CHAPTER ONE

INTRODUCTION

1.1 Historical Back Ground

Variable frequency drive is typically a tool of power electronics without having a great understanding of power electronics we can never get the depth of variable frequency drive.

The history of power electronics tells us that its evolution started in the very beginning of 20th century. And the first invention that was brought before the world by Peter Cooper was mercury-arc rectifier.[1] Then with the passage of time power electronics had under gone many changes and in the 3rd and 4th decade of 20th century it was evolved to gas tube electronics [1],[2] and saturated core

magnetic amplifiers.in the mid of 20th century many advancement were seen in field of power electronics and the work which came forward was silicon controlled rectifier (SCR) and thyristor.[1] After that power electronics has shown countless advancement in research and development field till today. The history of variable frequency drive is not much older as that of power electronics. Rather its evolution was very rapid and, in a very short period of time it has gain a very important place in industry. The first variable frequency drive was based on mechanical principals because power electronics had not made great advancements till that day. It was consist of adjustable pitch diameter pulleys.[3] AC induction motors were firstly designed in 1924 [3]and the speed of motors were dependent upon frequency and poles of motors. After the invention of motors it was thought that motors could be run on variable speed, for that matter the only possible solution was to vary the frequency, In order to run the motor on a variable speed, because frequency has direct relation with motor speed. Variable frequency dive based on pulse width modulation was firstly invented in early 60's in Finland.[4] But on commercial scale a great achievement was made by Martti Harmoinen at Helsinki Metro in 1972.[4] Initially variable frequency drives were based on 6 step voltage design.[3] But after some time a modified form was introduced. This was designed and presented by Phillips in mid-80's it consisted of sine coded PWM chip set.[3],[4] now there arises a point why variable frequency drive is used only for ac induction motors. The answer is as follow. Universally for induction motor's optimum working a slip is required and this slip produces required utilizable torque. Different techniques and methods used to improve the efficiency and working of ac induction motors like soft starters[5], voltage reduction method [6], slip compensation [7], and vector control.[8] But all these methods are not proved feasible for avoiding slip already present in the motor. Because this slip in the motor signifies the amount of energy that is dissipated in the form of heat and may harm many other sensitive component and windings of the motor thus the life time of motor is reduced.[9] Therefore a need of variable frequency drive based on pulse width modulation arises in application which does not require high torque and dynamic response.[10] Price is a very important factor for which this adjustable speed drive is being used because it has comparatively less cost associated with the installation and maintenance of the systems.[11] In last 10 years a great advancements has been made in variable frequency drives that are undoubtedly dependent upon the progress in power electronics field.[1] Now the drives coming in market have several better features unlike the previous ones. In the drives high efficiency capacitors are being used which are used to remove ripples in the voltage coming in to the DC bus this advancement in capacitors is leading the drive towards more energy savings as newly made capacitors offer 80% less power loss as compared to the older technology.[12] Furthermore the new drives comprises of DC choke which are used to prevent from unwanted harmonics.[2],[10] An extra feature added in the ac motor drives is heat management system by using this system heat is monitored properly and autonomous actions are performed accordingly.[13] The advancements in semiconductor devices have improved the efficiency of drives up to a greater extent.[14] Power management control which deals with sleep functionality of the device is a very key feature it save energy and unwanted power loss are prevented.[15] Many new advancements in layout of these drives like speed adjustment, keypad for input, and meters for providing information about maintenance and communication with other devices. These characteristics incorporated in the drive have not only beautified the product but also enhanced its ability and utilization.

1.2 Problem Statement

Induction motors are fixed speed motors used in most industrial processes due to their reliability, rugged nature, low maintenance and reduced cost. However, induction motors are nonlinear and complex systems owing to their characteristic which require complex control, circuitry and inverter over sizing. Motion is required in any industrial application be it domestic or industrial. Induction motor use is limited in many industrial applications requiring variable speed due to high costs incurred in methods of speed control and inefficiency of the methods used.

In this project the variable speed drive aims at making speed of an induction motor variable through varying the frequency and hence torque of induction motor. Planning starts at creating a simulink model of an induction motor connected to a variable speed drive. Simulation is then done for various parameters and results tabulated in graphical form. Process ensures efficient and effective power consumption and reduction.

