter's cutoff frequency which is shown in the Figure 2.16. The ideal filter has a rectangular shape, indicating that the boundary between the pass band and the stop band is abrupt and that the roll off slope is infinitely steep. This type of response is ideal because it allows us to completely separate signals at different frequencies from one another. Unfortunately, such an amplitude response curve is not physically realizable. We will have to settle for the approximation that will still meet our requirements for a given application. Deciding on the best approximation involves making a compromise between various properties of the filter's transfer function. The important properties are the following.

   Filter order: The order of a filter has several effects. It is directly related to the number of components in the filter and, therefore, to its price and the complexity of the design task. Therefore, higher-order filters are more expensive, take up more space, and are more difficult to design. The primary advantage of higher-order filters is that they will have steeper roll off slopes than similar lower-order filters.

Roll off rate: Usually expressed as the amount of attenuation in dB for a given ratio of frequencies. The most common units are "dB/decade" or "dB/octave." From Figure 2.16, four parameters are of concern:

Amax is the maximum allowable change in gain within the pass band. This quantity is also often called the maximum pass band ripple.

Amin is the minimum allowable attenuation (referred to the maximum pass band gain) within the stop band. f1 is the cutoff frequency or pass band limit.

fs is the frequency at which the stop band begins. These four parameters define the order of the filter.

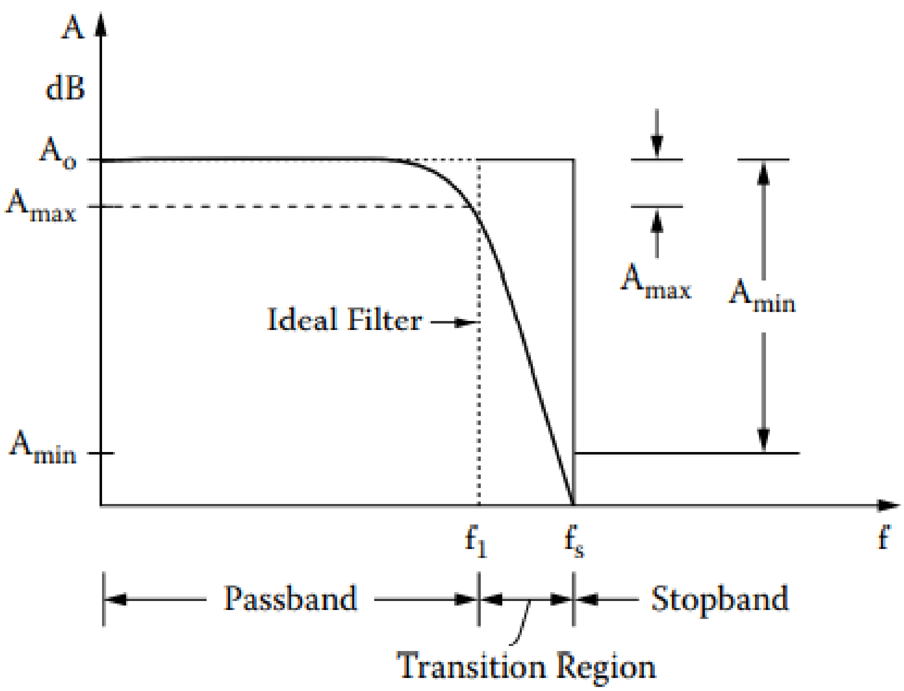

Figure 2.16: Low-Pass Frequency Response

2. **The high-pass filter**: which rejects signals below its frequency which is shown in the figure below

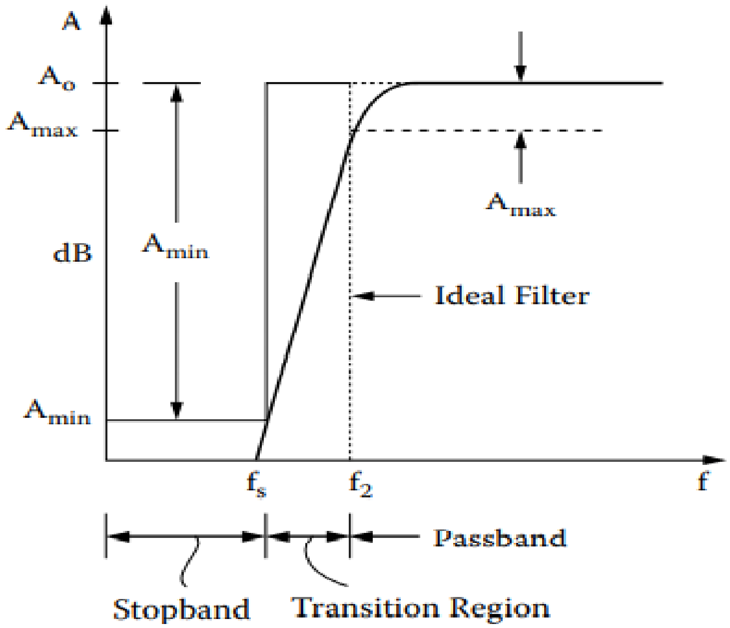

Figure 2.17 High-Pass Frequency Response.

3. **Band-pass filters**: pass frequencies within a specified band and reject components outside the band and it is shown in the Figure 2.18 below. Band-pass filters are geometrically symmetrical, i.e., symmetrical around a center frequency when plotted on linear-log graph paper with frequency on the logarithmic axis. The center can be computed by:

$$f_o = \sqrt{(f1 * f2)}$$

Where f1 is the lower cutoff and f2 is the upper cutoff frequency and fo is the average center cutoff frequency

For narrow filters, where the ratio of f2 to f1 is less than 1.1, the response shape approaches arithmetic symmetry. f_o can then be computed as the average of the cutoff frequencies

$$fo = \frac{f1+f2}{2}$$

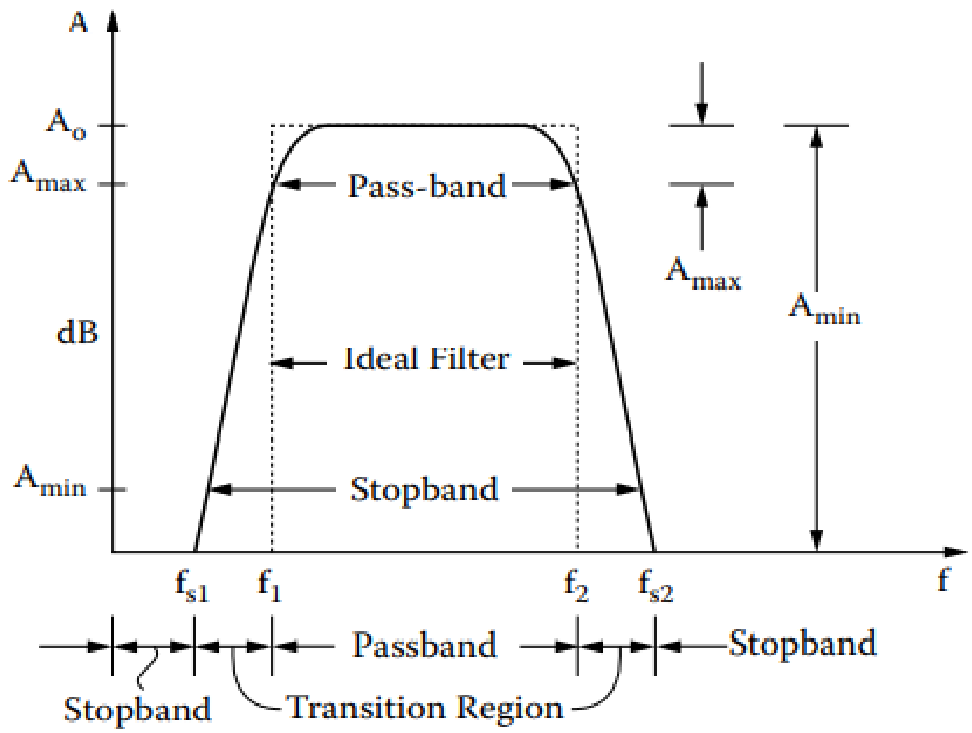

Figure 2.18 Band-Pass Frequency Responses.

4. **Band-reject filters:** reject frequencies within a specified band and pass components outside this band which is shown below in the figure 2.19

   The selectivity factor Q is the ratio of the center frequency of a band-pass filter to bandwidth which is described as follow:

   $Q = \frac{\text{fo}}{\text{BW}} = \frac{\text{fo}}{\text{f2}-\text{f1}}$, where fo center frequency, BW is band width, f1 is frequency 1 and f2 is frequency 2 which is described in the figure bellow.

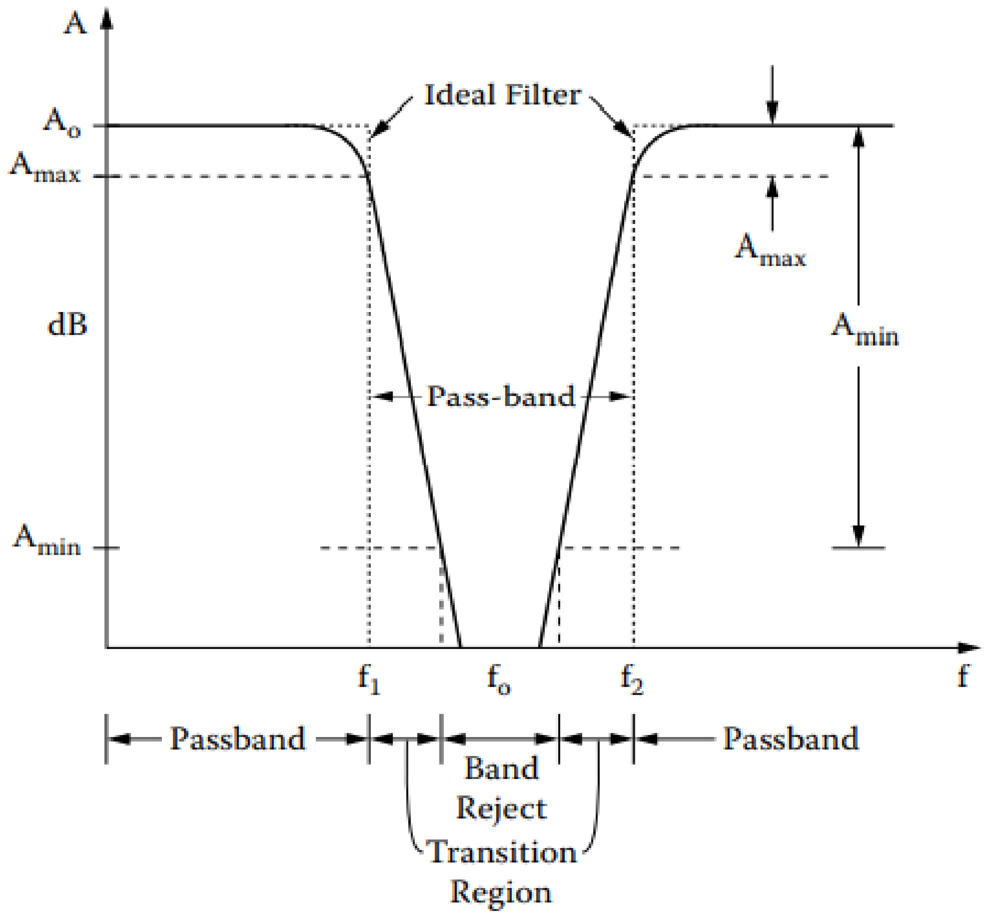

Figure 2.19 Band-Reject Frequency Responses

2.3.3 Types of power filters based on configuration

There are two basic types of filters in power electronics which are

1. Passive filters

2. Active filters

2.3.3.1 Passive filters

The filters used for filtering are all made up of passive components: resistors, capacitors, and inductors, so they are referred to as passive filters. This method of harmonic reduction blocks harmonics from being transferred to the electrical distribution system through the use of an inductive and capacitive (L-C) filter. A primary inductor with relatively high impedance blocks higher order harmonics, and a shunt connected tuned reactor is connected with a capacitor to mitigate the 5th and 7th harmonics. These filters have a relatively low cost compared to 12- or

18-pulse converters, though there are a few concerns with their use. They can be challenging to size as they can act as a magnet for existing harmonics that are on the system. When the drive is off, the capacitor can cause power factor and voltage rise problems, and in the event of capacitor failure, standard units offer no indication of this failure. These filters can be sensitive to future system changes, and careful application is required by the design engineer. A passive filter is simply a filter that uses no amplifying elements (transistors, operational amplifiers, etc.). In this respect, it is the simplest (in terms of the number of necessary components) implementation of a given transfer function. Passive filters have other advantages as well. Because they have no active components, passive filters require no power supplies. Since they are not restricted by the bandwidth limitations of op amps, they can work well at very high frequencies. They can be used in applications involving larger current or voltage levels than can be handled by active devices. Passive filters also generate little noise when compared with circuits using active gain elements. The noise that they produce is simply the thermal noise from the resistive components and with careful design; the amplitude of this noise can be very low. Passive filters have some important disadvantages in certain applications, however. Since they use no active elements, they cannot provide signal gain. Input impedances can be lower than desirable, and output impedances can be higher the optimum for some applications, so buffer amplifiers may be needed. Inductors are necessary for the synthesis of most useful passive filter characteristics, and these can be prohibitively expensive if high accuracy (1% or 2%, for example), small physical size, or large value is required. Standard values of inductors are not very closely spaced, and it is difficult to find an off-the-shelf unit within 10% of any arbitrary value, so adjustable inductors are often used. Tuning these to the required values is time-consuming and expensive when producing large quantities of filters. Furthermore, complex passive filters (higher than 2nd-order) can be difficult and time-consuming to design (Mohamed EI-Habrook, 2000).

