

A  
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ITS ENERGY SAVINGS**

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## **CERTIFICATE**

I **Tamal Aditya** hereby certify that the work which is being presented in the dissertation entitled “**RESEARCH TO STUDY VARIABLE FREQUENCY DRIVE AND ITS ENERGY SAVINGS**” in partial fulfillment of the requirements for the award of the Degree of M.TECH and submitted in the Department of Electrical Engineering of **SURESH GYAN VIHAR UNIVERSITY, JAIPUR** is an authentic record of my own work under the supervision of **Miss Vishu Gupta**, Department of Electrical Engineering, Suresh Gyan Vihar University.

The matter presented in this dissertation embodies the result of own work and studies carried out by me and have not been submitted for the award of any other degree of this or any other university.

This is to certify that the above statement made by the candidate is correct to best of my knowledge.

Date:

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**(Tamal Aditya)**

# **ABSTRACT**

As the demands of industrial needs varying the more outputs of the precise control of our basic electrical prime movers i.e. motor. As compared to AC motors the DC motors are easy to control but with increase in capacity they have their own limitations. Conversely AC motors particularly the Squirrel Cage induction motors are more economical but the speed control of these motor are quiet difficult because alteration of supply frequency is require. Nowadays with technological advancement in drives system, the control of AC motors is more economically, easy to use and the control the range of speed both below and above the base speed.

According to the requirement, these drives can fundamentally alter the voltage and the frequency which is being fed to the motor using the technique called Pulse Width Modulation (PWM). Because of user friendly feature and reasonable cost these devices are gaining more popularity. As the Variable Frequency Device use the embedded system they can be programmed for automatic control reducing the manual intervention and interfaced to the computer.

In the field of HVAC application the usage of Variable Frequency Drive have gained its number. Air handler, chiller, pumps and tower fans are the common application of VFD. A better understanding of Variable Frequency Drives with leads to improve in usage and determining of some appliances and High Voltage AC systems. A basic knowledge of operations, its terms, energy savings, and about the power factors is main aim of this dissertation also Harmonics mitigation by VFD and a simulation project to show how VFD is beneficial for energy savings. In addition to this paper will discuss the comparison between Variable Frequency Drives and other technologies with respect to industrial standards.

## Symbols and Abbreviations

### Symbols

$N_s$	Speed
Q	Flow
H	Head
P	Power
Hz	Hertz
$\phi_m$	Magnetic Flux
m	Modulation Index
F	Frequency
N	Number of turn per phase
L	Inductor
$I_{\text{stator}}$	Stator Current
$I_{\text{sw}}$	Switching Current
$R_{\text{stator}}$	Stator Resistance
P	Number of motor poles
$\text{Cos}\phi$	Power Factor
$\phi$	Power Factor angle
$w_r$	Full load Copper Losses of the transformer

V	Voltage
$V_{rms}$	Root Mean Square Voltage
$V_n$	Line to Line Voltage
$T_e$	Electromagnetic Torque
w	Speed
$W_m$	Rotor Speed
$\Omega$	Ohm
Fcn	Function Block
$\eta$	Efficiency

## Subscripts

a, b, c	phase a, b or c
s	stator quantity
r	rotor quantity

## Abbreviations

VFD	Variable Frequency Drive
AC	Alternating Current

DC	Direct Current
SCR	Silicon Controlled Rectifier
HP	Horse Power
ASD	Adjustable Speed Drive
VSD	Variable Speed Drive
KV	Kilo Volt
KW	Kilo Watt
MW	Mega Watt
HVAC	High Voltage Alternating Current
IGBT	Insulated Gate Bipolar Transistor
RPM	Revolutions per Minute
PWM	Pulse Width Modulation
KVA	Kilo Volt Ampere
NEMA	National Electrical Manufactures Association
CSI	Current Source Inverter
EMF	Electromotive Force
PLC	Programmable Logic Controller
CSF	Carrier Switch Frequency
LCD	Liquid Crystal Display

PID	Proportional Integral Derivative
BAS	Building Automation System
THD	Total Harmonic Distortion
IMD	Inter Modulation Distortion
IP	Intercept Point
SNR	Signal to Noise Ratio
TDD	Total Demand Distortion
DSP	Digital Signal Processing
AFE	Active Front End
LAN	Local Area Network
SinuMec	Sinusoidal Motor Efficiency Controller
RMS	Root Mean Square
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
GTO	Gate Turn Off Thyristor
VSC	Voltage Source Converter
FFT	Fast Fourier Transform
FLA	Full Load Ampere
DPF	Displacement Power Factor
TPF	True Power Factor

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# CHAPTER 1

## INTRODUCTION

### 1.1 Variable Frequency Drive

The industry of Variable Frequency Drive is growing rapidly and now it is more important for technician and the maintenance personnel to keep the installation of VFD running smoothly. The Variable Frequency Drive contains sufficient information for a technician to troubleshoot any AC Variable, virtually eliminating the need for manufacturer-specific manuals.

1. Variable Frequency Drive (AC drives) are used to stepless speed control of squirrel cage induction motors mostly used in process plants due to its ruggedness and maintenance free long life.
2. VFD control speed of motor by varying output voltage and frequency through sophisticated microprocessor controlled electronics device.
3. VFD consists of Rectifier and inverter units. Rectifier converts AC in DC voltage and inverter converts DC voltage back in AC voltage.

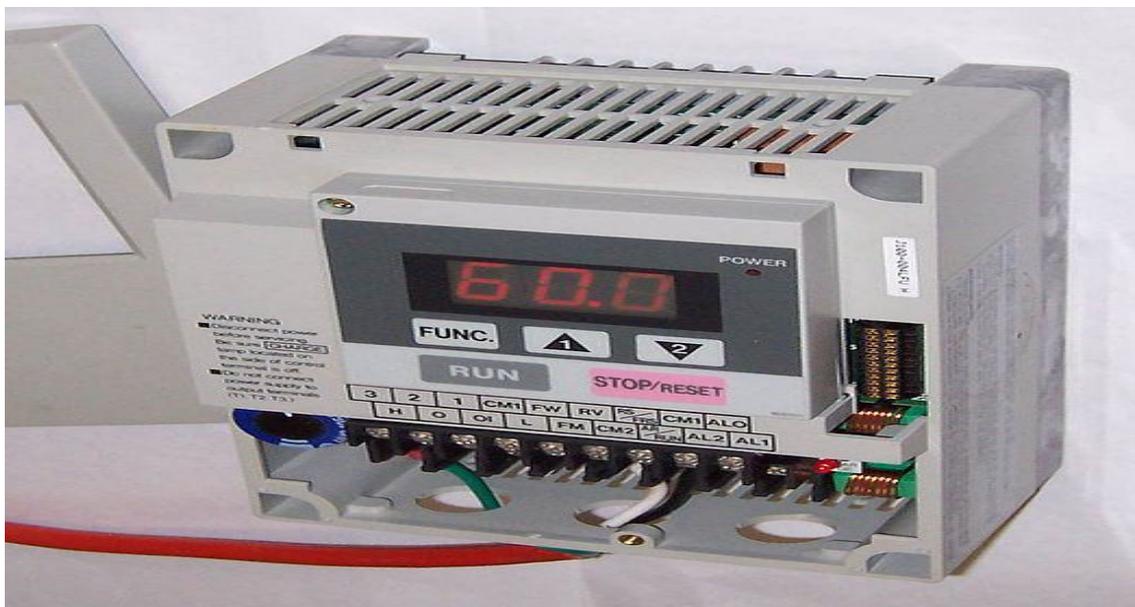


Figure no. 1.1 Variable Frequency Drive [20] [21]

In order to maintain proper power factor and reduce excessive heating of the motor, the name plate volts/hertz ratio must be maintained. This is the main task of Variable Frequency Drive.

The main parts of Variable Frequency Drive (VFD) are the converter, inverter and the controller. The converter rectifies the AC input to DC and the inverter converts the DC to an adjustable frequency and adjustable voltage AC signal. Both must be adjustable to provide a constant volt to hertz ratio. A circuit filters the DC before it is sent to the inverter. The controller regulates the output voltage and frequency based upon feed-back signal from process. If the load is a pump, this is usually a pressure sensor.

Voltage source inverters use a silicon controlled rectifier to build a sine wave for input to the motor. The steps used to build waveform create harmonics that are reflected to the power source. The steps of waveform causes current pulse that make the motor cog at low frequencies and damage keyways and couplings may result.

Current source inverters use an SCR to control the current to the motor. This is also done with multiple steps and has same problems with cogging and harmonics as the voltage source system. Many vendors only offer the voltage or current source systems for large horse power motors of over 300 HP.

## **1.2 Applying Variable Frequency Drives (VFD's):-**

The most types of adjustable speed loads are variable torque, constant torque and constant horse power loads. Variable torque load require much lower torque at low speeds than at high speed. In this type of load, the horse power varies approximately as the square of the speed. This type of load is found in centrifugal fans, pumps and blower.

One practical use of the VFD now is the household washing machine. For years, industrial washing machine have been employed VFDs on three phase motors. Today, VFD is low enough in cost to be incorporated into the home's washer. The VFD provides its ability to change the rotational directional of motor. This allows the washing machine to be a front load type, thus using less water in cycle. The VFD allows for over speeding of motor to accomplish this and

thus the clothes get much dryer while still in washing machine. This means that the drying time is reduced and saves electric costs overtime.

### **1.3 Easy Installation**

The installation process of VFD is quite simple as many parts of equipments are industrial manufactured and are transportable as each units are manufacture partly. The main parts of VFD i.e. the line for communication; power controlling auxiliaries and the motor connected wire all are easily transportable. The cooling parts are also manufactured partly and are easily transportable for its installation. There is only need to connect the installing contractor to the power line supply to the VFD.

### **1.4 Shrinking cost and size**

In today's life Electrical motor control for the purpose of industrial are used by many drives. Among these drives some are of fixed speed drives and some are of variable speed drive depending upon their application. However in earlier times the drives of variable speed had various limitations regarding their efficiencies, speed and space but after the invention of power electronics device and the application into the drives the scene is completely transformed, nowadays VSD which are constructed smaller in shape but also very efficient and highly reliable. The usage of it is more logical when it applies with least expensive in cost and simple to implement.

### **1.5 Common VFD Terms**

For controlling speed of the motor there are several terms used in the industrial field. The terms are used to have different meanings, while the acronyms are often used interchangeably.

## **1.5.1 Variable Frequency Drive (VFD)**

- For controlling the speed of the motor, this device basically consists of Power electronics equipments which aim to vary the supply frequency of the system.

## **1.5.2 Adjustable Speed Drive (ASD)**

- It is a more generic terms for the application in the field of mechanical and electrical for the means of speed controlling.

## **1.5.3 Variable Speed Drive (VSD)**

- This type of drives is used for controlling the speed of the driven equipments by the motor or the motor itself. Basically this type of devices are used in the speed drives of mechanical, electrical or hydrostatic types.

### **1.5.3.1 Mechanical Variable Speed Drive Method**

Historically, electrical VSD's (Variable Speed Drives) even DC Drives were complex and expensive and were only used for most important and difficult applications. The mechanical drives were developed for insertion between a fixed speed electric drive motor and shaft of the driven machine. Many engineers (mainly Mechanical Engineer) are still favored the Mechanical Variable Speed Drives for some applications mainly because of simplicity and low cost.

There are two types of mechanical variable speed drives:-

1. Belt and Chain Drives with adjustable diameter sheaves
2. Metallic friction drives

### **1.5.3.2 Hydrostatic Variable Speed Drive method**

This type of hydraulic VSD is most commonly used in mobile equipment such as transportation, earth moving mining machinery. A prime mover is basically responsible for driven a hydraulic pump usually at a fixed speed and transfer the hydraulic fluid to hydraulic motor. The hydraulic

motor and pump are usually housed in the same casing that allows closed circuit circulation of the hydraulic fluid from pump to motor and back.

The speed of hydraulic motor is directly proportional to the rate of flow of fluid and the displacement motor the hydraulic motor. Consequently the VSD is based on control of both fluid flow and displacement of motor and /or adjustment of the pump. Practically these drives are capable of a stepless adjustable from zero to full synchronous speed.

For making a hydraulic VSD ideal for earthmoving and mining equipments, the main advantages of hydraulic Variable Speed Drives are:-

1. High torque available at low speed
2. High power to weight ratio
3. The drive unit does not damaged even it is stalls at full speed
4. Hydrostatics VSDs are normal bi-directional

Up to a power rating of 25 KW, the output speed can be varied smoothly from about 40rev/min to 1450rev/min. Speed adjustment can be done manually from a hand-wheel or remotely using a servo-motor. The main disadvantage is poor holding capability. Speed may drop by up to 35rev/min between 0% and 100% load. Hydraulic speed drives are basically two types:-

1. Hydrodynamic types
2. Hydrostatic types

### **1.5.3.3 Electrical Variable Speed Drive Method**

In contrast to the variable speed control method of mechanical and hydraulic speed drive, the electrical variable speed drives are basically the speed of electric motor itself, rather than a intermediary device controlled. Variable speed drives that control the speed of DC motors are loosely called DC Variable Speed Drives or simply DC Drives and those that control the Speed of AC motors are called AC Variable Speed Drive or simply AC Drives. Almost all the electrical VSDs are designed for operation from the standard three phase AC power system supply system.