1.3 Objective

- Voltage and frequency input to induction motor are to be controlled to achieve desired speed response

- Minimize investment costs.
- Minimize day to day running costs.
- Increase efficiency of induction motor.
- Meet various constraints during normal and contingency conditions

1.4 Methodology

In this research we used MATLAB-simulink to simulate speed control of the Three-phase Induction motor using variable frequency drive (VFD).

1.5Project layout

The thesis include five chapters organized as follows Chapter one include Historical Back Ground, Problem statement, Objective, Methodology and project layout, chapter two include literature review ,chapter three include mathematical model, chapter four include results and discussion and chapter five include conclusion and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1Induction Motor Drive

In this modern era of industries, most of the processes need speed control or variable speed for precise results. Traditionally, for the speed variations, DC machines were used as their speed can be changed by changing input voltage level. But this is not the case in Induction motors, In fact, change in input voltage may damage thesemotors. But the advantages of Induction motors like simpleand strong construction and the requirement of driving and controlling their speed resulted in development of advanced motor drive technique. One such technique is the use of VFD. The recent upsurge in the use of VFD is due to the fact that along with providing variable speed for Induction motor, it also helps in making the system energy efficient.

Energy is significantly saved during lower speed operation of the motor. VFD also improves dynamic as well as steady state characteristics of the motor.

2.1.1 Squirrel Cage Induction Motor

Squirrel cage induction motors are simpler in structure than DC motors and are most commonly used in the VSD industry.

They are robust and reliable. They require little maintenance and are available at very competitive prices. They can be designed with totally enclosed motors to operate in dirty and explosive environments. Their initial cost is substantially less than that of commutator motors and their efficiency is comparable. All these features make them attractive for use in industrial drives.

The three-stator windings develop a rotating magnetic flux rotating at synchronous speed. This speed depends on the motor pole number and supply frequency: The rotating flux intersects the rotor windings and induces an EMF in the rotor winding, which in turn results in circulating current. The rotor currents produce a second magnetic flux, which interacts with the stator flux to produce torque to accelerate the machine. As the rotor accelerates, the induced rotor voltage falls in magnitude and frequency until an equilibrium speed is reached. At this point the induced rotor current is sufficient to produce the torque demanded by the load. The rotor speed is slightly lower than the synchronous speed by the slip frequency, typically 3%. In order to ensure constant excitation of the machine, and to maximize torque production up to the base speed, the ratio of stator voltage to frequency needs to be kept approximately constant.

Induction motor drive has three distinct operating regions:

1) Constant Torque

The inverter voltage is controlled up to a maximum value limited by the supply voltage. As the motor speed and the voltage are increased in proportion, constant V/F, the rated flux linkage is maintained up to the base speed. The maximum available torque is proportional to the square of the flux linkage. Typically, the induction motor is designed to provide a continuous torque rating of about 40–50% of its maximum torque.

2) Constant Power

For higher speed, the frequency of the inverter can be increased, but the supply voltage has to be kept constant at the maximum value available in the supply. This causes the stator flux linkage to decrease in inverse proportion to the frequency. Constant power can be achieved up to the speed at which the peak torque available from the motor is just sufficient to reach the constant power curve. A constant power speed range of 2–2.5 can usually be achieved.

Motors are being used worldwide on industrial or domestic level. Electricity is the most power full tool in order to run any motor. Among all the motors ac induction motors are used most commonly and extensively due to their large no of applications. But there is a need to eliminate the problem associated with ac induction motor and to run it in a very efficient way. For that matter many devices are used but the best among all the devices is Variable Frequency Drive which is used to control the speed and frequency of the motor and by reducing speed motors can be run at various loads. There is a direct relation between speed of motor and the frequency of motor operation. Therefore by varying the frequency of ac voltage the motor speed can be adjusted according to desirable value.

$$N = f*120/P \tag{2.1}$$

N = Speed of motor (RPM)

F = Electrical Frequency of motor

P = Number of poles of motor

These variable frequency drives are very important for HVAC systems where a very large power is consumed before motor reaches at its full speed and a very huge amount of inrush current is being drawn by motor causes this great loss of energy.[11],[5] This starting current can be reduced by making use of variable frequency drive and thus it saves energy up to a large extent. There are various application of variable frequency drive in different appliances like fans,[16],[17] pumps,[17] tower cooling systems,[18] micro wave ovens,[19] air conditioners and ship propulsion systems.[20] it has been said that from the energy consumed by ac motors 10% goes idle and 12% - 15% is lost when motor does not run at full load.[21] So there is a great desire of user to reduce this energy wastage and this can be possible only by making use of device like variable frequency drive because its biggest advantage is its energy saving.[11]