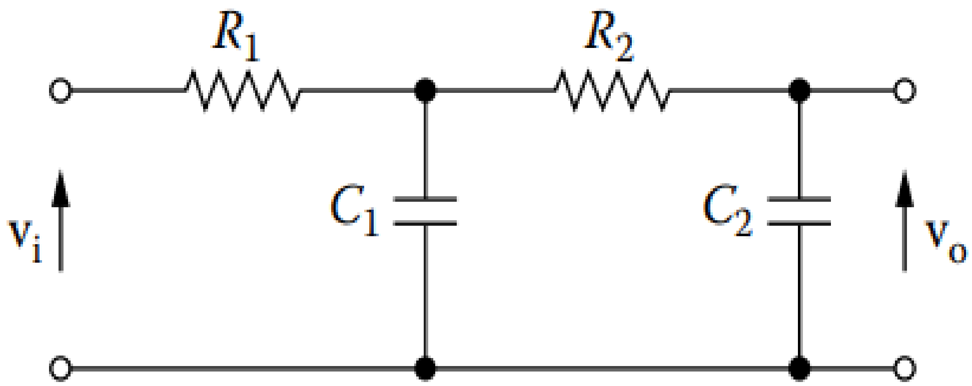

Figure 2.20 Low pass Passive Filters

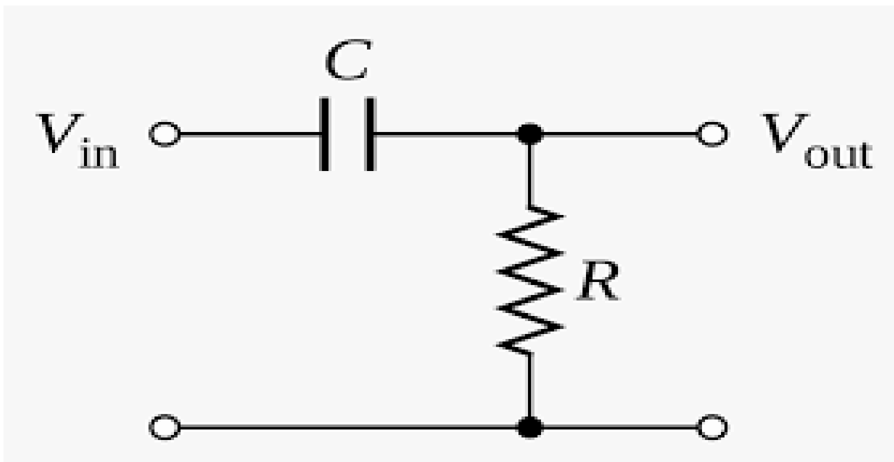

Figure 2.21 High Pass Passive Filter

2.3.3.2 Active power filters (APF)

Harmonic distortion in power systems can be suppressed mainly by, passive and active filtering. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion. The uses of passive elements do not always respond correctly to the dynamics of the power distribution systems. Passive filters are known to cause resonance, thus affecting the stability of the power distribution systems. Frequency variation of the power distribution system and tolerances in components values affect the passive filtering characteristics. As the regulatory requirements become more stringent, the passive filters might not be able to meet future revisions of a particular Standard. This may require a retrofit of new filters. Remarkable progress in power electronics had spurred interest in Active Power Filters (APF) for harmonic distortion mitigation. Active filtering is a relatively new technology, practically less than four decades old. The basic principle of APF is to utilize power electronics technologies to produce specific current components that cancel the harmonic current components caused by the nonlinear load. APFs have a number of advantages over the passive filters. First of all, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the APFs performances are independent on the power distribution system properties. Active filtering is a relatively new technology, practically less than four decades old. There is still a need for further research and development to make this technology well established (William,A.B, 1981).

2.3.4 Classification of active power filter according to power rating and speed of response required in the compensated system

Figure 2.22 shows the classification based on this criterion. The power rating of the compensated system and its speed of response play a major role in deciding the control philosophy to implement the required filter for avoiding the harmonics of the system to have long life for equipment and to reduce the unwanted costs of the equipment

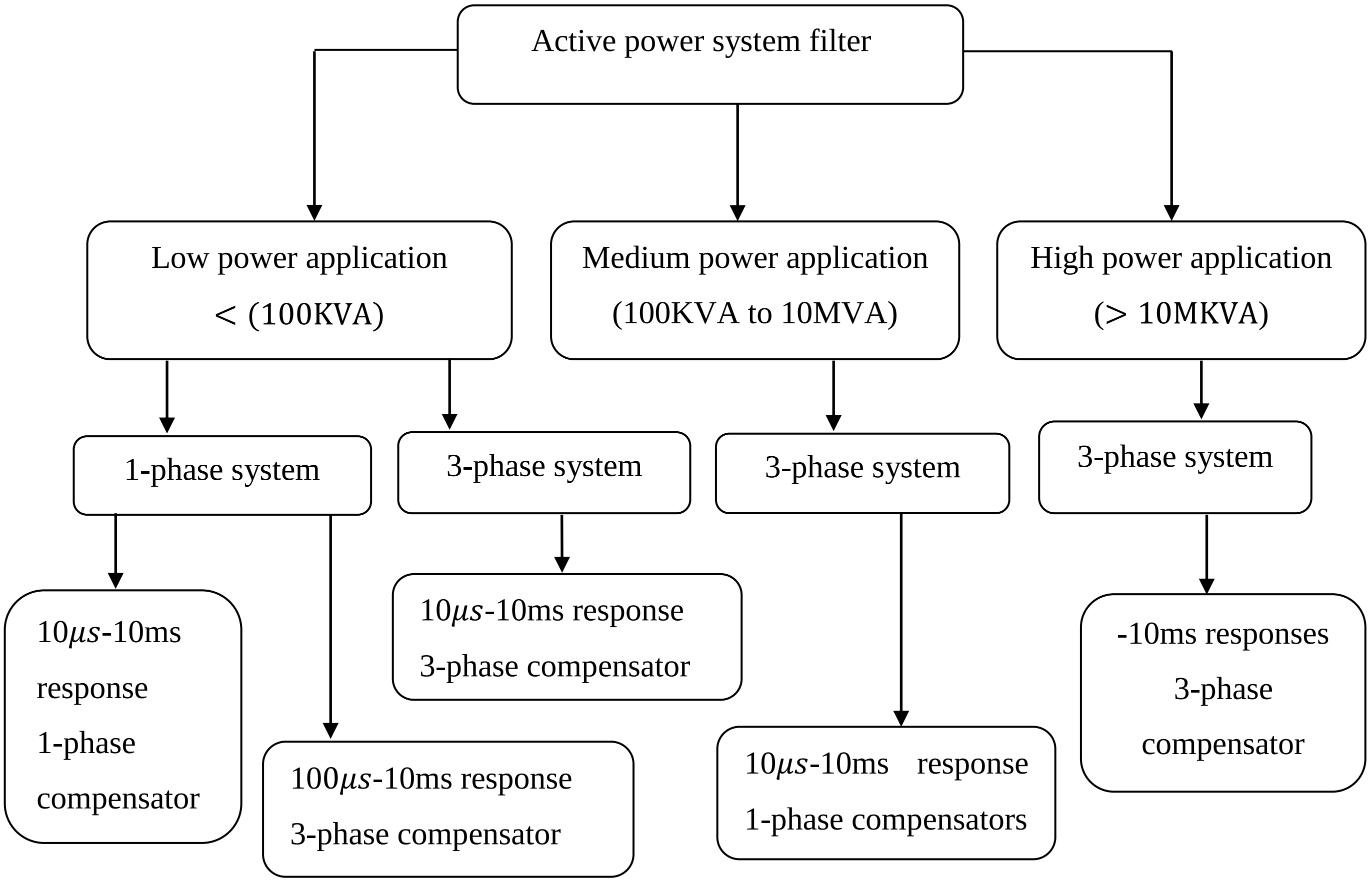

Figure 2.22 Subdivision of power System filters according to power rating and speed of response

Single-phase systems: Single-phase active filters are generally available in low power ratings. They are suitable for retrofit applications, such as in commercial or educational buildings with computer loads, small factories etc., where the current harmonics can be dealt with at the point of common coupling. Thus several lower-power filters can be connected on a given distribution site rather than using one large filter on the incoming supply. This is due to the large number of the single-phase loads within one building and the harmful consequences of the presence of large amounts of harmonic in the neutral line. This allows for more selective compensation as the operating conditions vary. On the other hand, residential loads do not generate such large values of concentrated harmonics, and hence the effects on the neutral are not significant. However, in the absence of compulsory harmonic regulations, residential customers are not likely to invest in single-phase active power filters (Jim Karki, 2002). The main advantage of single-phase filters is that they have to deal with low powers and hence can be operated at relatively higher frequencies leading to improved performance.

Three-phase systems: For three-phase applications, the choice of filters configurations depends on whether the three-phase loads are balanced or not. At relatively low power levels (1000 VA), a three-phase system can use either three single-phase or one three-phase compensator. For balanced loads, a single three-phase-inverter configuration is employed .This is acceptable if there is no requirement to balance currents or voltages in each phase and the aim is simply to eliminate as many current harmonics as possible, assuming that the magnitudes and respective phase angles in each phase are the same . For unbalanced load currents or unsymmetrical supply voltages, especially in three-phase four-wire distribution systems, three single-phase inverter circuits or alternative configurations may provide acceptable solutions. The connection of three single-phase filters is recommended by some designers, especially those who do not rely upon standard inverter configurations such as lattice structures, switched-capacitor techniques and power-regulator configuration. It can incorporate three independent current voltage-feedback signals that will balance the supply currents or voltages (Mohamed EI-Habrook, 2000).