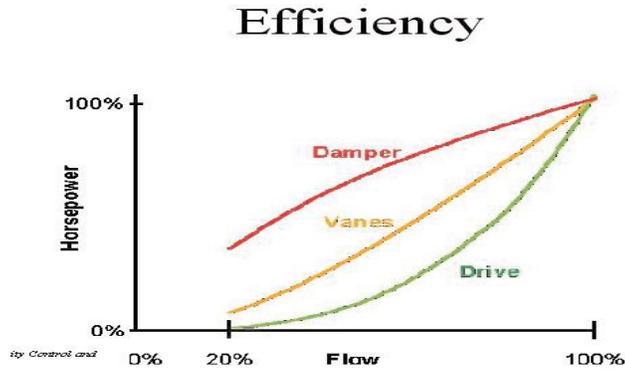


Figure no. 1.2 comparing between the capacity control of mechanical and speed [20]

## 1.6 Energy savings

Savings in Energy can be work with the applications of Variable Frequency Drive (VFD). These saving are achieved by eliminating throttling and friction losses affiliated with mechanical or electromechanical adjustable speed technologies. Efficiency, quality and reliability can also be improved. The application of variable frequency drive is load dependent.

Scope for power saving with Variable frequency Drive

Table no. 1.1 Relation between of flow, head and power with respect to speed

% SPEED	% FLOW	% HEAD	% POWER
$N_s$	$Q \propto (N_s)$	$H \propto (N_s)^2$	$P \propto (N_s)^3$
100	100	100	100
90	90	81	73
80	80	64	51
70	70	49	34
60	60	36	22
50	50	25	13
40	40	16	06
30	30	09	03

As we know the variation of flow, head and power with respect to speed are as follows:

1. Flow  $\propto$  Speed
2. Head  $\propto$  (Speed)<sup>2</sup>
3. Power  $\propto$  (Speed)<sup>3</sup>

The table shows the relation of flow, head and power with respect to speed for e.g. at 50% speed flow reduces to 50%, head reduces to 25% and power reduces to 13%.

## **1.7 Benefit of VFD in HVAC System**

The variable frequency drive (VFD) is the most successful energy management tool which ever used in HVAC system. On cooling tower eliminates drawbacks associates with starter-controlled fans. When a VFD is commanded to start the fan may be spinning. A VFD must correctly identifies motor rotation, slow the motor down to zero speed (when opposite rotation is detected), accelerate the motor in correct direction and not trip on an over-voltage or over-current condition.

Mechanical brakes or anti-ratcheting device can be used to ensure that a fan doesn't rotate in the wrong direction. A VFD eliminates the anti-ratcheting devices, time delay relays, etc as well as both the mechanical and electrical brakes.

In extreme cold weather condition the icing of tower can be averted by running the fan slower than required that raising the temperature of process water and the tower. Keeping the heat in the tower it also reverses a cooling tower fan. Thus VFD's accomplished this function and eliminates the reversing starters.

Likewise on hot days, when the air is thinner, fans can be run above 60Hz, providing additional cooling capacity. The current and/or torque limit function of VFDs will limit the current of motor such that the nameplate FLA rating is not exceeded. This is not possible without applying a VFD.

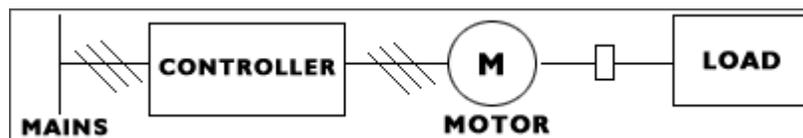
## 1.8 Manufactures

1. Danfoss Graham.
2. ABB.
3. Yaskawa Electric.

## 1.9 Controller

The aim of the Power Electronic Drive Controller is to obtain optimum performance from the motor, to obtain the maximum power from it over as wide a speed range as is required, to achieve highest operating efficiency from the motor and to obtain the best dynamic performance possible. In all case it is it is necessary for the motor and the controller to be matched together carefully if overall optimum performance is to be achieved. Hence the starting point of exploration into Variable Frequency Drive must be the motor, how it works, how it develops torque and how to understand it when operating as Variable Speed Drive.

Earlier the Variable Speed Motors have been DC motors and they reigned supreme in this field since electricity has been put to practical use. However there is an increasing area of application where the DC motor is unable to satisfy the performance required or cope with environment specified. In some cases it is the lack of commutator or brush gear which can decide on the use of an AC Motor. In others it is the need for speeds above those achievable with a DC motor in yet other it may be wish to apply a Variable Speed Controller to an existing fixed motor. It may even be the ready availability of an AC motor which is the deciding factor. Whatever the reason may be, the availability of a wide range of Variable Frequency Drive system is leading to a steady increase in the use of AC variable speed motor drives throughout the industry and this trend is clearly going to continue.



**Figure no. 1.3 Controller is connected to main supply and electrical machine [20]**

# CHAPTER 2

## VFD OPERATION

### 2.1 Operation

The Variable Frequency Drive comprises the parts - a input Rectifier unit, a inverter unit and a DC bus. The supply voltage is firstly pass through a rectifier unit where in gets converted into AC to DC supply, the three phase supply is fed with three phase full wave diode where it gets converts into DC supply. The DC bus comprises with a filter section where the harmonics generated during the AC to DC conversion are filtered out. The last section consists of a inverter section which comprises with six IGBT (Insulated Gate Bipolar Transistor) where the filtered DC supply is being converted to quasi sinusoidal wave of AC supply which is supply to the induction motor connected to it. In a basic DC-link variable frequency motor controller, the input AC power is converted to DC, filtered and then converted to variable frequency DC by an inverter. A set of SCR switches are used to convert the DC to three phase AC power to drive induction motor. Bypass diodes are needed for reactive power flow and to clamp the voltage to that of DC supply. The filter supplies a DC voltage to the inverter that is largely independent of load current due to filter capacitor. The inverter tends to keep the current constant. The AC to DC converter output may be fixed or variable (voltage or current) depending on the type of inverter and the filter used.

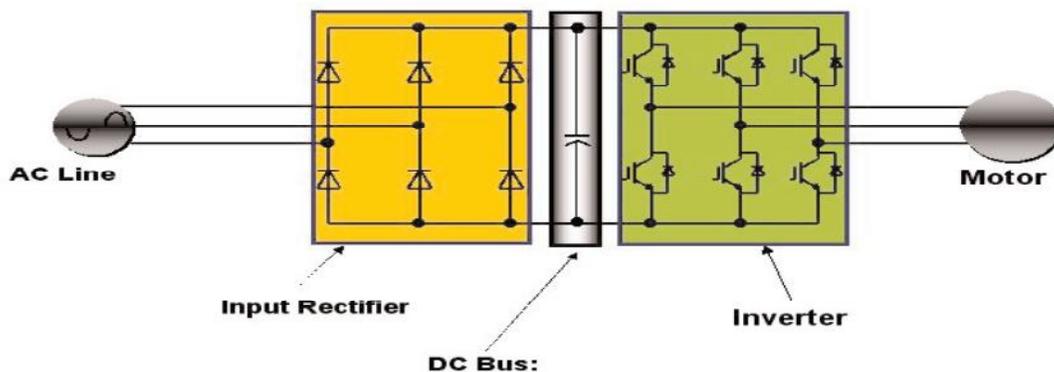


Figure no. 2.1 Mechanical capacity control [21]

As we know that the synchronous speed of motor is directly proportional to the supply frequency, therefore synchronous speed of the motor can easily vary by changing the value of the frequency. This is the main working phenomenon of the VFD.

**Example:**

For a 2-pole asynchronous motor, the synchronous speeds at different supply frequencies are:-

➤  $3600 \text{ rpm} = \frac{60 \times 120}{2}$

➤  $3000 \text{ rpm} = \frac{50 \times 120}{2}$

➤  $2400 \text{ rpm} = \frac{40 \times 120}{2}$

As the frequency can easily variable as compared with the poles of the motor therefore speed control drive is termed as Variable Frequency Drive (VFD).

## 2.2 Speed control of Induction Motor

Basically synchronous speed and the rated speed are the two terms of speed used in motor. The synchronous speed is defined as the speed of motor at which its magnetic field rotates. It is basically the theoretical speed of the motor when the shaft of the motor bears no load and the bearing of the motor faces no friction in the motor. The factors which affecting the synchronous speed are the supply frequency and the stator magnetic poles. The calculation by which the synchronous speed is to be calculated is given by the following equation:-

$$\text{Speed (rpm)} = \frac{\text{Frquency (Hertz)} \times 120}{\text{No. of Poles}}$$

Where;

Frequency = Supply Frequency of the Electrical power in Hz.

Number of Poles = Number of electrically magnetic poles presents in the stator of the motor.

In India, the supply frequency of the Electrical power is basically fixed i.e. 50Hz and the number of poles presents in the stator is basically the factor of design which affects the speed of the

motor. In practical the rotor speed of the induction motor slightly lags as compared with the synchronous speed at the time of running. This lags is basically expressed in percentage of the synchronous speed which is called as “Slip”. Slip is basically defined as the difference of rated speed from the synchronous speed and is divided with the synchronous speed. The equation for slip calculation is given below:-

$$\text{Slip} = \left( \frac{\text{Synchronous Speed} - \text{Rated Speed}}{\text{Synchronous Speed}} \right)$$

### **2.3 Constant V/F Ratio Operation**

All Variable Frequency Drives (VFDs) maintain the output voltage – to – frequency (V/f) ratio constant at all speeds for the reason that follows. The phase voltage V, frequency f and the magnetic flux  $\phi$  of motor are related by the equation:-

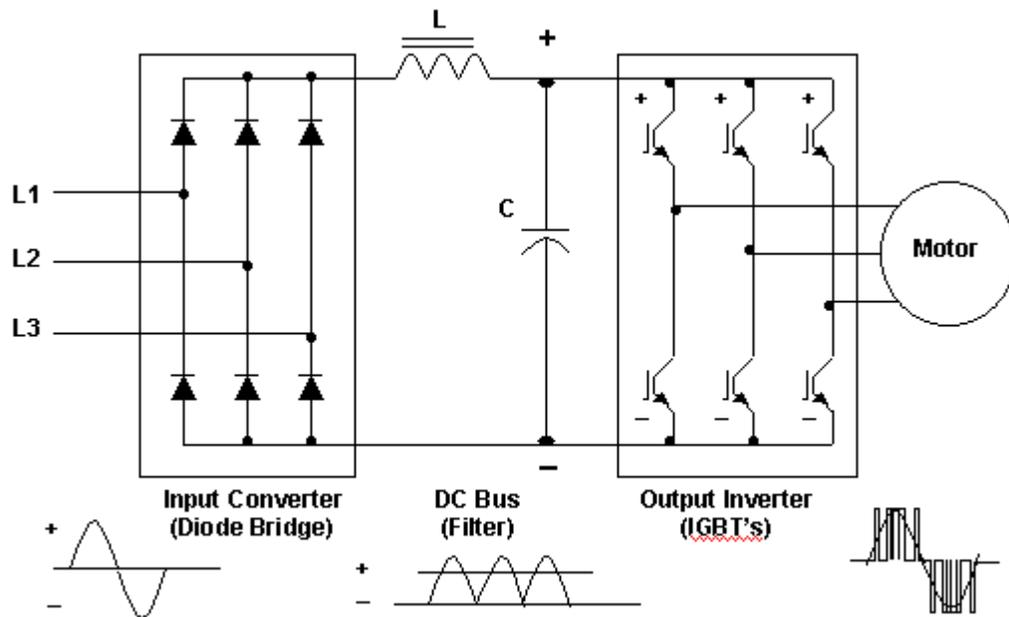
$$V = 4.44 f N \phi_m \text{ or } V/f = 4.44 \times N \phi_m$$

Where N = number of turns per phase.

If the same voltage is applied at the reduced frequency, the magnetic flux would increase and saturate the magnetic core, significantly distorting the motor performance. The magnetic saturation can be avoided by keeping the  $\phi_m$  constant. Moreover, the motor torque is the product of stator flux and rotor current. For maintaining the rated torque at all speeds the constant flux must be maintained at its rated value, which is basically done by keeping the voltage – to – frequency (V/f) ratio constant. That requires the lowering the motor voltage in the same proportion as the frequency to avoid magnetic saturation due to high flux or lower than the rated torque due to low flux.

## 2.4 How Drive Changes Motor Speed

As the drive provides the frequency and voltage of output necessary to change the speed of a motor, this is done through Pulse Width Modulation Drives. Pulse width modulation (PWM) inverter produces pulses of varying widths which are combined to build the required waveform. A diode bridge is used in some converters to reduce harmonics. PWM produce a current waveform that more closely matches a line source, which reduces undesired heating. PWM drive have almost constant power factor at all speeds which is closely to unity. PWM units can also operate multiple motor on a single drive.



**Figure no. 2.2 Circuit Diagram of Basic VFD [21]**

In a square wave inverter, each input is connected alternatively to the positive and negative power supply outputs to give a square wave approximation to an AC waveform at a frequency that is determined by gating of switches. The voltage in each output line phase shifted by  $120^\circ$  to provide a three phase source.

The switches provide a stair-step voltage for each motor phase at frequency below rated frequency of the motor, the applied voltage must be reduced otherwise the current to the motor will be excessive and cause magnetic saturation. A decreasing voltage level to keep the flux

constant can be done with square wave inverter decreasing DC voltage as motor speed is reduced below the rated speed. This can be done by a controlled rectifier but this problem with harmonics in the power system of supplying controller.