Variable frequency drive is basically comprises of three portions. These are as follow.[22]

- AC to DC Converter
- DC Bus

- Inverter (DC to AC convertor)

When a fixed AC voltages are fed into AC to DC rectifier the AC voltages are converted in DC voltages. Which are further directed towards DC bus which comprises of capacitors and used to store voltages and removes ripples in the DC voltage thus it smooth out the waveform.[23] Inverter is the last section which is the most important one because it performs the DC to AC conversion by approximate the square waveform with that of sine wave form whose pulse is adjusted in order to control the voltages and frequency of motors.[24] A very important tool of variable frequency drive is PWM which is the key technique for controlling motor speed.[25]

2.2 Working Principle

Variable frequency drive comprises of three major sections as described above and each section has its key importance. First section is rectifier section then a dc bus and finally we have an inverter section with which load is connected. An illustration of these sections is given below in figure 2.1.

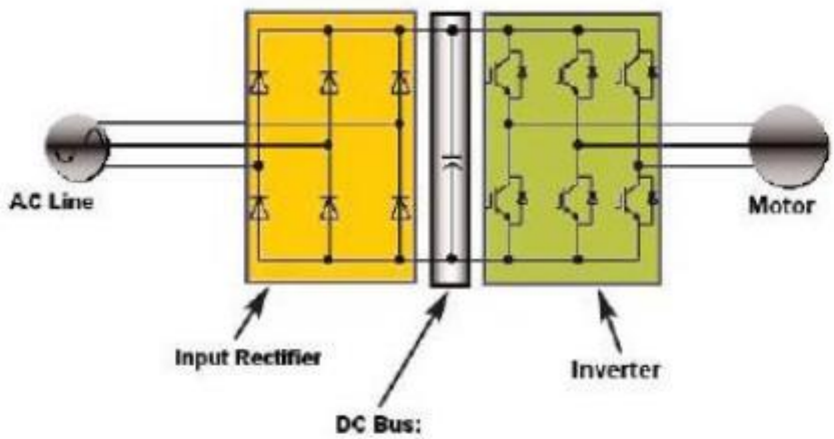

Figure 2.1: Block Diagram of VFD

2.2.1 Rectifiers

This section can comprises of diodes, transistors or silicon controlled rectifiers. But usually diodes are used because of their lower cost.[26] AC voltages coming from main line have positive and negative peaks. When these voltages are fed in to bridge type configuration of diodes of this rectifier section the negative peaks are vanished only positive peaks retain. In this way the frequency of the coming voltages doubles. This rectifier section also called AC to DC converter.[27] Further this pulsating dc is passed through a capacitor in order to remove ripples present in the waveform.[23] These ripples cause distortion and prevent smooth working of electrical appliances so they must be removed using a filter.[28]