Medium-power applications: In this category, three-phase systems ranging from l00kVA to l0MVA are mainly considered. Medium to high voltage distribution systems and high-power high-voltage drive systems were the effect of phase unbalance is more or less negligible, fall within this classification. Here the main aim is to eliminate or reduce the current harmonics. Because of economic considerations, reactive-power compensation using active filters at the high-voltage distribution level is not generally regarded as reliable because of the high voltage and its accompanying problems of isolation and series/parallel connections of switches. Even if step-down transformers are used, the resulting high currents are difficult to handle. Alternative approaches, including capacitive and inductive static compensators as well as quasidynamic systems (such as relay controlled LC circuits), tunable harmonic filters, line-commutated thyristor converters synchronous condensers and cascaded multilevel-inverter VAR compensators, are considered more suitable (Williams,A.B, 1981),

High-power applications: The implementation of very high-power dynamic filters is extremely cost ineffective, because of the lack of high switching-frequency power devices that can control the current flow at such power ratings, is a major limitation for such systems. As with medium-power applications, extra -high voltages of a few hundred kilovolts cannot be tolerated, even by state-of-the-art semiconductor devices which can with stand only a few kilovolts. The series-paralle1 combinations of these switches is possible, but difficult to implement and cost-ineffective. Fortunately, the harmonic pollution in high-power ranges, which include systems with ratings above 10MVA, is not such a major problem as in lower-power systems. These high-power systems include power-transmission grids and ultrahigh power DC drives as well as DC transmission systems. The effect of harmonics generated at the low-power side would be minimized, either naturally or by the installation of several medium- and low-power active filters downstream to contribute to the compensation in such cases. The staticVAR compensation is then the major concern and is usually compensated for by using traditional static power conditioner filters as well as several sets of synchronous condensers connected in parallel and cascaded multilevel-inverter VAR compensators. The required response time for such cases is in the range of tens of seconds, which is sufficient for contactors and circuit breakers to operate after taking the optimal-switching decision. Power fluctuations in the range of a few seconds are, on the other hand, treated by the generating stations' ancillary devices. One of the few applications of active filters in high-power systems is the Japanese bullet train (Sinkansen), which uses a parallel combination of several active filters (Mohamed EI-Habook, 2000)

2.3.3.4 Classification of active power filters based on connection in the system

There are three types of connection of active power filter in the system which are:

1. Series connected active power filter
2. Shunt connected active power filter and
3. Hybrid connected active power filter

1. **Series connected active power filter:** The active filter in this configuration produces a PWM voltage waveform which is added/subtracted, on an instantaneous basis, to/from the supply voltage to maintain a pure sinusoidal voltage waveform across the load. The main power-circuit configuration is shown in Figure 2.23. The inverter configuration accompanying such a system is a voltage-fed inverter without any current-control loops. Series active filters are less common industrially than their rivals, parallel active filters. This is because of the main drawback of series circuits, namely that they have to handle high load currents, which increases their current rating considerably compared with parallel filters, especially in the secondary side of the coupling transformer (increasing the I^2R losses and the physical size of the filter). The main advantage of series filters over

parallel ones is that they are ideal for eliminating voltage-waveform harmonics, and for balancing three-phase voltages. This, in fact, means that this category of filter is used to improve the quality of the system voltage for the benefit of the load. It provides the load with a pure sinusoidal waveform, which is important for voltage-sensitive devices (such as superconductive magnetic-energy storage and power system-protection devices). The circuits are shown below:

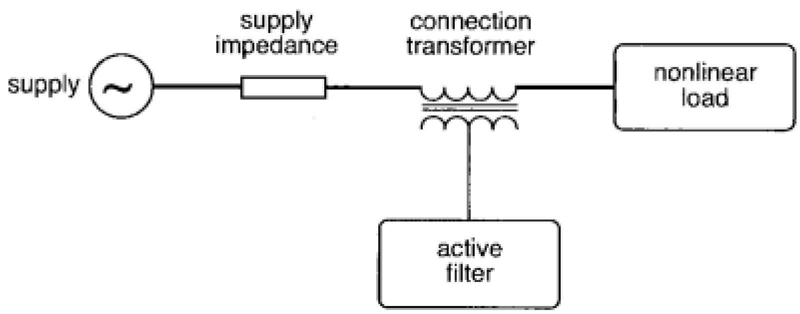

Figure 2.23 Series Connected Active Power Filter

2. **Shunt connected active power filter:** This class of filter configurations constitutes those most important and most widely used in industrial processes. It is connected to the main power circuit, as shown in the single-line diagram of Figure 2.24. The purpose is to cancel the load current harmonics fed to the supply. It can also contribute to reactive-power compensation and balancing of three-phase currents, as mentioned above. Parallel filters have the advantage of carrying only the compensation current plus a small amount of active fundamental current supplied to compensate for system losses. It is also possible to connect several filters in parallel to cater for higher currents, which makes this type of circuit suitable for a wide range of power ratings. This configuration consists of four distinct categories of circuit, namely inverter configurations, switched-capacitor circuits, lattice-structured filter and voltage-regulator-type filters (Mohamed EI-Habook, 2000).

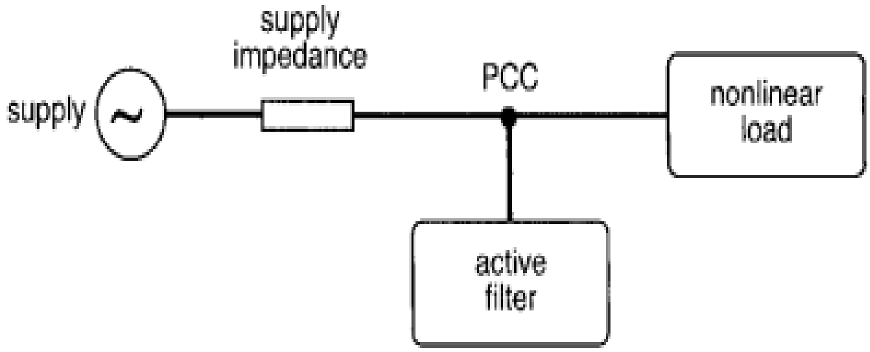

Figure 2.24 Parallel/Shunt Active Filter Configurations

3. **Hybrid connected active power filter:** Combinations of several types of filter can achieve greater benefits for different applications.

Combination of both parallel and series active filters: To gain the advantages of both series and parallel inverter-type configurations, a combination of both types of filter, shown in Figure 2.25, can be used to achieve the demanding power-system requirements. The demand for combined filters is limited because of their control complexity and higher cost. The control complexity is due to the dependency of the switching pattern of both parallel and series circuits. Consequently, these types of filter have received less attention than other to gain the advantages of both series and parallel inverter-type configurations, a combination of both types of filter, as shown in Figure below, can be used to achieve the demanding power-system requirements. Consequently, these types of filter have received less attention than other configurations . The arrangement is, however, frequently used for other purposes in power systems for Flexible AC Transmission Systems (FACTS).

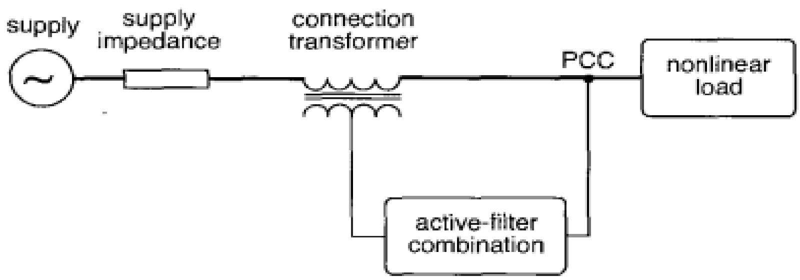

Figure 2.25 Combination of Parallel and Series Active Filters

Combination of series active and parallel passive filters: To reduce the complexity of the previous filter combination, the inverter-type series active filter, which constitutes high impedance for high-frequency harmonics, is accompanied by a parallel passive filter to provide a path for the harmonic currents of the load. This combination, represented by Figure 2.26, permits an improvement over the characteristics of plain series active filters and the extension of their capabilities to include current-harmonic reduction and voltage-harmonic elimination.

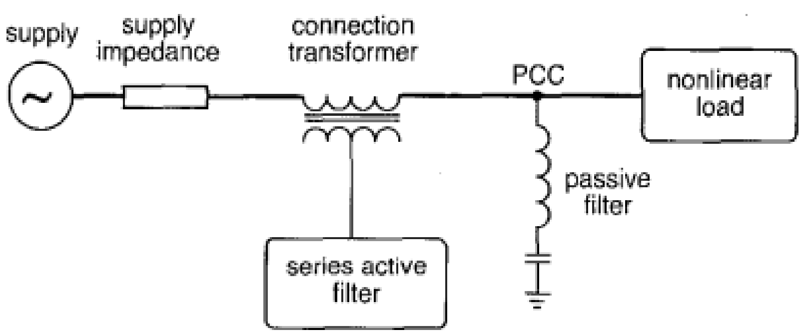

Figure 2.26 Combination of Series Active and Parallel Passive Filters

Combination of parallel active and passive filters: This combination, shown in Figure 2.27, represents a very important mixture of passive and active inverter-type filters. The active filter is designed to eliminate only part of the low-order current harmonics while the passive filter is designed to eliminate the bulk of the load-current harmonics. In such combinations, the system can be designed for higher powers without excessive costs for high-power switching. The main drawback of this technique is that it contains too many power components, especially for the passive filter. Since passive filters are permanently connected to the system, this approach is only suitable for single load with a predefined harmonic source (Mohamed EI-Habook, 2000).

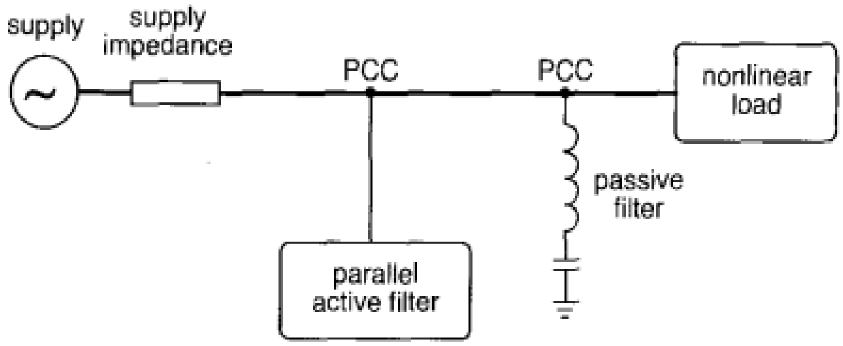

Figure 2.27 Combination of Parallel Active and Passive Filters

2.4 Comparision of active and passive filters

An active filter is a network of passive R, C elements, and one or more active elements. Its function is to simulate the action of the usual passive RLC filters. The active element is usually one or more op-amps. The single system parameter that dictates the filter technology is frequency. Figure 2.28 and figure 2.29 illustrates the advantages of active filtering compared to passive techniques as a function of frequency. Active filters offer accuracy, stable tuning, and high immunity to electromagnetic interference. The high input and low output impedance found in active filters allow combinations of two or more stages without the interaction found in passive cascades. Active filters function similar to simple, frequency-selective control systems; as such, any desired filter characteristic can be generated from the interconnection of integrators, inverter, summing amplifier, and integrators. Efficient and low cost active filter design, therefore, depends on the realization of a desired transfer function into a circuit that uses the fewest components while maintaining all performance requirements. Numerous circuits have evolved to meet this objective. Each circuit has been designed to optimize specific performance aspects. Some are easily tuned, others use a minimum number of components, and still others feature a fixed bandwidth. Most designers would rather not “reinvent the wheel”; however, they would like to develop a basic engineering understanding of the operation, advantages, and restrictions of each type of filter design. Once the concept of the active filter as a frequency-selective control system is understood, active filter analysis becomes straightforward

JamesW.Nilsson,2010).