## 2.5 Switching Bus with IGBTs

Nowadays the Insulated Gate Bipolar Transistor (IGBT) present in inverter which used to switch ON and OFF of the DC bus at specific intervals. Thus a variable AC voltage and frequency is being created by the inverter. The output sine waveform is being shown in fig 2.3. The control circuit present in the power circuit is signaling from the drives to turn ON at the positive half cycle or negative half cycle of a power device. This clears that as long as the power device remains ON, the output voltage remains higher. Also for frequency point of view the higher the frequency states for longer the power device ON.

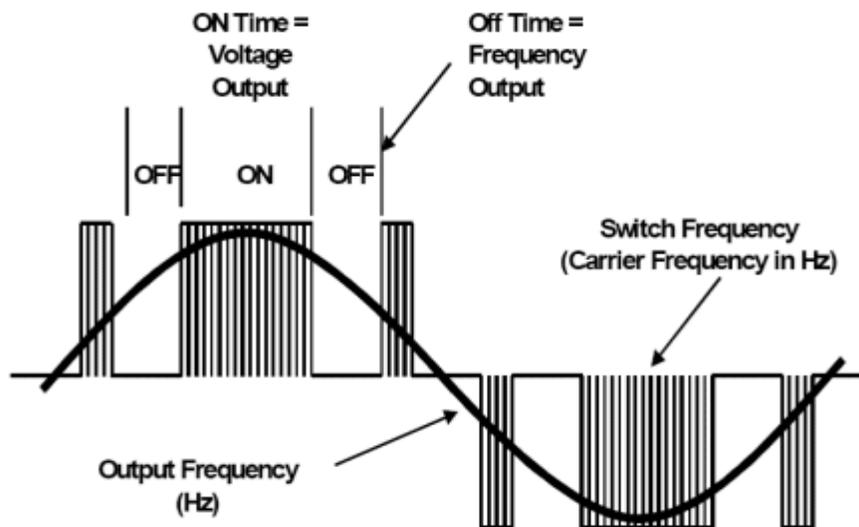


Figure no. 2.3 Drive Output Waveform Components [21]

Thus the carrier frequency is derived from the speed of the power device switch remains ON and OFF. It is also called switch frequency. Therefore higher the carrier frequency higher the resolution for PWM (Pulse Width Modulation) contains. The typical carrier frequency ranges

from 3KHz to 4 KHz or 3000 to 4000 times per second as compared with older SCR based carrier frequency which ranges from 250 to 500 times per second. Thus it is clear as much as higher the carrier frequency higher will be the resolution of output waveform. It is also noted that the carrier frequency decreases the efficiency of the drive because it led to increase the heat of the drive circuit.

## **2.6 VFD as Starters**

Variable Speed Drives (VSDs) take place of a starter. They have both starting capability and overload protection built in. In fact the microprocessor control the most drives provides additional protection against other faults (such as under-voltage, over-voltage, ground fault, loss of phase, etc.). Variable Speed Drives also provide for soft-start of the motor (if so programmed) reducing inrush current and reducing wear on belts and sheaves. While a starter not required when a VSD/VFD is used, one may be provided as a back up to the drive so that the motor can be run at a full speed in case the drive fails. The Variable Frequency Drive as a starter has following advantage:-

1. It provides a high starting torque compared to other methods.
2. Line current can be made sinusoidal with displacement power factor unity with a pulse width modulation (PWM) rectifier.
3. The same converter can be used on a time-sharing mode for other motors.
4. The converter can be bypassed after starting the motor to eliminate the converter losses.
5. At light loads the voltage can be adjusted to improve the running efficiency.

The Variable Frequency as a starter is very similar to Variable Frequency Drives (VFDs) in design and is gradually becoming widely used due to falling power electronics prices and stringent power quality standards on the line harmonics imposed on the variable frequency motor drives.

## 2.6.1 Low Inrush Motor Starting

Small induction motors can be started directly from lines. However, the starting inrush current in a large motor with high inertia can be high and last for a prolonged time, causing the motor to overheat. Moreover the lights may flicker under excessive voltage dip in the lines. Using a star – delta starter, an autotransformer or a phase controlled voltage step-down converter, the starting the motor with reduced voltage. All these methods result in low starting torque proportional to the applied voltage squared and are not really for starting a large motor with high initial torque load.

## 2.6.2 Soft Starters

During soft starting of a motor, the frequency and the voltage starts from a small value and ramp up to a full rated value in a linear ramp. However, near zero speed and frequency at starting, the inductive reactance is negligible and the voltage setting the air gap flux is  $V - I_{\text{stator}}R_{\text{stator}}$ . For constant air gap flux requires then  $(V - I_{\text{stator}}R_{\text{stator}})/f$  must be maintained constant. The required boost decays as the motor speeds up under increasing frequency and this ratio in the V/f ratio linearly ramping up. The rate at which V and f are ramped up depends on the load inertia. The ramping is done over a longer time for high inertia loads than for low inertia loads.



**Figure no. 2.4 VFD soft starter panel**

## 2.7 Low Full Load KVA

Basically the total amount of power present in KVA offers the limiting factor of energy that is to be transferred through other electrical devices. During period of peak demand if the required KVA by the equipments can be reduced then it will help to improve voltage sags, power shortages of Power and blackouts. Power factor and the unity efficiency are evenly measured while estimating Kilo Volt Ampere. This means that the power factor is indirectly proportional to KVA, but the equipment may be equal or worse in efficiency.

To closely match with the load a backup generator is typically the same sized is provided. The size of generator required can be reduced by lowering the KVA. with the application of Active front are used in the Variable Frequency Drives the ratio of KW/KVA is tends to be ideal i.e. 1:1 which resulting effect on the size of the generator, This is the reason that the power factor tend to unity and also the harmonics that give rise from the Variable Frequency Drive is very less. Also decreasing the value of KVA acquires the usefulness objects. So from the usage of same transmission objects the total power in (KW) can be conveyed.

A drive can control two main elements of a three phase induction motor. Basically the two parts of the motor are the rotor and the stator which works through magnetic interaction. A motor contains pair of pole. The iron pieces which are present in stator, wound in a specific pattern to provide a north south magnetic field.

With one pole pair which is isolated in a motor the rotor shaft rotates at a specific speed which is termed as base speed. This speed can be determines by the number of poles and the frequency applied to it. The formula includes the effect called “slip”. Slip is basically the difference between the speed of rotor and the stator magnetic field rotating. When a magnetic passes through the conductor of the rotor, the magnetic field of the rotor takes on of its own. These magnetic fields rotor will try to catch up to the rotating field of the stator. However this never happens and thus the difference is called slip. The slip is what that allows a motor to turn.

### **Motor Slip:**

$$\text{Shaft Speed} = 120 \times F/P$$

Slip for NEMA B Motor = 3 to 5% of Base Speed which is 1800 RPM at Full Load

F = Frequency applied to the motor

P = Number of motor poles

**Example:**

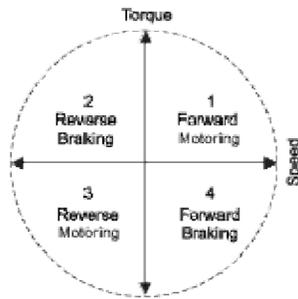
$$\text{Shaft Speed} = \frac{120 \times 60}{\text{No. of Poles}}$$

By changing the frequency we can change the speed of motor. Another way to change the motor speed by changing the no. of poles, but this change would be a physical change of the motor. It would further require rewinding and result increase in step changing to the speed. So keep in view of cost efficiency, convenience and precision, we change the frequency. Also the torque developing characteristics of every motor is the volts per hertz (V/Hz). To change the motor torque we can change this ratio. For example, an induction motor connected to a 460V, 60Hz source then the ratio of (V/Hz) will be 7.67. Thus as long as this ratio stays in proportion the motor will develop rated torque. A drive provides the output of many different frequencies. By changing the given output frequency of the drive, we will get a new torque curve.

## 2.8 Load characteristics of Induction Motor

In practical, the loads are of different types with variable speed torque curves are available. As develop motor torque is equal to requirement of load torque then the load system of the motor is said to be stable. With comparison to the time constant of mechanical, in most drives the electrical time constant of motor is negligible. Therefore during transient operation, the motor can be assumed to be an electrically equilibrium, implying that the steady state torque speed curve is also applicable to transient state operation.

Figure 8 represent the Four-quadrant diagram for mode of operation of variable speed drive. In Quadrant 1 both the speed and torque represent in positive direction, therefore the Quadrant 1 is termed as forward motoring quadrant. Similarly in Quadrant 3 both speed and torque represent in negative direction, therefore it is termed as reverse motoring.



**Figure no. 2.5 Four –Quadrant operation [20]**

Similarly in Quadrant 2 and 4 both the speed and torque are mutually opposed each other which resultant gives as braking effect. Thus both the quadrant 2 and 4 termed as reverse and forward braking.

For a trouble free operation of VSDs, the characteristics of loads are particularly important. Load refers to essentially to the output of torque and the corresponding speed required. Load characteristics can be classified as follows:-

- Constant torque and variable speed loads characteristics
- Variable torque and variable speed load characteristics
- Constant power loads characteristics
- Constant power and constant load characteristics

### **2.8.1 Constant Torque and Variable Speed Load Characteristics**

The torque required by this type of load is constant regardless of speed. In contrast, the power is linearly to the proportional of the speed. Equipments such as conveyors, screw compressors and feeders have this type of characteristics.

## **2.8.2 Variable Torque and Variable Speed Load Characteristics**

This is most commonly found in industry and sometime it is called as quadratic torque load. The torque is the square of speed, while the power is the cube of the speed. This is typical torque speed characteristics of a fan or a pump.

## **2.8.3 Constant Power Load Characteristics**

This type of load is rare but is sometime found in industry. The torque varies while the power remains constant. The torque is inversely proportional to the speed at which the theoretically meaning is the infinite torque at zero speed and zero torque at the infinite speed. This type of load is characteristics of the traction drives, which require high torque at low speeds for initial acceleration and then a much reduced torque when at a running speed.

## **2.8.4 Constant Power and Constant Torque Load Characteristics**

This is commonly applicable in the paper industry. With the linearly in the power increasing, basically in this type of load as the speed increases, the torque is constant.

## **2.9 Commutation and Control Methods**

There are basically two methods for the commutation of Variable Frequency Drive (VFD). These are:-

### **2.9.1 Forced – Commutated VFD**

With lagging power factor induction motor load, the inverter thyristors need to be forced commutation with capacitor and diodes. The leakage inductance of the motor plays a significant role in the commutating circuit design for the inverters. Therefore such VFD is designed for use

with only specific motor. Also it can be used for regenerative braking without additional circuits on the positive side.

## 2.9.2 Load – Commutated VFD

The load – commutated thyristors in a CSI is widely used with large multi megawatt synchronous motor for pumps, compressors, rolling mills and ship propulsion. For high power drives, 12 pulse converters are used to lower harmonic content. The VFD is load – commutated by leading power factor of the synchronous motor that can achieve by over exciting the rotor field to obtain higher back – emf induced in motor armature. The frequency and the phases of the three phase current are synchronized to the rotor position and the current commutation in the inverter thyristor is accomplished by using motor back – emf. Slow speed thyristor can be used both sides. This makes the inverter simple, cost effective, energy efficient and reliable compared to CSI with an induction motor.



Figure no. 2.6 Variable Controller [21]

## 2.10 Automated Systems and Machine Control

The VFD is used to do more than vary the speed of an electric motor. First, in order to run the motor, the VFD must be programmed for the control scheme that is expected to utilize. Next, the VFD is expected in many automated systems to perform some minor logic operations,

determining when and how fast to run the motor it is controlling. Basic VFD control schemes typically are called two wire or three wire control schemes. Two – wire control schemes utilize just two wires for the sequencing (run/stop) phase of operation, whereas three wire schemes need a third wire. Thus the starting, stopping and directional (motor rotation) commands necessary to motor operation are picked up here. All machines with AC motors and VFD control have to have a determination made as to how these signals are to be sequenced and from where they shall come. The drive is not all knowing; the user must tell the drive this basic control scheme.

The reference is the term given to that signal that the drive receives, typically from an external potentiometer or PLC controller, that directly relates to how fast it is to make the AC motor run. Reference signal can be in a 0 to 10 volts DC, 0 to 5 Volts DC mode or can be 4 to 20 milliamperes. These signals can be scaled inside the drive to correspond to low and high speed of the motor. They are usually bias adjustments for these signals, as many times as they are not true and exact voltages. This flexibility by the VFD allows for deviations to be corrected. Additional control terminals at the drives are low voltage inputs and outputs, with many being configurable by the user for the machine or process. There are contacts to indicate that the VFD is running ok and there are no faults. Additionally, many drives come equipped to send analog signals out to drive – speed meters. Thus it is possible to utilize many control options whenever setting up a VFD on any one machine. The VFDs, equipped with extensive and programmable capabilities, can be made to be very different from different from one another when the machine or automated – process needs have to be met.

## **2.11 Transmission line effects**

The Variable Frequency Drive consists of a chain of pulses which is switched at the carrier frequency of the output voltage of Pulse Width Modulation (PWM). The transmission line effect of cable between drive and the motor must be considered as the rapid rise time of these pulses. The pulses tend to reflect back from motor terminals into the cable, as the transmission line impedance of cable and motor are different. Putting high stress on the cable and the motor winding and also the eventual insulation failure the resulting voltage can produce up to twice the

rated line voltage for long cable runs. The longer Carrier Switching Frequencies (CSF) of 2.5 KHz is allowed by longer cable distances when the Carrier Switching Frequency can produce audible noise at the motor. The manufacturers of Variable Speed Drives (VSD) usually after du/dt filter that basically decrease the steepness of the pulses for application requiring long motor cables whereas the sinus filter is recommended for very long cables or old motor is with insufficient winding insulation . As the life of older motor is to be expected shorten therefore the VFD should purchase as per the motor rated for applications.

## **2.12 Integrated Motor and Drives**

A number of motor and drive manufactures are now producing integrated motor/VFD units. These units consist of a motor and a specially designed VFD, produced as a single package, with the VFD unit mounted on the variously on the top, side or end of the motor. Currently these designs are available up to approximately 22 kW (30HP). Integrated motor and drives can feature a number of advantages:-

1. Motor and VFD are properly matched.
2. Installed cost can be less than separate motor and VFD.
3. No special cables between VFD and motor, saving installation time and screened cables.
4. Reduced over –voltage on the motor winding due to short length of connections, leading to a longer life of insulation.
5. No output cables. Hence radiated emissions are minimized.
6. VFD shares motor cooling system.
7. Better compatibility between all components of the drive system, reduces noise and vibration.
8. Often easier and faster to retrofit in a building or industrial installation.

## **2.13 Dynamic braking**

Dynamic braking basically determines that when a motor used as a generator by absorb energy from the system. The Variable Frequency Drive system includes a resistor/chopper combination that allows for dynamic braking of the tripper. The VFD chopper/resistor system is designed to handle a minimum of 15 stops (and 15 starts) per hour. During soft stop, the VFD will dynamically slow the tripper to a full stop in a maximum of 3 seconds.

Normal stopping is done by dynamic braking only. Neither the motor brakes nor the rail clamps are used during dynamic braking. This allows longer life on brake pads.

## **2.14 VFD Display and keypad**

The operating values of VFDs are being displayed in engineering / user units. The display shall be given in English words i.e. no alphanumeric codes are acceptable.

1. Motor speed (RPM, Percent and Engineering units)
2. Motor current
3. Calculated motor torque
4. Calculated motor power (KW)
5. Output frequency
6. Output voltage
7. DC Bus voltage

A backlit LCD display included in the keypad. The following assistants shall use the keypads:-

1. Start – up assistants
2. Parameter assistants
3. Maintenance assistance
4. Trouble shooting assistance

The keypad shall be removal, capable remote mounting and shall be allow for uploading and downloading of parameter settings. It also includes the hand off auto selection and speed control. There is a fault reset and help button on the keypad. The help button shall include “On – line” assistants for programming and trouble shooting.

A built in time clock with a battery for a backup in the VFD keypad, the time clock shall be used to date and time stamp faults and records of parameters operating at the time of fault. The VFD automatically reverts to hours of operation since initial power up, if the battery fails. The time clock also programmed to control the functions of start/stop constant speed, PID parameters sets and output relays. The Variable Frequency Drive shall have capability of communicating building automation system. (BAS) via a RS – 485 port.

## **2.15 Variable Frequency Drive Design Consideration**

In providing a VFD in a new installation, all components can be designed accordingly. However in a retrofit, installing a VFD is not as simple as changing the motor starter. All components need to be carefully addressed. The system design needs to be analyzed. Several issues are noted in the following list:-

1. A VFD normally requires a larger motor and a heavier wiring from the motor starter. Special motors may be used that are provided with reinforced insulation.
2. A VFD is only about 96 or 97 percent efficient. The difference in the efficiency results in the generation of substantial heat in the motor starter, which must be dissipated. As a result the electrical room containing the VFD may require additional ventilation or air conditioning.
3. VFDs are not recommended for high static head applications. Because of the relationships between speed and horsepower, a much larger motor is typically needed for high static head applications and may not be most efficient installation.
4. Other design issues include larger wiring required, potential resonance with other equipment, long cable runs and potential induced voltages.

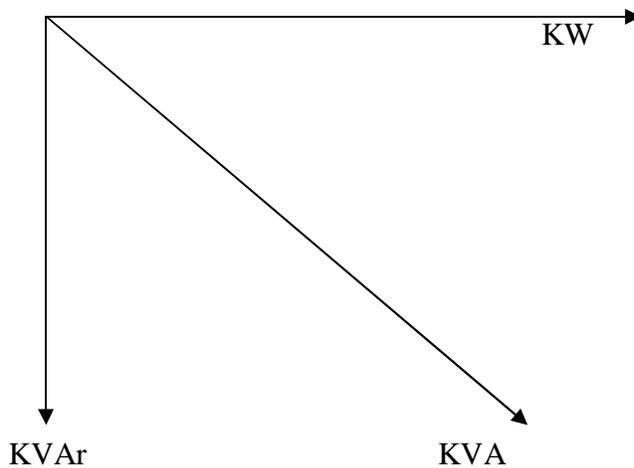
# CHAPTER 3

## RELATION BETWEEN VFD AND POWER FACTOR

### 3.1 General

The Variable Frequency Drive (VFD) basically contains capacitors which are present in DC bus is used to maintain Power Factor on the line side. Therefore any additional use of other power factor correction equipments on the line side supply to the motor or use of expensive capacitor bank is not require. The Variable Frequency Drive (VFD) itself offer high power factor in the line side supply to the motor.

Power Factor of an Electrical Network/Installation/Load is defined as the cosine of angle by which the Apparent Power i.e. KVA is out of phase with respect to the Active Power i.e. KW. A simple vector diagram is given below where Power Factor is equal to  $\cos\phi$  (lagging).



**Figure no. 3.1 Power Triangle**

We know that Power Factor =  $\cos\phi$

From the above diagram-

$$1. \text{ KVA} = \sqrt{(\text{KW})^2 + (\text{KVAr})^2}$$

2.  $\text{Cos}\phi = \text{KW}/\text{KVA}$   
 $= \text{KW}/\sqrt{(\text{KW})^2 + (\text{KVAr})^2}$
3.  $\text{KW} = \text{KVA} \times \text{Cos}\phi$
4.  $\text{Tan}\phi = \text{KVAr}/\text{KW}$

It is now clear that in order to reduce the flow of reactive the Power Factor will have to be improved. At unity Power Factor (i.e.  $\text{Cos}\phi = 1$ ) the flow of reactive power is zero and is thus the ideal condition.

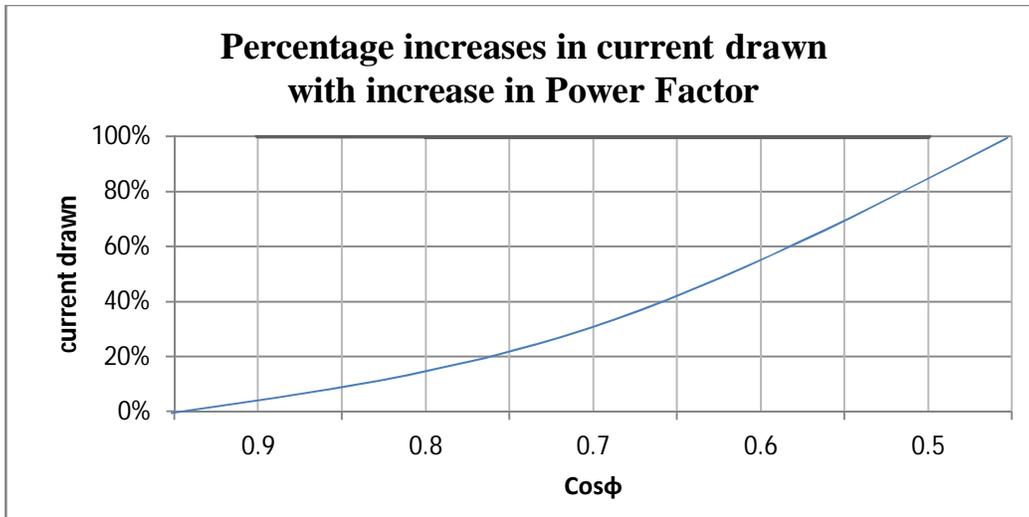
### **3.2 Problems of Low Power Factor:-**

Low Power causes a variety of problems which result in increase in losses and in efficient system operation. The major problems that are created due to low power factor are elaborated below:-

#### **3.2.1 Current Drawn**

For a given Active Power i.e. KW requirement a low Power Factor will result in an increase in the current drawn for the supply. The graph given on the next page gives the variation of percentage increase in the current drawn on the Power Factor decreases.

It can be seen from the graph that, if the percentage increase in current drawn at unity Power Factor is 0% of the rated current the corresponding percentage increase in current drawn at 0.5 Power Factor will be 100% i.e. twice the rated current will be drawn. This means that with low Power Factor the transformers, switchgear, distribution cables, etc in the installation will have to be over sized to carry this increased current. In addition to this the  $I^2R$  losses will increase significantly due to low Power Factor.



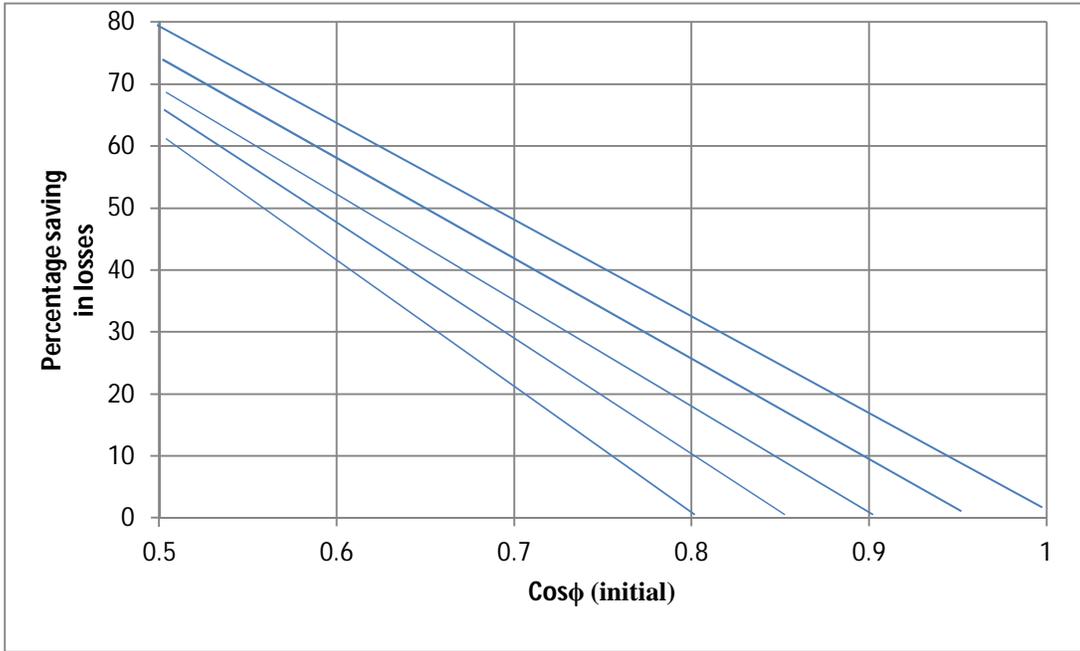
**Figure No. 3.2 Percentage increase in Current drawn with increase in Power Factor**

### 3.2.2 Cable Losses

As explained above improvement in Power Factor means reduction in the line current. For a given cable the losses are proportional to the square of this current. Consequently by improving Power Factor from an initial value of  $\text{Cos}\phi_1$  to the final value of  $\text{Cos}\phi_2$ , the reduction in  $I^2R$  losses is given by the expression: –

$$\begin{aligned} \text{Percentage Saving in losses} \\ = \{1 - (\text{Cos}\phi_1 / \text{Cos}\phi_2)^2\} \times 100 \end{aligned}$$

The graph given below shows the percentage saving in  $I^2R$  losses. We can see an improvement in  $\text{Cos}\phi$  from 0.7 to 0.9 reduces losses by 40%



**Figure No. 3.3 Percentage saving in losses with increase in power factor**

### 3.2.3 Transformer Losses

The losses in transformer are generally two types:-

- a. Losses in the core i.e. Iron Loss and
- b. Losses in the winding i.e. Copper Loss

The Iron Loss are approximately equal to the power consumed by the transformer under no load conditions and for all practical purposes are assumed to be constant irrespective of load variation on the transformer. The Copper Loss however vary from the square of the current and thus become directly related to the factor of the load which being supplied from the transformer. The saving in transformer losses due to power factor improvement is given by the expression.

$$\text{Saving in Loss} = W_r \times K_1 [(1/\text{Cos}\phi_1) - (1/\text{Cos}\phi_2)]$$

where  $W_r$  = full load Copper Losses of the transformer

$$K_1 = \frac{\text{Conected load in KW}}{\text{KVA rating of the transformer}}$$

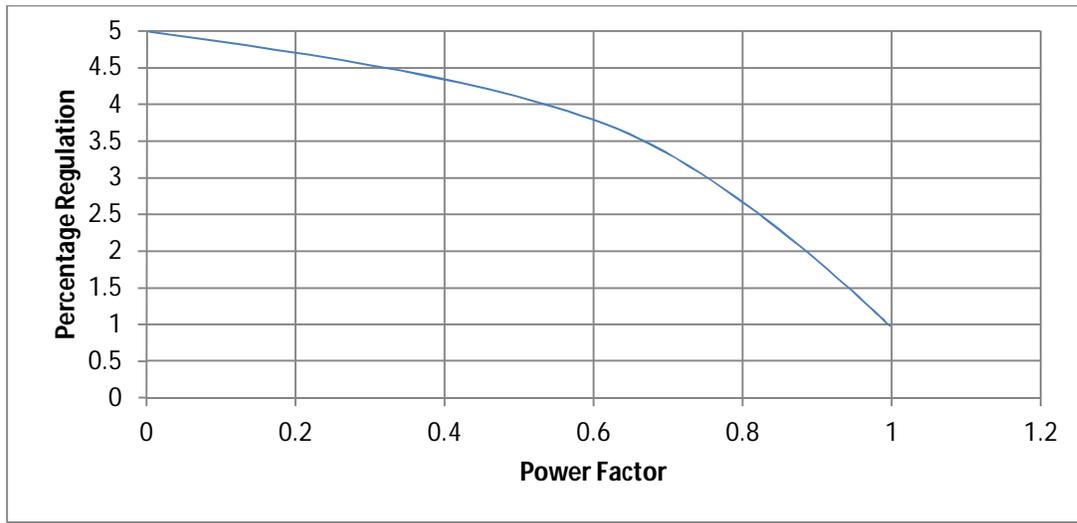
$\text{Cos}\phi_1 = \text{Initial Power Factor}$

$\text{Cos}\phi_2 = \text{Final Power Factor}$

Thus it is obvious that improvement in Power Factor has significant cost saving of reduction of Transformer Losses.