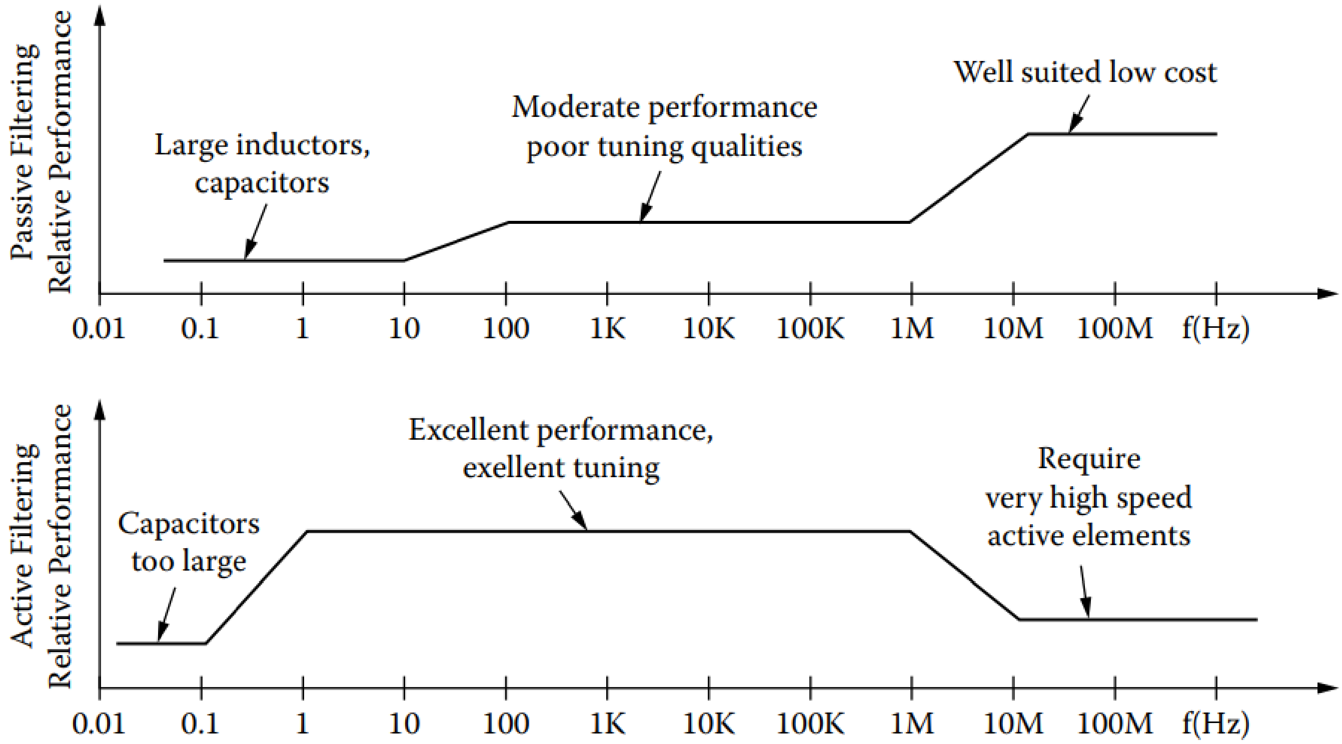

Figure 2.28 Comparing Filtering Techniques of Passive and Active Filters

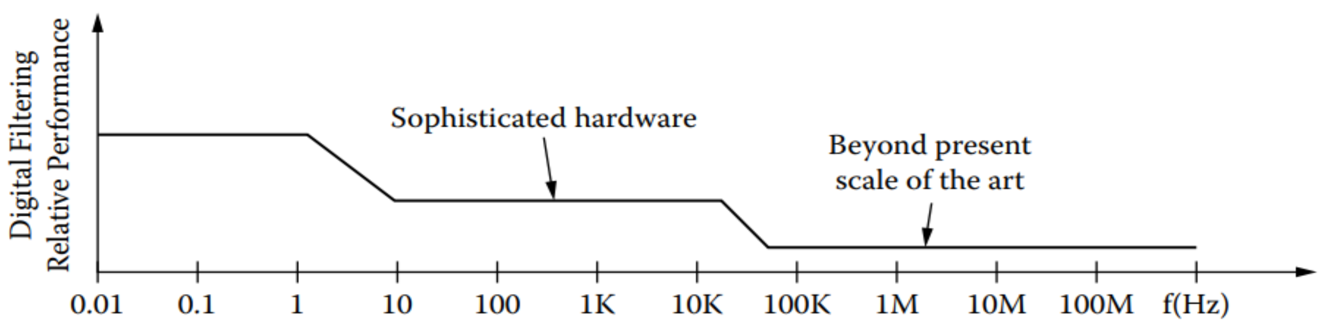

Figure 2.29 Comparing Filtering Techniques of Digital Filter with Passive and Active Filter

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter includes data analysis, mathematical modeling of the harmonic reduction of VFD drive motor as well as the design, comparisons of VFD drive motor system with high active power filter setup in MATLAB. The analysis of the identified pump motor specification and VFD drive with the designed harmonic reduction high pass active power filter is performed. Comparisons of variable frequency drive pump motor with high pass active power filter and without filter are reviewed in the previous chapter. it is known that the benefits of using active high pass harmonics power filters in the VFD drive system to reduce harmonics which is generated by the drive and finally after analysis of every data which is measured by using the harmonics analyzer whether it fulfills the IEEE-519 standard or not. It is already fulfilling the IEEE-519 standard that the tolerable harmonics is 5%, if harmonics is greater than this it causes harmful effect. Therefore, it should be reduced using the appropriate techniques and methods. In this chapter it will be analyzed properly.

3.2 Materials

The materials which are used for doing this thesis are MATLAB software version 21.0a, harmonics analyzer.

MATLAB software version 21.0a: It is the general purpose computing software which consists of a vast range of specialized toolboxes. This toolbox performs symbolic algebraic/mathematical manipulative operations with a lot of built-in interactivity. It is a high-level mathematical package designed for doing numerical computations and graphics. It also has powerful symbolic math ability. It is undoubtedly popular among computer and multi-disciplinary scientists, engineers and particularly with experts in the area of computational mathematics and Engineering. MATLAB is a powerful language for technical computing. The name MATLAB stands for MATrix LABoratory, because its basic data element is a matrix (array). MATLAB can be used for math computations, modeling and simulations, data analysis and processing, visualization and graphics, and algorithm development. MATLAB is widely used in universities and colleges in introductory and advanced courses in mathematics, science, and especially engineering. In industry the software is used in research, development, and design.

Harmonics analyzer: It is used for measuring and checking the presence of harmonics and to know the magnitude of harmonics which is found in the system after the variable frequency drive (VFD).

3.3 Methods

The following method is used to study the specific objectives of the proposed thesis. First the closely related works are reviewed. Then the necessary data's used throughout this work is collected by measuring the harmonics of the system by using harmonic analyzer. The specifications value of the induction motor, variable frequency drive (VFD) and measurements of harmonics are taken from kessem sugar factory. Then the collected data is analyzed for the purpose of understanding and developing the system design. The design of the high pass active filter is design to reduce the harmonics which is generated by variable frequency drive (VFD). Then the system is simulated by using MATLAB/Simulink /Code. The result of the simulation is compared, which is simulating with high pass active filter and without high pass active filter. In general the method throughout the research study can be summarized as the following flow chart Figure 3. 1: Block diagram of the research methodology. The block diagram of the proposed system is shown below: Figure 3. 2: Block diagram of the proposed thesis research system. In this thesis the high pass active filter is used to reduce harmonic which generated from variable frequency drive (VFD). Then the output of the high pass active filter which the reduced power given to the induction motor, this extends the life of every equipment after the active filter because the harmonics from the variable frequency drive damage equipment including the induction motor. The Collected data (measurable), finally analyzed and calculated the THD and the obtained result is analyzed and compared with standard values of IEEE-519. The proposed or designed system is developed in MATLAB and simulating results of it will be analyzed and compared.

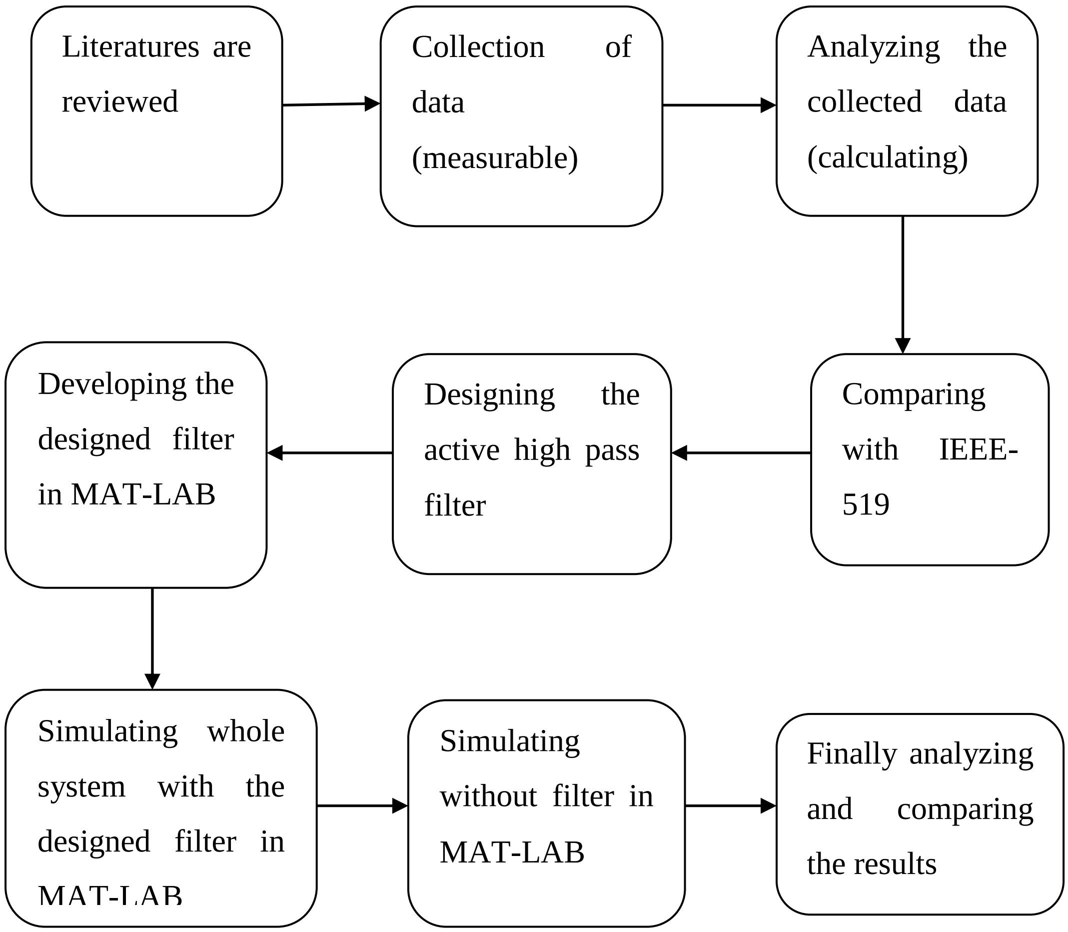

Figure 3.1 Block Diagram of the Research Methodology

The block diagrams of the proposed research is shown below

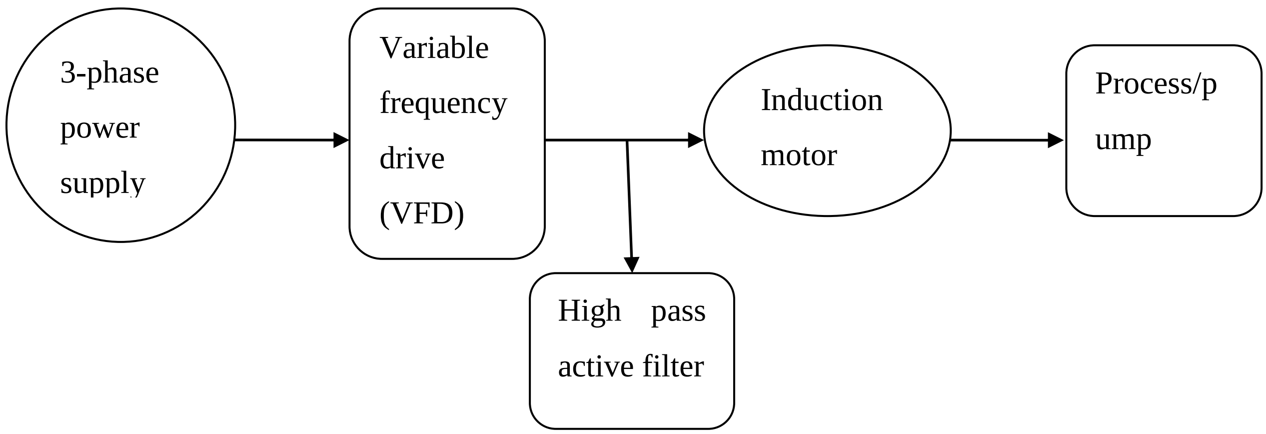

Figure 3.2 Block Diagram of the Proposed Thesis Research System

The working principles of this block diagram are most variable speed applications involving an electric motor generally employ a variable frequency drive (VFD). A brief discussion of electric motors and the major types of VFD's are as follows:

The speed of an Alternating Current (AC) motor depends on three principle variables:

1. The fixed number of winding sets (known as poles) built into the motor, which determines the motor's base speed.
2. The frequency of the AC line voltage. Variable speed drives change this frequency to change the speed of the motor.
3. The third variable is the amount of torque loading on the motor, which causes slip.

Because slippage occurs, the actual motor speed is somewhat lower than the nameplate value for the motor.

The following equation is used for calculating motor speed:

$$\text{Synchronous speed} = \frac{120f}{\text{number of poles}} \quad (3.1)$$

Once the motor is fabricated, the only variable that can change in the synchronous speed equation is the frequency (Hz) of the power supply. The motor speed is directly proportional to the frequency. Rather than supplying the electric motor with a constant frequency of 60 Hz, the

VFD takes the electrical supply from the utility and changes the frequency of the electric current which results in a change of motor speed. Before the power reaches to the motor the unwanted signal (harmonics) is filtered to keep the motor safe.