### 3.2.4 Voltage Regulation

It is well known that when a transformer operates on load there is a voltage drop in the secondary voltage in comparison to the no load secondary voltage. The regulation of percentage in a transformer indicates this voltage drop. Improvement in Power Factor has a positive impact in terms of reducing the voltage drop on secondary of a transformer and thereby improving its regulation. The graph given below shows the variation of percentage regulation with Power Factor. Consequently system efficiency is improved due to better voltage regulation.



**Figure No. 3.4 Percentage increase in Voltage Regulation with increase in Power Factor**

### 3.2.5 Levy of Penalty

All Electricity supply companies and State Electricity Boards in India normally levy penalty for Power Factor in an installation. The penalty is normally levied as a percentage of the electricity

bill for a given installation. Generally Power Factors below 0.85 will result in the levy of such penalty. However it has been seen recent times that the minimum Power Factor levied has been increased five and again in certain cases is as high as 0.9. Consequently low Power Factor will have a very severe impact in terms of cost, if penalty is levied, making it desirable to improve the Power Factor beyond the specified level.

### **3.3 Benefits of Power Factor Improvement**

It is obvious that the improvement in Power Factor results in significant benefits to consumer both in terms of system efficiency as well as cost savings.

The benefits of Power Factor improvement are summarized as follows:-

1. Reduction in Current Drawn.
2. Reduction in Cable Losses.
3. Reduction in Transformer Losses.
4. Improvement in Voltage Regulation.
5. Saving in KVA Demand charges.
6. Saving in Penalty.
7. Enhancement in the life of switch gear/cable etc.

# **CHAPTER 4**

## **HARMONICS AND ITS EFFECT**

### **4.1 Variable Frequency Drive and Harmonics Distortion**

After discussing the advantages of Variable Frequency Drives there oftentimes give rise to a question about the term of Harmonics. As the Variable Frequency Drive (VFD) changes the speed of standard AC induction motors by changing the voltage and frequency of the electricity supplied to the motor. The conversion of AC to DC and again vice versa tends and then electronically re-creating a waveform with a necessary voltage and frequency.

Through their internal own internal circuitry, namely the recreation of a sine wave through the high speed switching, Variable Frequency Drives (VFDs) are the source of harmonics. Some simple harmonics filters upstream and downstream of the drive will provide suitable protection.

### **4.2 Harmonic Definition**

Harmonics may be introduced into the electrical system due to the nonlinear characteristics of some power loads and there operation. Harmonics components of current and voltage are multiples of normal 60 Hz AC sine wave. These harmonics can cause motor, transformer and conductor overheating, capacitor failure, malfunctioning of relays and control and reduce system efficiencies.

### **4.3 Are Harmonics Harmful?**

Harmonic currents may cause the overheating of the conductors and insulating materials due to phenomenon known as skin effect. At lower frequency sinusoidal current will flow through the

entire cross section of a conductor. This provides the lowest conductor resistance and loss. At frequency increases, current tends to flow more toward conductor's surface and away from its cross section. The conductor resistance and loss can increase substantially. In the case of phase to neutral nonlinear loading and resultant third harmonic content, the 180 Hz current on neutral conductor will exhibit this property.

## **4.4 Introduction to Harmonic Terms**

### **4.4.1 Distortion**

Dynamic range of op amp may define in several ways. One of the most common way to specify harmonic distortion, total harmonics distortion (THD) or Total Harmonic plus noise (THD+N). Other related specifications include Inter Modulation Distortion (IMD), Intercept Points (IP), etc.

#### **4.4.1.1 Total Harmonic Distortion - THD**

THD is the ratio of harmonically related (2 $\times$ ,3 $\times$ ,4 $\times$ , and so on the fundamental frequency) signal components caused by amplifier nonlinearity. Only the harmonically related signals are included in the measurements. The distortion components which make up THD are usually calculated by taking the square root of the sum of squares of the five or six harmonics of fundamental. In many practical situations, however there is negligible error if only the second and third harmonics are included since the higher order terms most often are greatly reduced in amplitude.

##### **4.4.1.1.1 Total Harmonic Voltage Distortion - THD (V)**

At the time of harmonics when the current flows through the resistance or reactance, a voltage drop is developed and a voltage distortion of fundamental voltage waveform is caused by these harmonics voltage. Thus the total magnitude of voltage distortion is called Total Harmonic Voltage Distortion or THD (V).

The Total Harmonic Voltage Distortion THD (V)% =  $100 \times \sqrt{(V_3)^2 + (V_5)^2 + (V_7)^2 + (V_n)^2} / V_1$

#### 4.4.1.1.2 Total Harmonic Current Distortion – THD (I)

The THD (I) is basically the ratio between the current harmonics and the fundamental current which are calculate for that point of instant.. It is a harmonic current distortion waveform taken from the specific movement at the time determining the values is calculated.

$$\text{Thus the THD (I)\%} = 100 \times \sqrt{(I_3)^2 + (I_5)^2 + (I_7)^2 + (I_n)^2} / I_1$$

#### 4.4.1.2 Total Harmonic Distortion plus Noise

THD + N is the residual signal with only fundamental removed. It is important to note that the THD measurement does not include the noise terms, while THD + N does. The noise in the THD + N measurement must be integrated over the measurement bandwidth. In the narrow band applications, the level of noise may reduced by filtering, in turn lowering the THD + N which increasing the signal to noise ratio (SNR). Most times when a THD specification is quoted, it is really THD +N specification. Thus THD +N given as:-

$$\text{THD + N voltage} = \sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2 + V_{\text{noise}}^2} / V_s$$

#### 4.4.1.3 Total Demand Distortion (TDD)

The Total Demand Distortion (TDD) is defined as the harmonics current distortion in percentage of maximum demand load current. The maximum demand load current interval could be either 15 min or a 30 min interval.

$$\text{Total Demand Distortion (TDD)} = \sqrt{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2} / I_{\text{LOAD}}$$

Where  $I_2, I_3, I_4, \dots, I_n$  are the individual harmonic current components and  $I_{\text{LOAD}}$  is the maximum load current at the point of common coupling.

## **4.5 Harmonics Mitigating Techniques**

Various techniques improving the input current waveform are discussed below. The intent of all techniques is to make the input current more continuous so as reduce the overall current harmonics distortion. The different techniques can be classified into following techniques

1. Passive Techniques
2. Active Techniques
3. Hybrid Technique – combination of passive and active Technique

### **4.5.1. Passive Technique**

The passive techniques includes capacitor based harmonics filter, Multi pulse Technique and additional of inductive impedance – line reactor or dc link chokes.

#### **4.5.1.1. Line Reactors**

A line reactor makes the current waveform less discontinuous resulting in lower current harmonics. Since the reactor impedance increases with frequency, it offers larger impedance to the flow of higher order harmonic current.

On knowing the input reactance value, the expected current harmonic distortion can be estimated. Input reactance is determined by series combination of impedance of AC reactor, input transformer and power cable.

#### **4.5.1.2 Capacitor – Based Passive Filters**

Passive filter consists of passive components like inductors, capacitors and resistors arranged in predetermined fashion either to attenuate the flow of harmonic components through them or to shunt the harmonic component into them. Passive filters can be many types. Some popular ones are series passive filters, shunt passive filters and low pass broadband passive filters. Series and shunt passive filters are effective only in narrow proximity of the frequency at which they are

tuned. Low – pass broadband passive filters have a broader bandwidth and attenuate a larger range of harmonics above their cut off frequency.

### **4.5.2 Active Technique**

The rectification technique which is basically developed by motor – drive manufacturers, do not generate low order harmonics. These drives use active front ends. Instead of using diode as rectifiers, the active front end ASDs makes use of active switch like IGBTs along with anti parallel diode. In such active front – end rectifiers, power flow becomes bidirectional. The input current can be wave shaped and made sinusoidal to have low value of low order harmonics. Apart from active front end there also exists shunt active filter used for actively introducing a current waveform into the ac network which when combined with harmonic current, results in an almost perfect sinusoidal waveform.

### **4.5.3 Hybrid Technique**

This technique is basically the combination of passive and active technique. In this type of technique the hybrid filters have large bandwidth and good dynamic response. Control is accomplished using Digital Signal Processing (DSP) chips. The hybrid structure also need current and voltage sensors and corresponding analog to digital (A/D) converters.

## **4.6 Power line harmonics**

Harmonics in the square wave inverter have two sources. At the input, the controlled rectifier generates harmonics that produce electrical noise in the power system. These can be filtered, but these reduce efficiency and the power factor, which is already low in controlled rectifier.

The output waveform also produces serious harmonics. The stair-step output waveform have only odd harmonics. The third and ninth harmonics cause no problem, since they are in phase and cancel at the input to the star connected motor. The rest of harmonics mainly the fifth and

seventh cause current that increase losses in the motor and produces no torque. These harmonics are filtered some by inductance of the motor. The combinations of these problems have resulted in the use of Pulse Width Modulation (PWM) system. These systems use a more complicated switching scheme.

## **4.7 Multi-Pulse VFDs**

With harmonic distortion concerns with VFD on every engineers mind, future drive packages will have to address these concerns. As more and more drives are added to facility's power grid, along with other non linear loads (computers, switching power supplies, etc), the distortion level increases. The variable frequency drives can come equipped with input filters or reactors to help reduce their contribution, but the twelve, eighteen and twenty – four pulse drive systems can do away a great deal of distortion. The twelve pulse system requires a special dual secondary transformer which feeds two six pulse diode converter bridges in the VFD. A phase shift of 90 electric degrees provides a cancellation of distortion caused by diode rectification. An eighteen pulse system requires utilizes triple secondary on the input transformer and the eighteen diodes and the twenty – four – pulse system follows the same pattern. With diode cost coming down this approach is being employed more often.

Harmonics concerns and high speed communication platforms between drives and other controllers will continue to be driving forces of the technology. Local Area Networks (LAN) and the ability to synchronize VFDs to one another are demands that building automation system and factory automation systems are making. Variable Frequency Drives will continue to change in these areas.

### **4.7.1 Twelve pulse VFD Design**

The harmonics content in the output AC can be further reduced by pulsing the inverters 12 times instead of six times. Both the 6 pulse and 12 pulse converters (often incorrectly called 6 phase and 12 phase converters) use 3-phase power mains. The 12-pulse inverter uses a three winding transformer with one primary and two secondaries of equal ratings, one connected in star and

other in delta. The outputs of two secondaries are  $30^{\circ}$  out of phase, pulsing the inverter's one block six times and the other block also six times, with total pulse in the combined output 12 times.

The main advantages of the 12 pulse design is elimination of the  $5^{\text{th}}, 7^{\text{th}}, 17^{\text{th}}, 19^{\text{th}}, \dots$  harmonics, thus improving the quality of the output power. Among the inverters commonly used for high power applications, 12-pulse line commutated full wave topologies prevails.

For further harmonic reduction, 18-pulse converters can be designed using a four winding transformer – one primary and three secondaries – and 24 pulse converters can be designed using two sets of three winding transformers in parallel with  $15^{\circ}$  phase shift from each other on the primary side.

# **CHAPTER 5**

## **COMPARISON BETWEEN VFD AND OTHER TECHNOLOGIES**

### **5.1 General**

The Variable Frequency Drive which is a part of Variable Speed Drives basically used to change the line voltage to source voltage as a resultant the frequency and the voltage can be controlled accordantly. For maintaining possible speed and efficiency of the motor, the ratio of voltage and frequency of the system could be operating to equal the invariable torque/load curves. While controlling the speed of motor other technologies are also available. The sinusoidal motor controllers of variable load are also used in invariant application of speed. The Sinusoidal Motor Efficiency Controller (SinuMEC) basically power electronics device which is a pure Sinusoidal Voltage Controller. This chapter covers comparison between the operations of Variable Frequency Drive (VFD) and Sinusoidal Motor Efficiency Controller (SinuMEC).

### **5.2 The SinuMEC Advantages**

#### **5.2.1 Pure Sine VS. Harmonic**

As a pure sine wave is produced by the SinuMEC, which results no pollution of harmonics being introduced into the network. Moreover as the SinuMEC consists of transformers in series so therefore it can reduce the harmonics pollution where ever present in the network. A Variable Frequency Drive generates the current harmonics mainly by 30% or more than that of fundamental frequency. However when the harmonic filtering unit set up in the front side pollution remains same in between the drives and the motor.

### **5.2.2 Possible solutions**

It should be noted that the harmonic cannot be eliminated, it can only mitigated. So therefore the better right smart for separate out the harmonics is not to produce it. So far no such techniques are present which can separate out all harmonics in one turn. Therefore for the separation out of harmonics there are many kinds of other solutions are available such as passive filters (reactor/inductor in the circuit) and application of active filtering unit also the using of transformer such as zigzag transformer, the complete isolation of the source. It is generally considered that the cost of load that creates harmonics is lower than the cost of mitigating harmonics.

### **5.3 Internal Losses**

As each and every electrical device has its efficiency ( $\eta$ ), the losses in the VFD is about 4% to 8% which is comparatively higher than SinuMEC about 0.5%. It is noted about the modern Variable Frequency Drives with pulse width modulation have lower Total harmonic Distortion which is comparatively beneficial with earlier technology of Variable Frequency Drives. The Variable Frequency Drive saves 3.5% to 7.5% of potential savings at same output voltage with compared to SinuMEC.

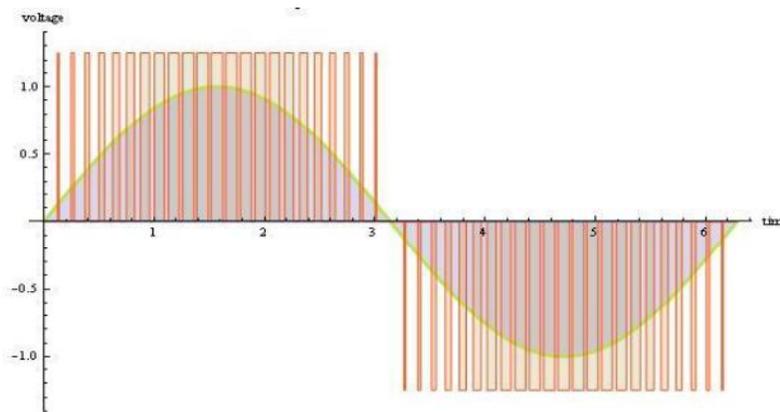
### **5.4 Motor Life Expectancy**

Basically there are 3 categories of parameter for anticipation of life of motors:-

1. Voltage Stress
2. Operating Temperature
3. Mechanical Stress

The controllers of motor affect the operating temperature and voltage stress but do not affect the mechanical stress. The life span of the motor increases as there is reduction in the voltage stress and also the level of the voltage. More ever using Variable Frequency Drive reduces the RMS voltage as they are using Pulse Width Modulation which is given in Fig 5.1.

Zero stress appears on the pure sine wave which is overcome by approach the zero cross section area also the reduction in RMS voltage. The reduction in voltage the Variable Frequency Drive increases the stress of the voltage while the SinuMEC reduces it. However the generation of non linear by using Variable Frequency Drive that makes extra accent as a consequence of corona power, reflective waves and Partial Discharge (PD).



**Figure no. 5.1 Pulse Width Modulation of VFD [21]**

The temperature inside the motor rises up to  $8^{\circ}\text{C}$  to  $10^{\circ}\text{C}$  if the generation of harmonics occurred in the Variable Frequency Drive. From the law of Arrhenius, the increasing of every  $10^{\circ}\text{C}$  decreases the effectiveness of insulation by 50%.. It means that existing installation of VFD, it reduces the motor efficiency for lifetime. From the above statement it means that by using SinuMEC it increases the life span of motor while the VFD decreases it.

## **5.5 Price**

The cost stand only with SinuMEC is comparatively less than the Variable Frequency Drive. The Variable Frequency Drive basically requires additional filters for mitigating the harmonic pollution, this leads in encourage gaining the difference of cost in prefer of SinuMEC. There are many other types of solutions for filtrations are available which are responsible for providing different levels of filtration. Thus it leads to increase the price difference between the SinuMEC and VFD.

## **5.6 Advantages of VFD over SinuMEC**

The Variable Frequency Drive provide a very accurate voltage level as it provide step – less operation as compared to SinuMEC. Since the above savings are significantly that the efficiency calculated is very less that it is not much beneficial to establish change in voltage of the motor.

Since more accurate voltage provide by VFD, the efficiency of the motor increases to 1.5%. But as considering the internal losses the between the Variable Frequency Drive and the SinuMEC is changed as reorder. It is noted that apart of wastage the energy engaged from the variable Frequency Drive it is not in terms of fundamental harmonics. In case it basically important to use current transformer and power meter that can be measures with a minimum 25 harmonics that clears the bandwidth of CT highlighted that the rating of transformer should be a minimum of 3 KHz.

## **5.7 With so many disadvantages, why there are VFDS?**

Basically the Variable Frequency Drive is designed to control the speed of the motor not up to the level of voltage. To consider the speed of Variable Frequency Drive application along the induction motor, there is fixed solution so whatever the disadvantage were Discussed along with Harmonics related problems, life span of motor and losses all are taken to be consider.

Thus for fixed application usage SinuMEC are the best solutions available for pure sine wave with the voltage control.

## 5.8 Difference between SinuMEC and VFD

	<b>SinuMEC</b>	<b>VFD</b>
<b>Harmonics</b>	Operation of pure sine wave and filter some harmonics in network delivers to the motor.	Responsible for generation of harmonics in the motor and other networks.
<b>Power factor</b>	Improves Displacement Power Factor and True Power Factor	Improves Displacement Power Factor but may worsen True Power Factor
<b>Internal losses</b>	Internal losses are around 0.5%.	Internal losses are around 4% - 8%.
<b>Current Transformation</b>	Basically the line current is less than motor current.	Both the motor and line current are same.
<b>Motor Life Expectancy</b>	increases motor life expectancy	Decreases motor life expectancy.
<b>Operation</b>	It is stepped operation.	It is step less operation.
<b>Price</b>	40% is less than VFD only (without optional filter)	Basically it requires optional filter which may increases the price.

## **5.9 Why VFD why not Cycloconverter?**

The cycloconverter is direct ac – ac frequency converter and is mainly used with the synchronous motor, having a greater air gap as opposed to the induction motor. The cycloconverter typically uses many power electronics devices, making it more expensive and less efficient. Also it add lag in the motor current due to phase control modulation. It's typical power factor is around 0.75, which is at the low end of the 0.7 – 0.9 range that many industry standard allow. The cycloconverter is old converter technology, whose time had passed for a while but is now getting new attention for certain benefits. It works well in icebreakers and dynamic positioning ships requiring very high torque at low speed. However, its use is limited for output frequency up to 30% - 40% of the supply frequency.

## **5.10 Advantage and Disadvantage of VFD**

### **5.10.1 Advantages of VFD:-**

1. Large energy savings at lower speed.
2. Increased life of rotating components due to lower operating speed.
3. Reduced noise and vibration level.
4. Reduction of Thermal and mechanical stresses.
5. Lower KVA
6. High power factor

### **5.10.2 Disadvantage of VFD:-**

1. Reliability problem which depends on the type of drive selected.
2. Electronic variable speed devices generated system harmonics which can be mitigated by installation of harmonics filters.

# CHAPTER 6

## SIMULATION

### 6.1 Aim

Simulate Variable Speed Motor Control.

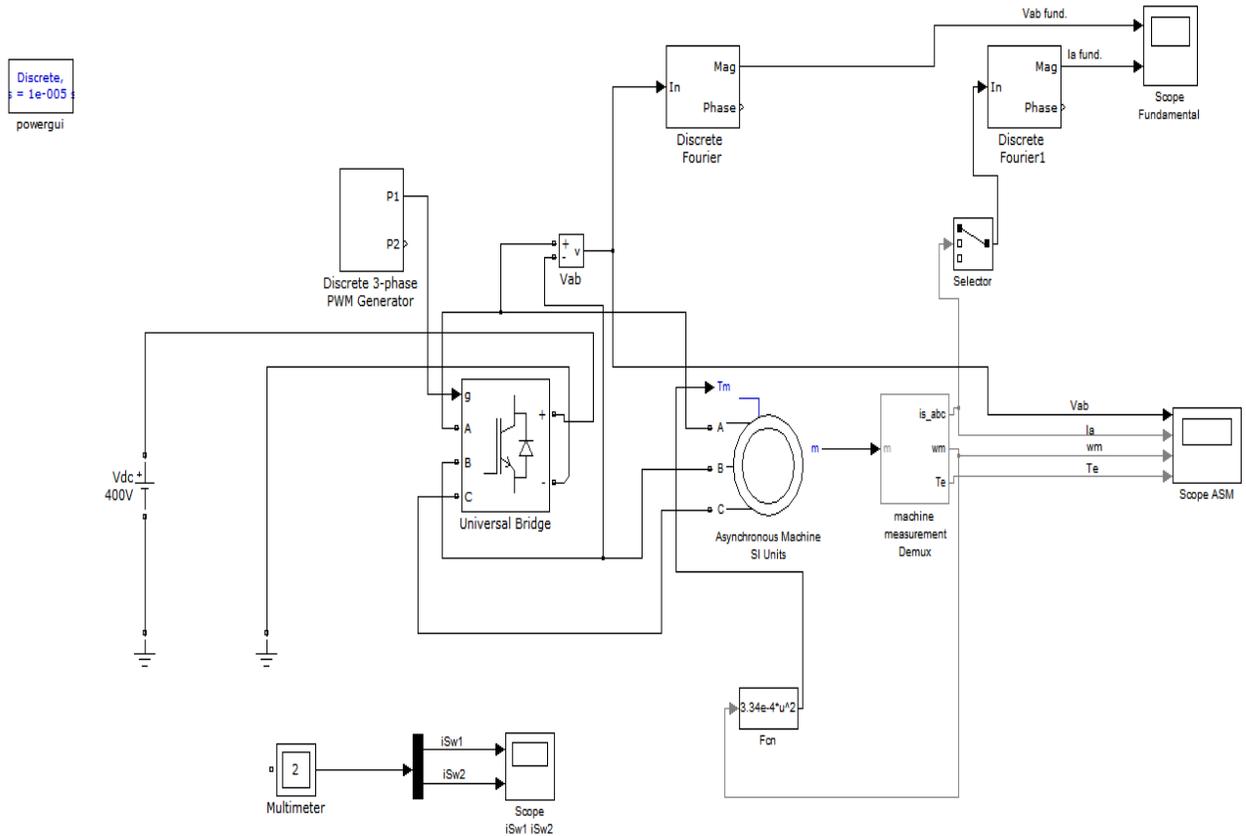
### 6.2 Theory

For variable speed control of AC electrical machines several power electronics switches such as IGBTs, MOSFETs and GTO use as forced – commutation method. Earlier techniques such as the DC motor and Thyristor Bridge which are replaced with new techniques such as Voltage Sourced Converters (VSC) are fed by Pulse Width Modulation (PWM) to the asynchronous machine. Since there is flexible control of torque and speed in DC machines, the same can be obtained by the combination of pulse width modulation technique with new control techniques for example- Field Orientation and Direct Torque Control methods. In this section a simulation of AC drive controlling an asynchronous machine is been described.

The machine library of simulation consists of four most common three phase machine asynchronous machine, permanent magnet synchronous machine, simplified and complete synchronous machine. The following machine can be used either used as generating mode or motoring mode. With the combination of elements such as linear and nonlinear for e.g.- breakers, load line transformer, etc, these machines simulates the transient of electromechanical in the electrical network itself for simulation of drives they are combined with power electronics devices. The power electronics library of simulation contains diodes, thyristors, GTO, MOSFET and IGBT. These several blocks interconnected with each other to form Three Phase Bridges.

## 6.3 Building and Simulation of the PWM Motor drive

The following step should be followed to build PWM – Controlled Motor.



**Figure no. 6.1 Simulation circuit of Variable Speed Motor Control**

### 6.3.1 Assembling and Configuring the Motor Blocks

1. A new window of simulation is opened and saved it as PWM motor control.
2. The library of power electronics is opened and the block of Universal Bridge is copied into the PWM motor control model.
3. The universal Bridge dialog is opened and its parameters are set as :-

**Table no. 6.1 Parameters of Universal Bridge**

<b>Power electronics device</b>		IGBT/Diode
<b>Snubber</b>		
	<b>Rs</b>	1e5Ω
	<b>Cs</b>	Inf
	<b>Ron</b>	1e-3Ω
<b>Forward Voltages</b>		
	<b>Vf</b>	0V
	<b>Vfd</b>	0V
<b>Tail</b>		
	<b>Tf</b>	1e-6 s
	<b>Tt</b>	1e-6 s

It is to be noted that the dialog box of Universal Bridge is integral by the circuit called snubber. Since the value of capacitor (Cs) is set as Infinite i.e. (short – circuit) of the snubber circuit, therefore resistive elements are to be use in the snubber circuit. As in case of Power System library present in Simulation software, the non linear element is re-create as source of current therefore Insulated Bipolar Transistor (IGBT) generally do not use snubber circuit as to allow, connection to an inductive circuit we have to provide a parallel path across each IGBT. The high resistance value of snubber circuit does not affect its performance.