3.4 analyses of the measured data (harmonics)

The following data are measured and analyzed to checked the presence of harmonics in VFD drive by using power quality analyzer. In kessem sugar factory the presence of harmonics in VFD drive causes so many problems in induction motors of pump, in drive itself, disturbance of the whole system, interruption, even collapse of voltage occurs. Therefore, the paper focuses on reducing these problems. Depending up on the measured values which are analyzed as follow, high pass active filter is designed to reduce the harmonics and to avoid the problem that happens frequently in kessem sugar factory.

Table 3.1 Harmonics Measured at the Input of VFD drive (on power supply side of VFD drive)

No.	Harmonics	3^{rd} order	5^{th} order	7^{th} order	13^{th} order	19^{th} order	21^{th} order
1	I_1	0.2	5.9	3.3	0.4	0.2	0
2	I_2	0.2	5.5	3.1	0.3	0.11	0
3	I_3	0.1	4.9	3.0	0.2	0.2	0
4	V_1	0.1	3.04	2.02	0.68	0.11	0.01
5	V_2	0.1	3.82	2.34	0.69	0.21	0.05
6	V_3	0.88	3.63	2.15	0.53	0.08	0.02

To know the individual phase harmonic distortion (THD), we have to calculate by using the following formula:

$THD_I=\sqrt{(\sum_{h=2}^{6} I2)}/Im$

THD_{I1}=56.54%, THD_{I2}=56.77%, THD_{I3}=61.53%, and

$THD_v=\sqrt{(\sum_{h=2}^{6} V2)}/Vm$

THD_{v1}=70.28%, THD_{v2}=64.16%, THD_{v3}=65.68%,

These are the distortion due to the VFD drive which is measured before the drive system.

Table 3.2 Harmonics at the Output of VFD Drive (on the load sides of VFD drive)

No.	Harmonics	3^{rd} order	5^{th} order	7^{th} order	13^{th} order	19^{th} order	21^{th} order
1	I_1	0.98	0.5	0.4	0.2	0.1	0.2
2	I_2	1.2	0.7	0.5	0.3	0.2	0.1
3	I_3	1.3	0.7	0.5	0.4	0.16	0.1
4	V_1	51.81	28.05	19.74	10.39	5.45	4.25
5	V_2	86.93	41.5	30.91	14.64	12.17	9.43
6	V_3	47.61	25.28	17.02	8.21	4.64	4.25

$THD_I=\sqrt{(\sum_{h=2}^{6} I2)}/Im$

$THD_{I1}=72.15\%$, $THD_{I2}=72.16\%$, $THD_{I3}=74.40\%$, and

$THD_v=\sqrt{(\sum_{h=2}^{6} V2)}/Vm$

$THD_{v1}=70.71\%$, $THD_{v2}=64.7\%$, $THD_{v3}=68.08\%$,

These are the total harmonic distortion which is measured after VFD (at the out puts of the drive system) drive with the harmonics analyzer.

3.5 designing high pass filter

There are many ways of constructing active filters. One general-purpose circuit that is widely used is that of Sallen and Key. We refer to the Sallen and Key circuit as a VCVS because it uses an op-amp and two resistors connected so as to constitute a voltage-controlled voltage source (VCVS). Such a configuration offers good stability, requires a minimum number of elements, and has low impedance, which is important for cascading filters and for easily using in the system for the required purpose. In order to design the required filter we have to know the application area where it is used, the types of filter we used, the transfer function, the order of the filter, the variable which is estimated to calculate the other variables which are exactly fit for the required application. The following figure shows how we can convert low pass filter to high pass filter.

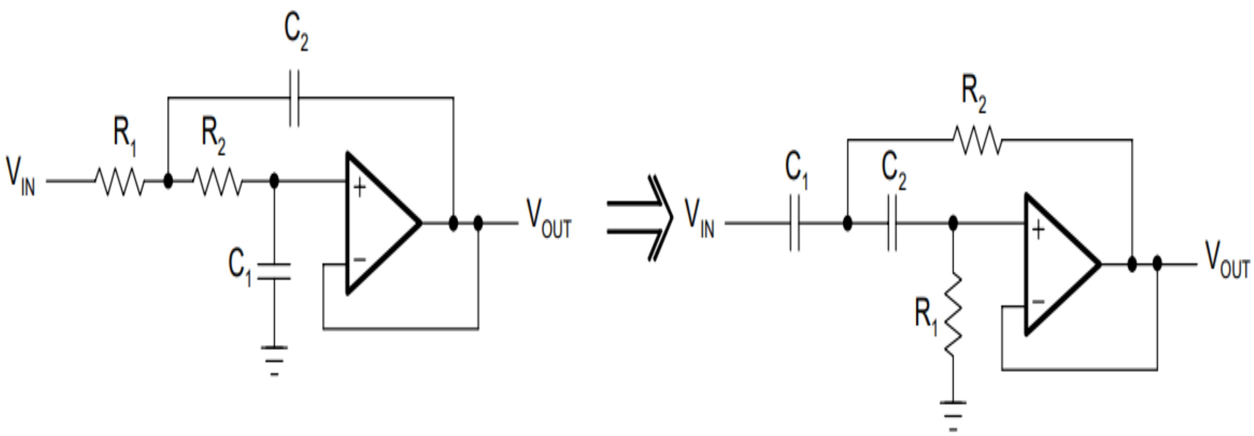

Figure 3.3 Converting unity gain low pass filters to high pass filters

The general transfer function of a high-pass filter is:

H(s)= $\frac{A\infty}{\prod_i (1+\frac{ai}{s}+bi/s2)}$……………………………………….. (3.2)

Where A∞ is the pass band gain

Since Equation (3.2) represents a cascade of second-order high-pass filters but the transfer function of a single stage is represented as:

H(s)= $\frac{A\infty}{(1+\frac{ai}{s}+bi/s2)}$…………………………………...….…… (3.3)

For the first order filters the transfer function is with b1=0, a1=1 and it will be come as follow

H(s)= $\frac{\mathrm{Ao}}{(1+\frac{1}{s})}$…………………………………...…………… (3.4)

For proposed thesis the filter which i use for reducing the generated harmonics in the VFD drive is inverting high pass active filter. To determine the values of the components of the circuit, there must be estimated value. The proposed high pass filter is as follow:

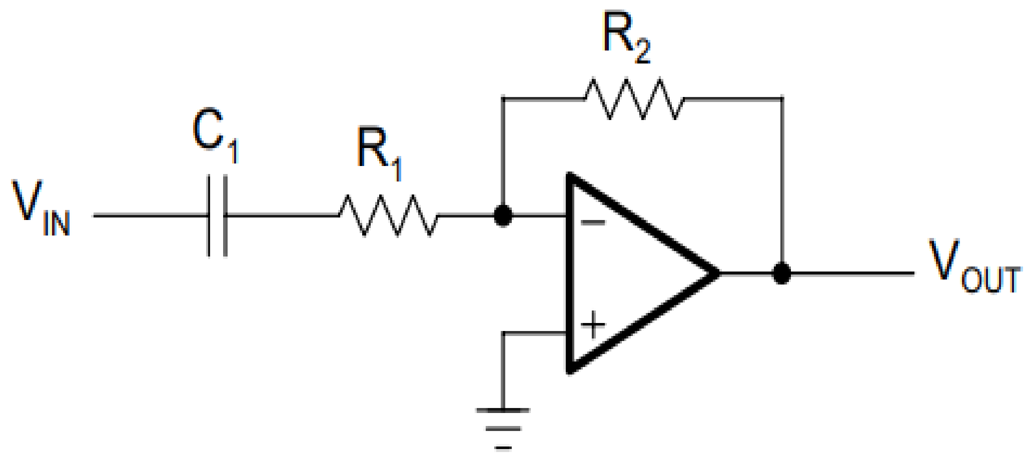

Figure 3.4 High Pass Active Power Filter

3.5.1 Frequency response normalization

Several parameters are used to characterize a filter's performance. The most commonly specified parameter is frequency response. When given a frequency-response specification, the designer must select a filter design that meets these requirements. This is accomplished by transforming the required response to a normalized high pass specification having a cutoff of 1 rad/s. This normalized response is compared with curves of normalized high pass filters that also have a 1 rad/s cutoff frequency. After a satisfactory high-pass filter is determined from the curves, the tabulated normalized element values of the chosen filter are transformed or denormalized to the final design. The basic for normalization of filters is the fact that a given filter's response can be scaled or shifted to a different frequency range by dividing the reactive elements by a frequency-scaling factor (FSF).The FSF is the ratio of the desired cutoff frequency of the active filter to the normalized cutoff frequency, i.e.

$$FSF = \frac{w1}{wn} = \frac{2\pi f1}{1} = 2\pi f1 \ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

The FSF must be a dimensionless number. So, both the numerator and denominator of Equation (3.5) must be expressed in the same units; usually rad/s. Frequency-scaling of a filter has the effect of multiplying all points on the frequency axis of the response curve by the FSF. Therefore, a normalized response curve can be directly used to predict the attenuation of the denormalized filter. Any linear active or passive network maintains its transfer function if all resistors are multiplied by an impedance-scaling factor (ISF) and all capacitors are divided by the same factor ISF. This occurs because the ISFs cancel one another out in the transfer function. Impedance scaling can be mathematically expressed as:

$$R = ISF \times Rn \quad \text{......................................} (3.6)$$

$$C = \frac{Cn}{ISF} \quad \text{..} (3.7)$$

Where Rn and Cn are the normalize values.

Frequency and impedance scaling are normally combined into one step rather than performed sequentially. The denormalized values are then given by

$$R = ISF \times Rn \quad \text{...} (3.8)$$

$$C = \frac{Cn}{ISF \times FSF} \quad \text{.......................................} (3.9)$$

$$R1 = \frac{1}{(WC * a1 * C1)} \quad \text{...} (3.10)$$

$$H(S) = -\frac{\frac{R2}{R1}}{1 + \frac{1}{wcR1C1}} \quad \text{..} (3.11)$$

The negative sign indicates that the inverting amplifier generates a 180° phase shift from the filter input to the output

$$A\infty = -\frac{R2}{R1} \quad \text{..} (3.12)$$

The required filter which is used for reducing the generated harmonics from VFD drive is with the cutoff frequency (fc) of 50HZ and unity gain (A) and determining the other parameters based on the standard and accepted formulas:

fc =50HZ, A=1, w1=1rad/sec

Therefore: normal values are assumed as:

Cn=1F

Ran=1ohm

ISF=10^4

FSF=$\frac{W2}{W1} = \frac{2\pi f1}{1} = 2\pi \times 50 = 100\pi$

Denormalizing the parameters

$$C = \frac{Cn}{ISF \times FSF} = 1/(10^4 \times 2\pi \times 50)$$

C=0.318μF

R1 $= \frac{1}{(WC*a1*C1)} = 1/(2\pi \times 50 \times 1 \times 0.318\mu F)$

R1=5.007kohm$\approx 5kohm$

A=$-\frac{R2}{R1}$

Since, gain (A) =$1, 1 = -\frac{R2}{R1} \leftrightarrow R2 = R1 =$ 5kohm

Because the designed filter is with unity gain. Therefore, the designed filter is with parameters:

C=0.318μF

R1=5kohm

R2=5kohm

3.5.2 Switching sequence of the VFD drive

The following figures show the switching sequence of the output transistors (IGBT) used in a VFD to produce a three-phase AC waveform. Since each of these devices are functioning as solid-state switches, the circuit operation can be easily visualized by representing these devices as open or closed mechanical switches. Switches closed to the positive bus are shown in red, switches closed to the negative bus are shown in black, and open switches are shown in gray. When a particular winding is connected to the same bus potential (either positive or negative) the voltage across that winding will be zero. If a winding is connected so that the positive voltage is connected to the first letter of the winding label (for example the A in AB) the voltage produced across that winding is positive. If a winding is connected so that the positive voltage is connected to the second letter of the winding label (for example B in AB) the current flow reverses and the voltage produced across that winding will be of a negative polarity. Below each diagram is a table listing of the number of electrical degrees through which the switches operate and the resultant phase voltage produced. Note: On a six-step drive the output devices will be closed throughout the listed operating range; on a PWM drive, pulses will be produced through this range. See next page for generated waveform (Mike Glampe, 2017).