4. Opened the library of machines and copied the asynchronous machine SI unit block and Machine Measurement Demux block into the PWM motor control model.
5. The dialog box of Asynchronous is opened and its parameters are set as:-

**Table no. 6.2 Parameters of Asynchronous Machine**

<b>Nominal power, voltage (line-line) and frequency</b>	[3×746, 220, 60]
<b>Stator resistance and Inductance</b>	[1.115 0.005974]
<b>Rotor resistance and Inductance</b>	[1.083 0.005974]
<b>Mutual inductance</b>	0.2037
<b>Inertia constant, friction factor and pole pairs</b>	[0.02, 0.005752, 2]

The above parameter is about asynchronous machine of 3 HP of two pole pair with the supply frequency of 60 Hz also nominal power of 3×746 VA with line to line nominal voltage is 220Vrms. From the above data we can calculate the synchronous speed i.e. 1800 rpm which is slightly greater than nominal speed.

6. The parameter of asynchronous machine is basically set as squirrel cage of rotor type. As during the normal condition of operation there would be a case of short circuited in terminals therefore the terminals a, b and c are not accessible.
7. The block of Machine Measurement Demux is opened. As it allows to access specific interval signal of machine so this block is connected as output of the machine measurement. First of all machine type of asynchronous is selected and rest all the signals are deselected:- is\_abc (three stator current), Te (electromagnetic torque) and  $w_m$  (rotor speed).

### **6.3.2 Loading and Driving the motors**

We have implemented the characteristics of torque speed of motor load. Let the torque speed characteristics be quadratic, for example – fan or pump type load.

As we know that :-

$$T = k \times \omega^2$$

Where the torque is represents by (T) and speed is represent by ( $\omega$ ).

Also the torque is proportional to the square of speed.

Since we have nominal power =  $3 \times 746$

Synchronous speed = 188.5

$$= 3 \times 746 / 188.5$$

$$= 11.87 \text{ Nm}$$

Or constant k from above equation

$$K = T / \omega^2$$

$$= 11.87 / 188.5$$

$$= 3.34 \times 10^{-4}$$

1. The library of user defined function of simulinks is opened and the block Fcn is copied into the PWM motor control model. The block menu opened and expression of torque and entered the function of speed  $3.34e - 4 * \omega^2$ .
2. The input of the Fcn block must be connected to the speed output of Machine Measurement Demux block which labeled  $\omega_m$  and its output of the torque input of the motor which labeled  $T_m$ .
3. The Electrical source library opened and DC Voltage source must be copied into their model PWM Motor Control. The block menu is opened and voltage is set to 400 V.
4. The measurement library is opened and Voltage Measurement Block copied into PWM Motor Control model
5. From the element library of simulinks, the ground blocks are copied and completed the requirement for power elements and the interconnection of Voltage Sensor.

### 6.3.3 With Pulse Generator Controlling of Inverter Bridge

A pulse generator is required for controlling bridge inverter and such elements are available extra library of power library.

1. The block of Discrete/Extra is opened and three-phase discrete pulse width modulation Generator is copied in PWM motor control model. The pulses are generated for two level or three phase bridge by this block. Two level of single bridge pulse width modulation generator used by generated two set of pulse by this block. Internally three pulse width modulating signals are generated as the converter operates in an open loop. The output pulse  $P_1$  is connected to the input block of the universal bridge.
2. The block of discrete 3-phase pulse width modulation generator is opened and its parameter are as :-

**Table no. 6.3 Parameters of Discrete Three Phase PWM Generator**

<b>Type</b>	2 level
<b>Mode of Operation</b>	Un – synchronized
<b>Carrier Frequency</b>	18×60 Hz (1080 Hz)
<b>Internal generation of modulating signals</b>	Selected
<b>Modulation index m</b>	0.9
<b>Output voltage frequency</b>	60 Hz
<b>Output voltage phase</b>	0 degrees
<b>Sample time</b>	10e – 6 s

1. To see how the PWM implemented, the further steps are as follows:-  
Diagram>Mask>Look under Mask menu item. The entire simulink blocks are used to

made the control system. The block has been discretized so that the pulses changes to multi pulse of the specific time step. Step time of  $10\mu\text{S}$  of the switching period of 1080Hz corresponding to +/- 0.54 %.

With comparison between switching frequency of triangular wave i.e. (1080Hz) and synthesizing of output voltage i.e. (60Hz) there is only one method for the generation of Pulse Width Modulation. The block of discrete three Phase Pulse Width Modulation Generator utilize by this method. It is clear from the under mentioned equation that the line to line output RMS voltage is directly proportional to the modulating index (m) and the input DC Voltage ( $V_{dc}$ ) .

$$V_{LLrms} = \frac{m}{2} \times \frac{\sqrt{3}}{\sqrt{2}} V_{dc}$$

$$= m \times 0.612 V_{dc}$$

### 6.3.4 Signal and Measuring the fundamental voltage and current

1. For measuring the component of fundamental frequency i.e. (60Hz) which is implant in phase current and voltage  $V_{ab}$ . Library of Discrete Measurement is opened and block of Discrete Fourier is copied into the PWM motor control model.

The parameters of Discrete Fourier Block are as:-

**Table no. 6.4 Parameter of Discrete Fourier Block**

<b>Fundamental Frequency</b>	60Hz
<b>Harmonics Number</b>	1
<b>Initial Input</b>	[0 0]
<b>Sample time</b>	$10e - 6$ s

The output of  $V_{ab}$  Voltage sensor is connected to this block.

2. The Discrete Fourier block is duplicated. For measuring the phase A current, we have selected the first element is\_abc output of ASM Measurement Demux block.

From the simulink Signal Routing library a selector block is being copied. Its menu is opened and set Index vector (dialog). The output of selector is connected to second Fourier Discrete block and its input to the is\_abc output of the Machine Measurement Demux block.

3. At last scope is being added to the model. One scope is being duplicated into the model circuit. All four parameters i.e. motor current, voltage, speed and electromagnetic torque is basically exhibit by using scope.

Parameters of Scope are as:-

**Table no. 6.5 Parameters of Scope Block**

<b>Number of axes</b>	4
<b>Time range</b>	0.05 s
<b>Tick labels</b>	Bottom axis only

As from the result of TCR simulation the above inputs (4 inputs) are being joined and marked.

At the time of simulation these marked are highlighted on the top of each graph.

The parameters of scope present in Scope Properties >Data History is set as:

**Table no. 6.6 Parameters of Data History in Scope Properties**

<b>Limit data point to last</b>	Deselected
<b>Save data to workshop</b>	Selected
<b>Variable name</b>	ASM
<b>Format</b>	Structure with time

After the simulation, the above 4 signals are exhibits in a structural type array called ASM.

4. From the four input scope it is being replicated into two input scope. The fundamental components of Vab voltage and Ia current is being displayed by this scope. The input of scope is being connected to output of Fourier blocks. As shown in the result of TCR it is being described that the two connections is being marked.

And the simulation of the starting motor is ready.

### **6.3.5 Simulation With continuous integration algorithm of PWM Motor Drive**

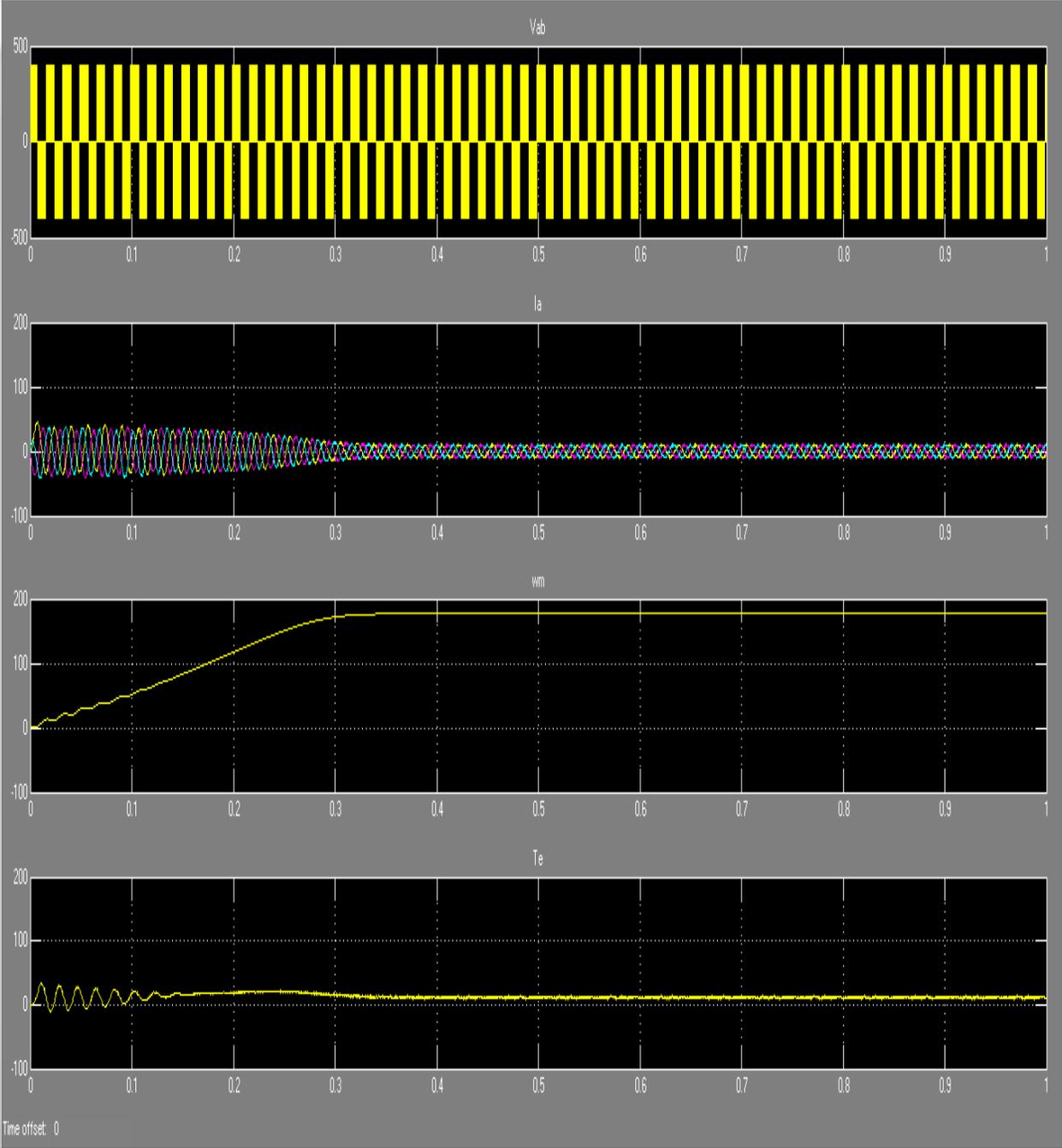
The dialog box of Simulation>Configuration parameter is opened. In this following steps ode 23tb integration algorithm is selected. The relative tolerance is set as  $1e - 4$ , the Max step size and the absolute tolerance is set to auto and the stop time to set as 1 s. After that the simulation is started.

A speed of steady state is 181rad/s i.e.1728rpm is gained by the motor after 0.5s is being started. Normally the magnitude of 60Hz and current to 90A where as at the time of starting the steady state value is 10.5A. As it is noticed that the magnitudes of fundamental frequency of 60 Hz hold in the by parts wave which given as:-

$$220 \times \sqrt{2} = 311V$$

Likewise at the starting time, it is expected to have strong oscillation of electromagnetic torque. If we zoomed on the torque in the steady state, we would observe a noisy signal with a mean value of 11.9 Nm which corresponding to the load torque. Since the component of fundamental frequency of 60Hz is superior, in case of motor current we could see all harmonics are filter out from inductance of stator.