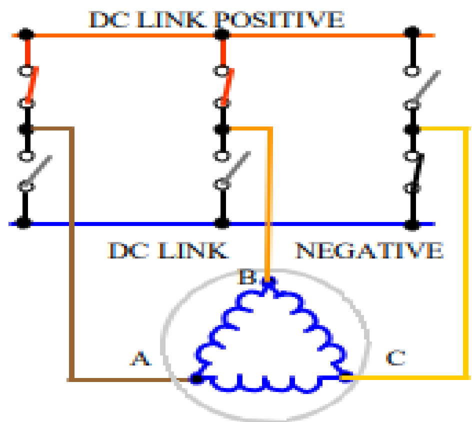

Figure 3.5 Three- Phase motor with 0-60° phase sequence

0-60 degree
VAB=0
VBC=+E
VCA=-E

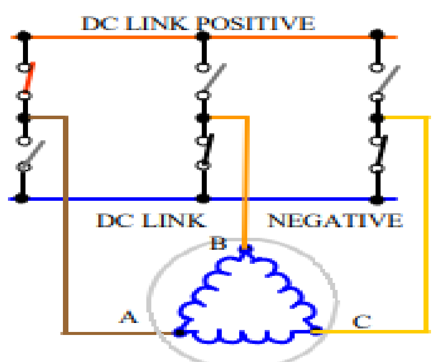

Figure 3.6 Three- Phase motor with 60-120° phase sequence

60-120 degree
VAB=+E
VBC=0
VCA=-E

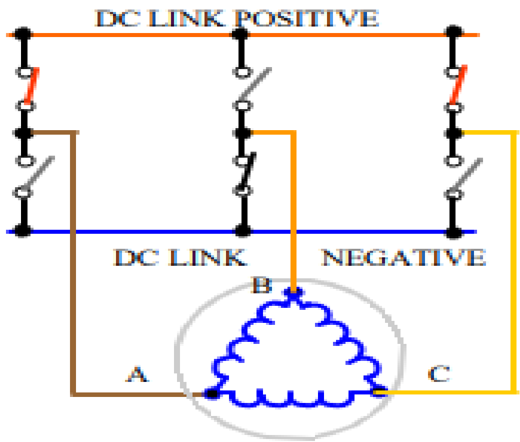

Figure 3.7 Three- Phase motor with120-180° phase sequence

120-180 degree
VAB=+E
VBC=-E
VCA=0

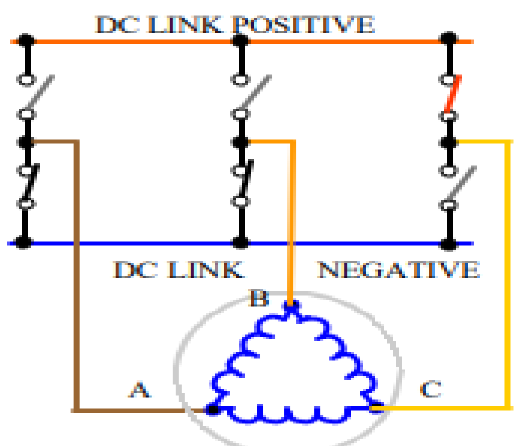

Figure 3.8 Three- Phase motor with180-240° phase sequence

180-240 degree
VAB=0
VBC=-E
VCA=+E

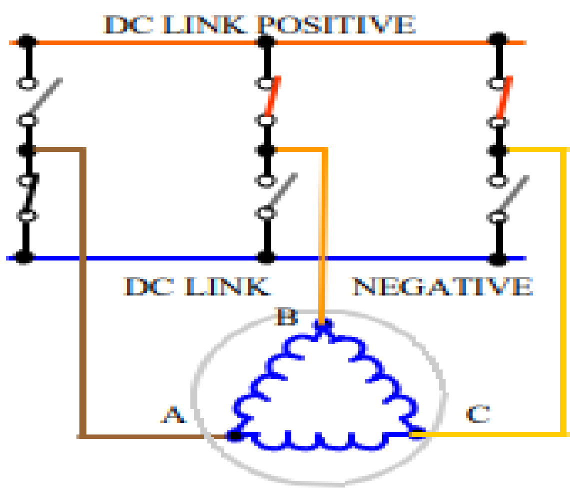

Figure 3.9 Three- Phase motor with 240-300° phase sequence

240-300 degree
VAB=-E
VBC=0
VCA=+E

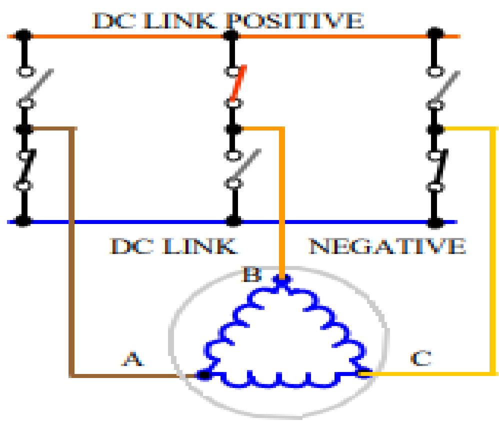

Figure 3.10 Three- Phase motor with 300-360° phase sequence

300-360 degree
VAB=-E
VBC=+E
VCA=0

When the above switching sequences are expressed in table form it is shown as below:

Table 3.3 Switching Sequence of IGBT in VFD drive

Steps of IGBT switching	1	2	3	4	5	6	7	8	9	10	11	12
Tr1	ON					ON	ON				ON	
Tr2		ON	ON					ON	ON			
Tr3				ON	ON					ON	ON	
Tr4			ON	ON					ON	ON		
Tr5					ON	ON					ON	ON
Tr6	ON	ON					ON	ON				
PhaseU(A)	N	_	S	S	_	N	N	_	S	S	_	N
PhaseV(B)	_	N	N	_	S	S	_	N	N	_	S	S
PhaseW(C)	S	S	_	N	N	_	S	S	_	S	S	_

CHAPTER FOUR

4. RESULTS AND DISCUSSION OF THE RESEARCH

The simulation results explained in this chapter is performed for the same parameter values of the systems under study. Due to this study the problem which is happen in kessem sugar factory pump motor VFD drive system with the specification parameter described in the table 4.1 is highly reduced to low value which is near to zero. The results of the harmonics occurred after using the designed filter is reduced and the IEEE-519 standard also allows the low amounts or magnitudes of harmonics in the system. This is shown in the outputs of the mathlab simulink which is simulated without filter and with the designed filter. The harmonics measured which is generated due to the VFD drive at the inputs of the drives(on the supply side of VFD drive), current harmonics THD_{I1}=56.54, THD_{I2}=56.77%,THD_{I3}=61.53%,and voltage harmonics are THD_{V1}=70.28%,THD_{V2}=64.16%,THD_{V3}=65.68% and the harmonics measured at the outputs of the VFD drive (on the load side of the VFD drive) and the calculated THD of current and voltage are as Current harmonics, THD_{I1}=72.15%, THD_{I2}=72.16%, THD_{I3}=74.40% and voltage harmonics,THD_{V1}=70.71%, THD_{V2}=64.70% and THD_{V3}=68.08%. These values are measured using the harmonics analyzer and the harmonics analyzer measures the current and the voltage harmonics but not total harmonics distortion (THD). The total harmonics distortion which are described above are calculated values by taking the measured values from chapter 3 in table 3.1 and in table 3.2 respectively. Due to the use of high pass active power filter in the system the reduced harmonics which are shown in the figure below. The reduced total harmonics distortion values in current and voltage are THD_I=0.064% and THD_V=0.017% respectively. Therefore, the use of high pass active power filter in VFD drive is more effective to reduce harmonics than the passive filters and other methods. The simulation models are shown in the appendix A. As a result of the study the factory will be profitable due to the reduction of harmonics, because the life time of induction machines, cables, VFD drive…will be increased due to the highly reduction of harmonics in the system. An organization to be profitable and beneficial, it must decrease the expense, currently the motors and VFD drives are imported from abroad and the foreign currency is highly increased. Therefore harmonics reduction in the system is advantages from many views. Not only for the organization but also it is good for the country from reduction of foreign currency.

Table 4.1 Results of the Research with and without active filter

Parameters/specifications		units	Standalone VFD	Active filter with VFD
VFD power rating		KW	55	55
Input current		Amps	125	125
Fundamental 50 Hz current		Amps	125	125
Input current distortion	I1	%THD	56.54	0.064
	I2	%THD	56.77	0.064
	I3	%THD	61.53	0.064
Input voltage distortion	V1	%THD	70.28	0.017
	V2	%THD	64.16	0.017
	V3	%THD	65.68	0.017
Output current distortion (load side harmonics)	I1	%THD	72.15	0.064
	I2	%THD	72.16	0.064
	I3	%THD	74.40	0.064
Output voltage distortion (load side harmonics)	V1	%THD	70.71	0.017
	V2	%THD	64.70	0.017
	V3	%THD	68.08	0.017

4.1 Results of simulink

The results of matlab is as follow without active high pass filter and with active high pass filter

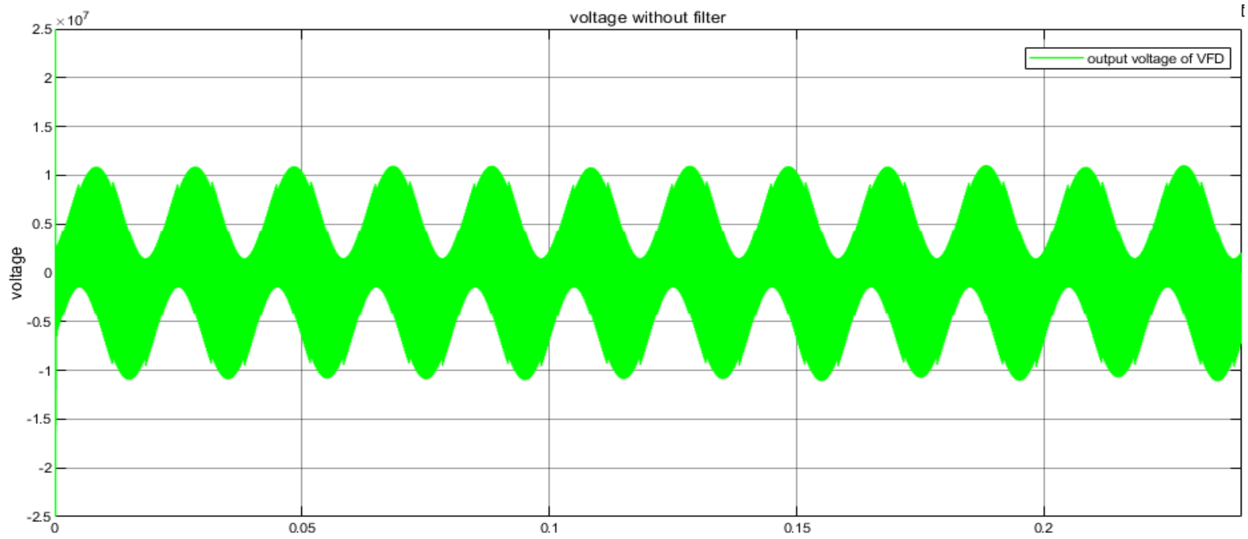

Figure 4.1 Output Voltage of VFD drive without active high pass power filter (IGBT)

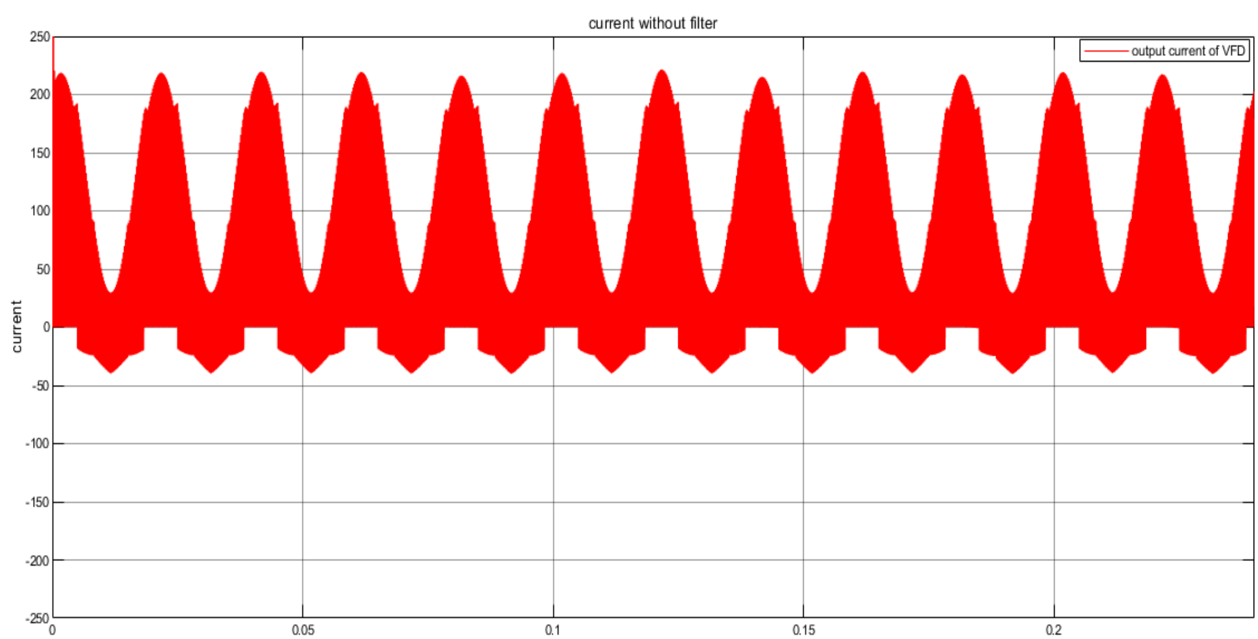

Figure 4.2 Output Current wave form of VFD drive without active high pass power filter

From this it can be understand that the symmetrical current is not occurred due to the effects of high harmonics. That is way the insulations of cables, the motors winding wire and the body temperature increases within a short period of time and as we see in the Figure 4.4 below the symmetrical output is occurred after we use active high pass filter. This insures the output of Figure 4.2 is due to the effects of high harmonics.