### 6.3.6 At full voltage the result of simulation by PWM Motor Drive



**Figure no. 6.2 Simulation Graph of Voltage, Current, Speed and Torque of the Asynchronous Motor**

### 6.3.7 Using the Multimeter Block

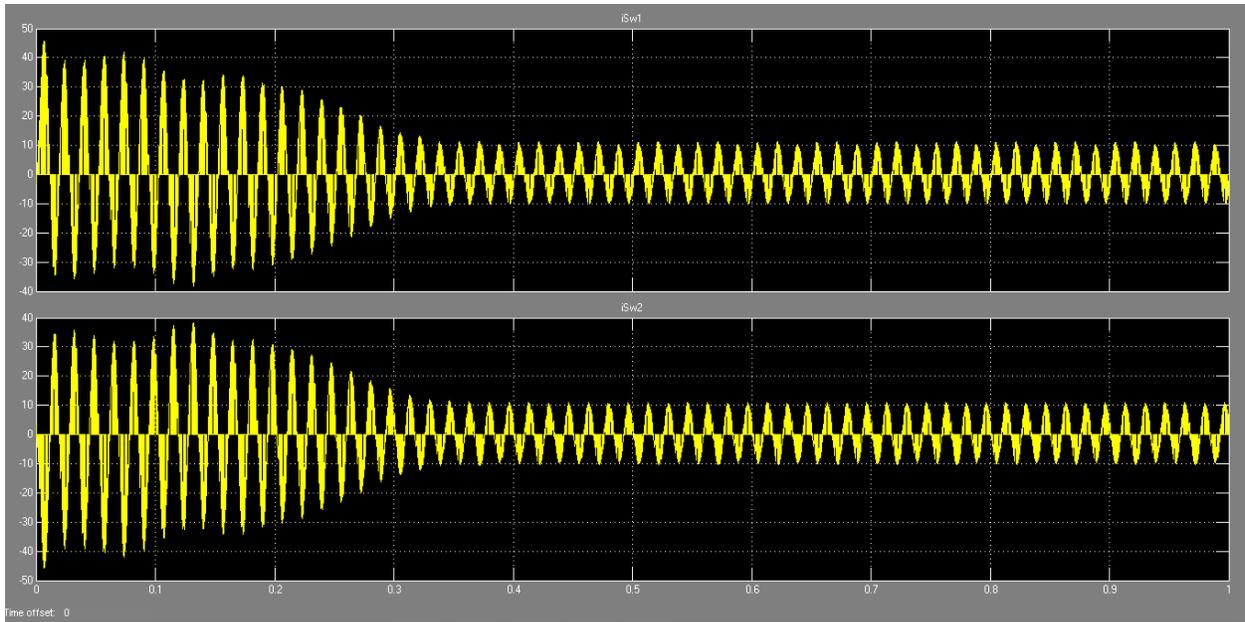
With the presence of all six the individual switches are accessible the Universal Bridge basically not a customary type of subsystem. A multimeter block is used to measure switching current and voltage as it also provide gain for the internal signals of bridge.

1. The dialog box of universal bridge is opened and device current set as measurement parameter.
2. A block of multimeter is copied from the measurement library into the PWM motor model. By double click on the multimeter block, a new window is opened which tends to show six switch currents.
3. Two currents are selected of the bridge arm connected to phase A. They are identified as:-

**Table no. 6.7 Switch Currents of multimeter**

iSw1	Universal Bridge
iSw2	Universal Bridge

4. Clicked on closed option of the no. of signal two in the icon of multimeter is being displayed.
5. By using a Demux Block the two output signals of multimeter is inputted into the scope.
6. The simulation is restarted. For first 20 ms the waveform obtained are shown in this plot.



**Figure no. 6.3 Simulation Graph of multimeter switches**

As noticed from switches 1 and 2 the switching current is antonymous to each other. The current flowing through IGBT points the positive current, whereas current through anti parallel diode points the negative current.

It is noted that the use of multi meter is not restrict to the block called universal bridge. The presence of numerous blocks in the libraries of Electrical Source and Measurement has parameter for measurement where we can select voltages, currents or saturable transformer fluxes. The use of multimeter block is also used to reduce current and voltage sensor into the model which makes it easier to follow.

### **6.3.8 Discretize Pulse Width Modulation of Motor Drive**

It is noted that in the simulation it is comparatively long in the use of algorithm of variable step integration one. For simulating 1 sec it may take 10 sec. Thus simulation can be done at fixed step of time to less the time period of simulation.

Powergui is opened then clicked on the configure parameter of powergui block is set as discrete. Sampling time is set as  $(10e - 6 \text{ s})$ . A sampling time of  $10\mu\text{s}$  is discretizing by the asynchronous machine at the time of simulation is started.

We need not require any other method like integration of variable step method as there are not many continuous state presents. The fixed step and the discrete options are selected from the dialog box of solver which is a part of configure parameters present in the simulation button.

Thus after starting the simulation it is being observed of three times faster than with continuous system.

### 6.3.9 Performing Harmonics analysis using the FFT Tool

At the time of simulation is running the fundamental component of voltage and current are allowed by two Discrete Fourier Blocks. Thus for observing harmonics component we would require Discrete Fourier Block for each harmonic. This approach is not convenient.

For displaying the frequency spectrum of current and voltage waveform we require FFT tool of Powergui. With time variable generated by the scope block, the signals get stored in ASM structure and signals are saved into the ASM structure is sampled at fixed step which satisfy the demand of FFT tool.

Thus clicked on the Powergui icon where FFT analysis is further clicked and a new window is opened. Signal is analyze and time window and the frequency range is parameters are set as follows:-

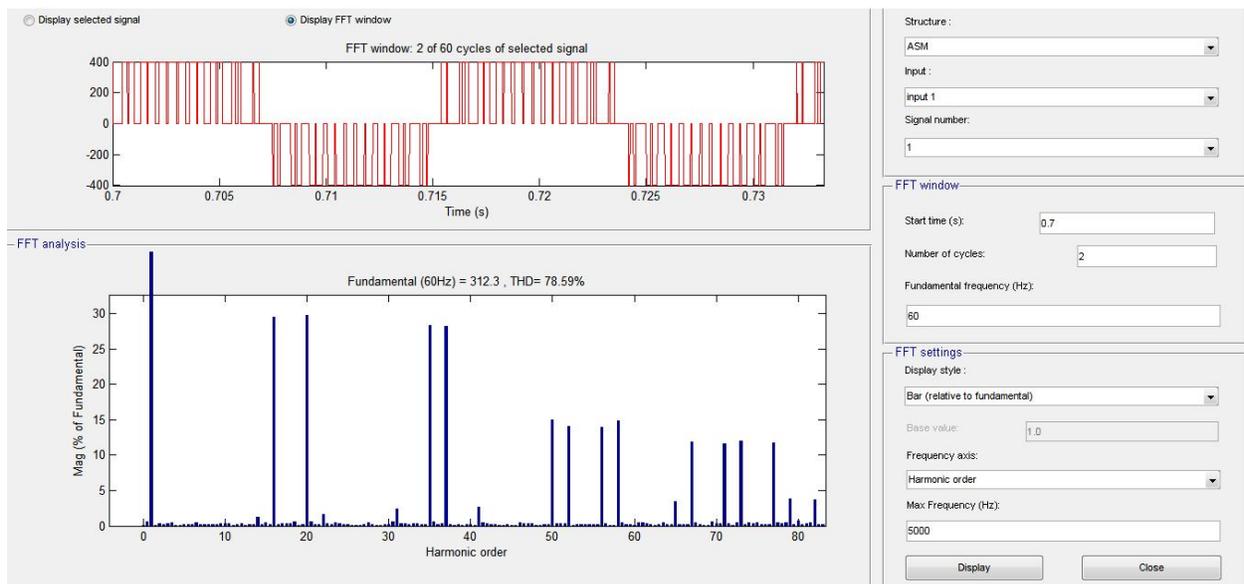
**Table no. 6.8 Parameters of FFT present in powergui block**

<b>Structure</b>	ASM
<b>Input</b>	Vab
<b>Signal number</b>	1
<b>Start time</b>	0.7 s
<b>Number of cycles</b>	2
<b>Fundamental frequency</b>	60 Hz

<b>Max frequency</b>	5000Hz
<b>Frequency axis</b>	Harmonic order
<b>Display style</b>	Bar (relative to Fund or DC)

As Display option clicked the analysis of the signal is shown and spectrum of frequency is being shown at the bottom of this window.

### 6.3.10 Analysis of Line to Line Voltage of Motor by Fast Fourier Transformation



**Figure no. 6.4 FFT analysis of the Asynchronous motor**

As the fundamental component and the Total Harmonics Distortion of  $V_{ab}$  is shown in the new window and the value of fundamental of inverter voltage is (312V) which comparatively more than the predefined value i.e. (311V for  $m=0.4$ ).

As given from the multiple carrier frequency which is given as in general formula  $(n \times 18 + k)$  the harmonics are shown in the percentage value of the fundamental component.

For new spectrum of current is being displayed, change the inputted selected from  $V_{ab}$  to  $I_a$ .

## 6.4 Results

The simulation result of fundamental speed is being calculated from a 4 pole Asynchronous motor of 3 HP and also the analysis of harmonics being calculated by using FFT tool of simulation of maximum frequency 5000 Hz.

**Table no. 6.9 Data analysis of Frequency**

Frequency (f)	RPM ( $N_s$ )	THD of Voltage	THD of Current
80	2400	106.25%	30.49%
75	2250	81.86%	19.65%
70	2100	67.89%	14.91%
65	1950	55.46%	12.20%
60	1800	78.59%	11.46%
55	1650	55.85%	18.72%
50	1500	76.85%	32.86%
45	1350	126.29%	37.35%

Thus from the analysis of table no.10 it is clear that the frequency variation leads to the harmonics change in the machine also as the speed decreases or increases beyond the nominal point of range in frequencies, the Total Harmonics Distortion in voltage as well as in current increases also the THD in voltage is higher than THD in current. It is also to be noted that too much variation in frequency also leads to increase in the THD voltage as well as THD current levels. Thus the THD (V) level increases with as the value of fundamental frequency increases from 70Hz and also the fundamental frequency decreases 45 Hz or below. Therefore the range of variations of fundamental frequency should be kept in between 70 to 45 Hz. It is also to be noticed that the values of THD (V) in case of 70Hz, 60Hz and 45Hz is quit high as compared to

other frequency presents in between them, this is because of presence of ODD Harmonics in these frequencies, as we know that the ODD harmonics are more harmful for the promotion of Distortion in the circuit than the EVEN Harmonics. Since the maximum frequency is set as 5000Hz therefore it can be easily calculated the order of Harmonics. The calculation of ODD Harmonics and EVEN Harmonics is given in table no.11

**Table No. 6.10 Calculation of order of Harmonics**

Fundamental Frequency	Speed (RPM)	Order of Harmonics	THD of Voltage	THD of Current
80	2400	62.5(even)	106.25%	30.49%
75	2250	66.66(even)	81.86%	19.65%
<b>70</b>	<b>2100</b>	<b>71.42(odd)</b>	<b>67.89%</b>	<b>14.91%</b>
65	1950	76.92(even)	55.46%	12.20%
<b>60</b>	<b>1800</b>	<b>83.33(odd)</b>	<b>78.59%</b>	<b>11.46%</b>
55	1650	90.90(even)	55.85%	18.72%
50	1500	100(even)	76.85%	32.86%
<b>45</b>	<b>1350</b>	<b>111.11(odd)</b>	<b>126.29%</b>	<b>37.35%</b>

Thus the variation of THD in between the fundamental frequencies is keep changing therefore there are variation for distortion which leads to the calculation of energy savings is quite possible as well as speed control of the motor.

These harmonics can be further reduced by the applications of filters in the circuit. As earlier discussed in section 4.8 i.e. the Harmonics Mitigation Techniques where various types of techniques are explained which help in filtering the harmonics. It could be act as a future reference of this dissertation report.

## **CHAPTER 7**

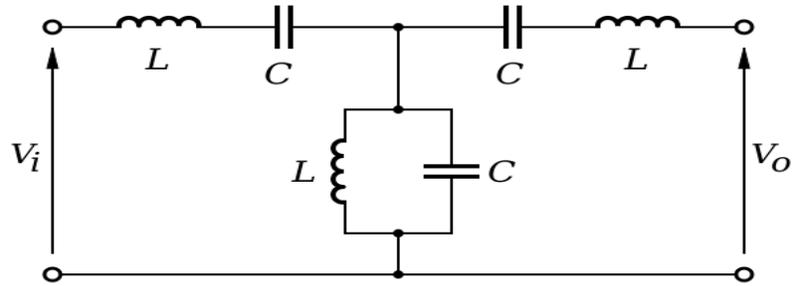
### **CONCLUSION AND FUTURE WORK**

After the detailed study of Variable Frequency Drive, it becomes possible to control the speed of electric motor as well as to conserve the electrical energy, as we know that the energy conservation has become an important subject to all over the world. Increase in efficient energy use, decrease in energy consumption and/or consumption from conventional energy sources is reduced that leads to the conservation of energy.

For high performance providing by the Variable Frequency Drive for maximum process productivity always required a complex engineering consideration. However rapid improvements in AC control technology combined with ready availability of standard fixed frequency of AC motor have increased the number of possible solution. With the process of pulse width modulation, the frequency given to the induction motor can be set in order to control the speed of the induction motor. Thus the consumption of electrical energy is depends on the load requirement. However the variation of frequency leads to the harmonics distortion which can be mitigate by several techniques of harmonics mitigation.

The elimination techniques of harmonics are generally applied to lowest harmonic because as the filtering is more practical at higher harmonics, the filtering component can be smaller and less expensive. Also application of several multilevel inverters provides another approach to harmonics cancellation. For the mitigation of harmonics from the circuit of the inverter application of active filters are required into the circuit such as Band Pass Active Filter.

Basically Band Pass Filter can be applied in this circuit as a future reference of this dissertation. A Band Pass Filter is a electronic device or circuit that allow to pass signals between two specific frequencies but discriminates against the signal at other frequencies.



**Figure No. 7.1 Circuit diagram of Band Pass Filter**

At last the conservation of energy may result in increase in financial, capital, environment quality, national security, personal security and human comfort. The individual and commercial user can increase energy use efficiency to maximum profit which leads to help for the individual and organization that are direct consumer of energy security.

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