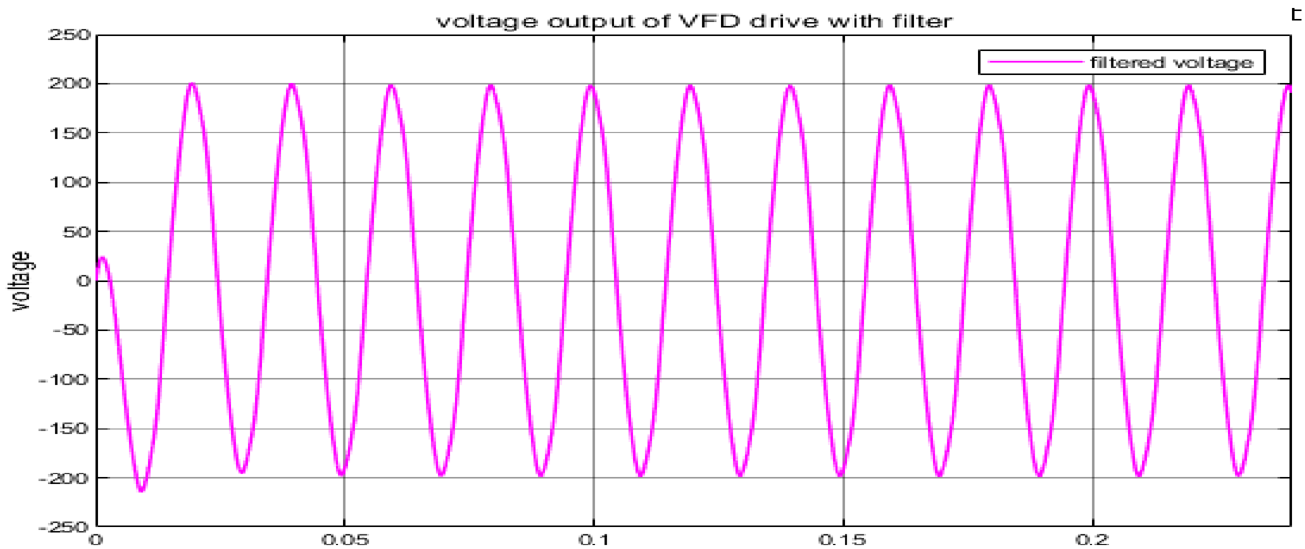

Figure 4.3 Output voltage wave form of VFD drive with active high pass power filter

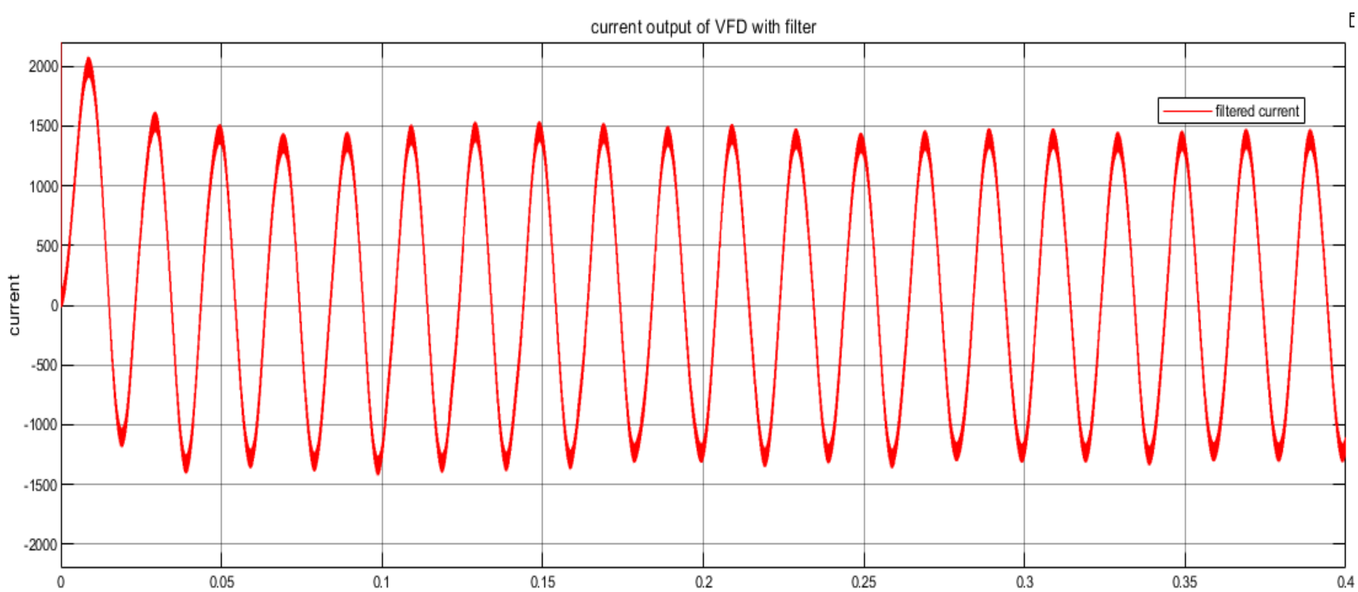

Figure 4.4 Output Current wave form of VFD drive with active high pass power filter

The result shows that the active power filter changes the outputs of the VFD drive by decreasing the harmonics which is generated by it. Therefore, the active filter in the system must be installed in order to get the required results, to work the with induction motors without failure for a long time. Due to the filtering of voltages and currents by using the active power filter we get the following harmonics outputs on currents and voltages. The current harmonics wave form looks like as follow:

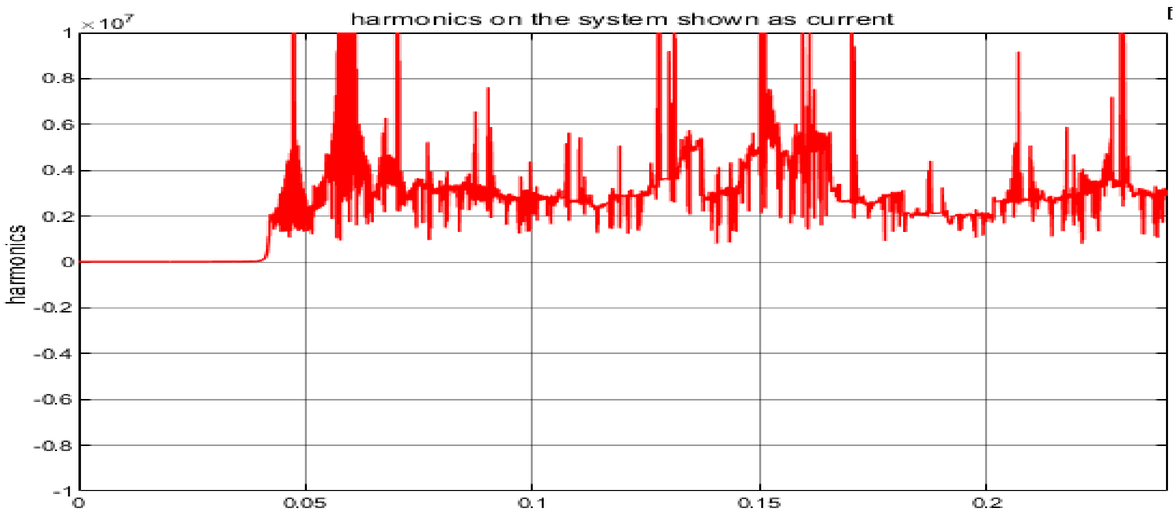

Figure 4.5 Harmonics filtered by active high pass power filter

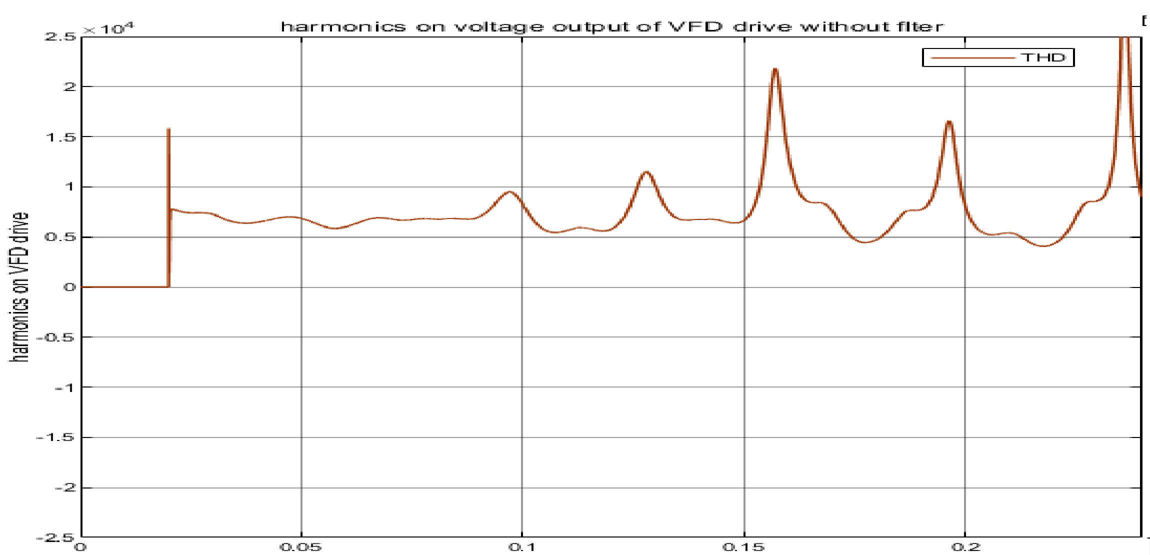

Figure 4.6 Harmonics on voltage wave form of VFD drive

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This thesis presents a shunt active power filter as a reliable and cost-effective solution to power quality problems (harmonics) in induction motors drive by VFD drive. The active high pass power filter presents good dynamic and steady-state response and it can be a much better solution for reducing harmonics in VFD drive systems, Power factor correction and current harmonics reduction than the conventional approach (capacitors to correct the power factor and passive filters to compensate for current harmonics). Besides, the shunt active power filter can also compensate for load current unbalances, reducing harmonics current which is generated in the power lines of the VFD drive. Therefore, this active filter allows adjustment of the power source which reaches to the induction motor, non-linear loads, as a symmetrical resistive load with reduced harmonics because it is known that harmonics is the main problem of VFD drive. The proposed low-cost solution allows the use of a large number of low-power active filters in the same facility, close to each problematic load (or group of loads), avoiding the circulation of current harmonics, reactive currents and neutral currents through the facility of power lines. This solution reduces the power lines losses and voltage drops, and avoids voltage distortions at the load terminals, avoids failure of drives, limits the expense of the organization by increasing life time of the electrical machines, cable, VFD drive etc.

5.2 Recommendations

I recommend that the organizations which use motors (machines) should be use variable frequency drive with active high pass power filter from different views. The organization becomes more beneficial due to several ways. These are saving electrical power, keeping equipment safe and increasing their life time, possible to control the operation depending on the requirement of the process, controls the operation depending on the resources of the organization, keeping sudden failure of the equipment during operation.The research results shows and proves the advantages of using active power filter in the variable frequency drives and its function on production of forming stable electrical systems on the factory as well as on electrical network. This makes the organization more beneficial and profitable. Therefore kessem sugar factory must have plan to install the active filter to void equipment failure.

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APPENDEX

APPENDEX A

VFD SIMULINK MODEL The SIMULINK MODEL of VFD drive is shown below

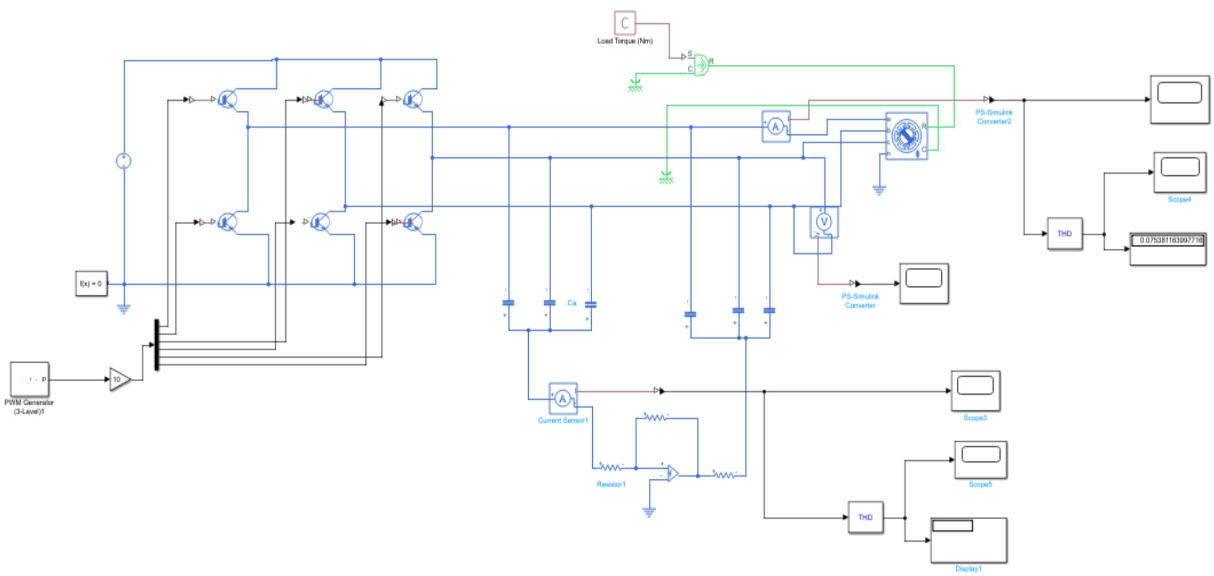

Figure A.1Simulink Model of Variable frequency drive with high pass active power filter

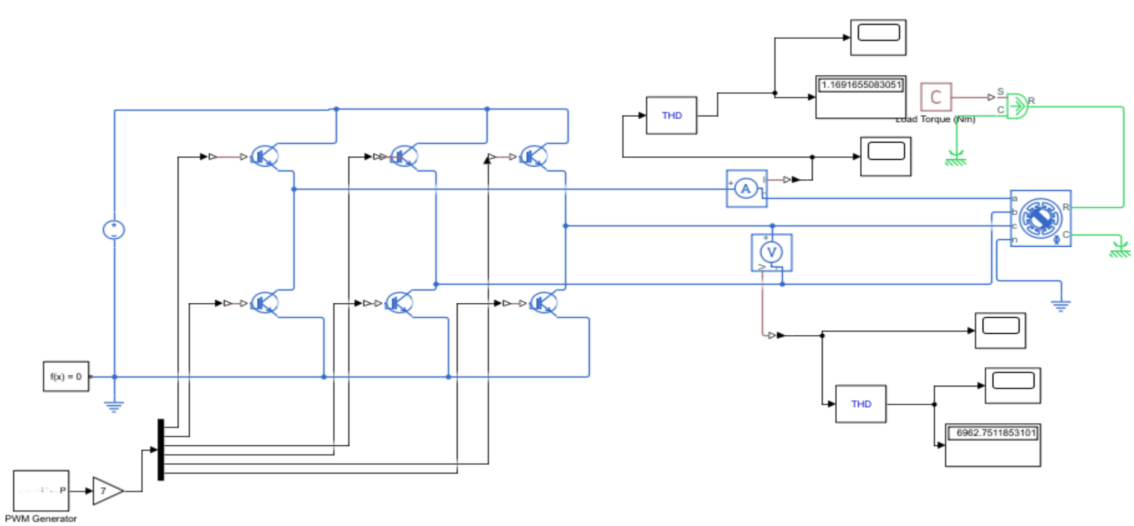

Figure A.2 Simulink Model of Variable frequency drive without filter

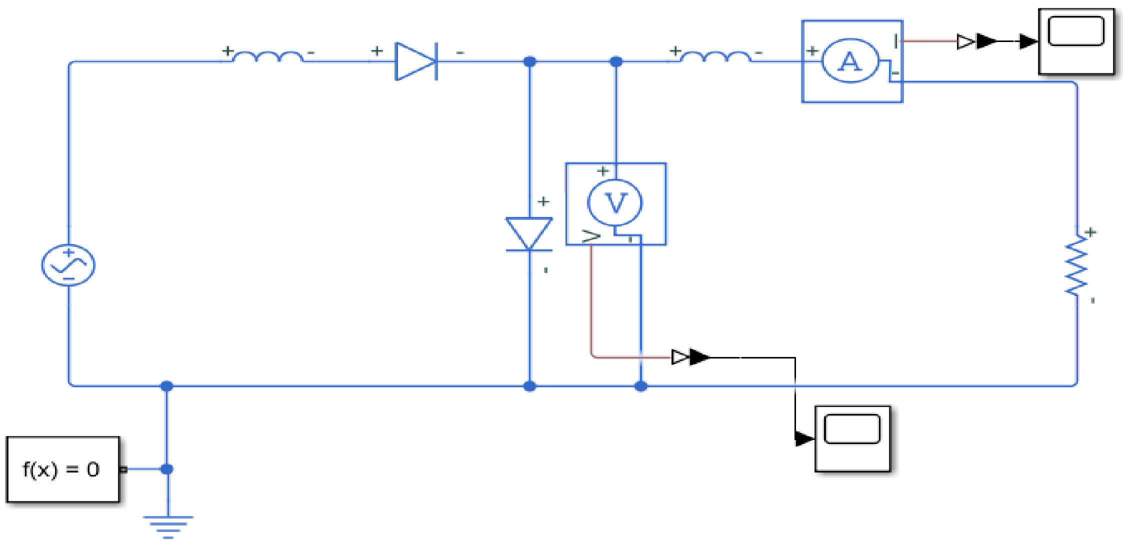

Figure A.3 Simulink Model of Current Source Harmonics (CSH)

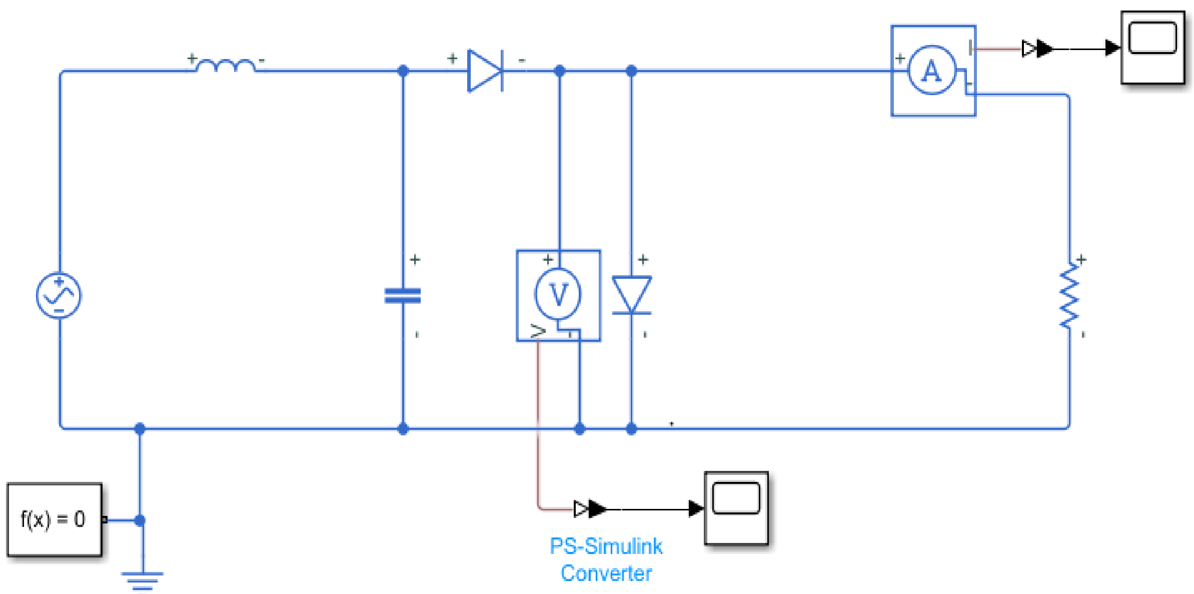

Figure A.4 Simulink Model of Voltage Source Harmonics (VSH)

Figure A.5 Connection of Harmonics Analyzer on load side of VFD drive

Figure A.6 Connection of Harmonics Analyzer on voltage supply side of VFD drive

Figure A.7 Phase1 Current Harmonics reading on the Harmonics Analyzer on load side of VFD drive

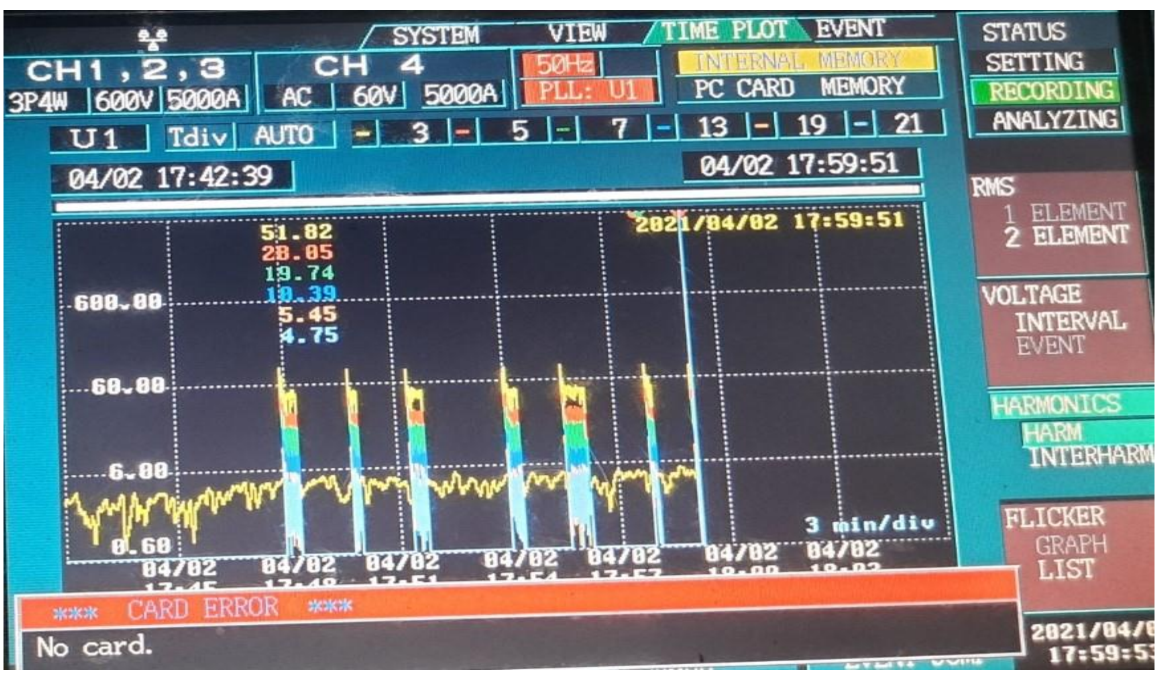

Figure A.8 Phase1 Voltage Harmonics reading on the Harmonics Analyzer on load side of VFD drive