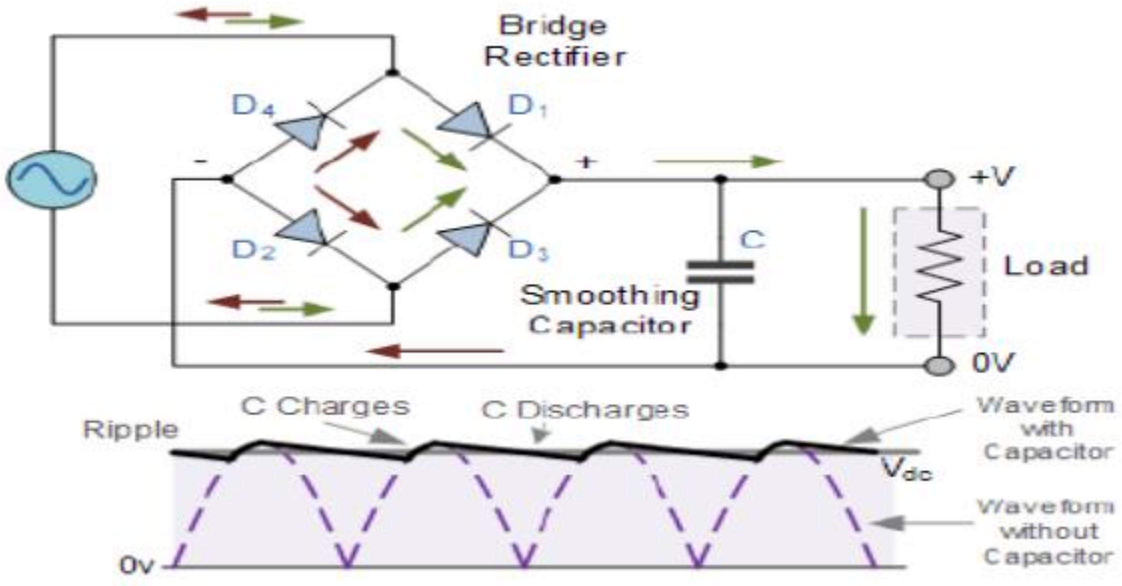

Figure 2.2:The circuit diagram of AC to DC converter

2.2.2 DC bus

DC bus is used to store voltages coming from AC to DC converter. This consist of capacitors and some other items like inductors or chokes[29] in order to smooth the power supply coming from the previous section. Thus ripples are further removed by storing voltages in this DC bus. Thus this DC bus can be of great use not only for removing ripples but also helps in improving power factor correction.[30]

2.2.3 Microcontroller based PWM

Pulse width modulation is the basic technique used very widely for controlling motor speed and frequency.[31] This can be done by using microcontroller. In this research we selected a range of 5Hz to 50Hz frequency using PWM. The basic principle of PWM is a sine wave is generated in the microcontroller which is super imposed on a triangular wave.[32] This results in a square wave which is then fed to inverter section. The width of this square wave can be controlled by changing the duty cycles of the pulse. Basically duty cycles describes the time for which pulse waveform turned on and off thus by switching the waveform between two discrete levels the square wave is approximated with a sine wave of desired duty cycles. A PWM representation is shown in figure 2.3.

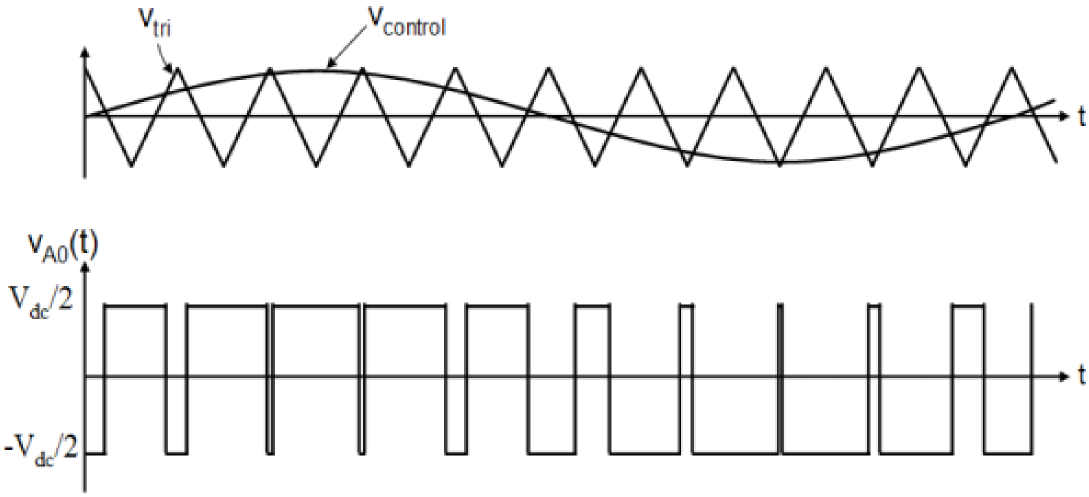

Figure 2.3: PWM Representation

2.2.4 Software and hardware based PWM

The above mentioned technique was programmed using microcontroller firstly on proteus and simulated.

Further this was implemented on controller hardware and the results were observed and matched with software results on oscilloscope.

2.2.5 Inverters

The square wave generated using PWM is then fed into inverter section. This section consists of insulated gate bipolar junction transistor (IGBT's) which are power transistors.[1] These IGBT's have very fast switching speed and their voltage and current ratings are also high so they are preferably used in variable frequency drives.[33] In inverter sections these IGBT's are connected in H-bridge configuration. These IGBT's are fed by two PWM's one is normal while the other one is its complement. This is because first we need to excite number 1 and 4th IGBT this will create a waveform rising in clock wise manner. While the complement of the PWM is used to create a waveform rise in anti-clock wise manner thus a complete cycle of the waveform would be achieved. But there is one important thing to note that there is a need to introduce a small dead time.[34]

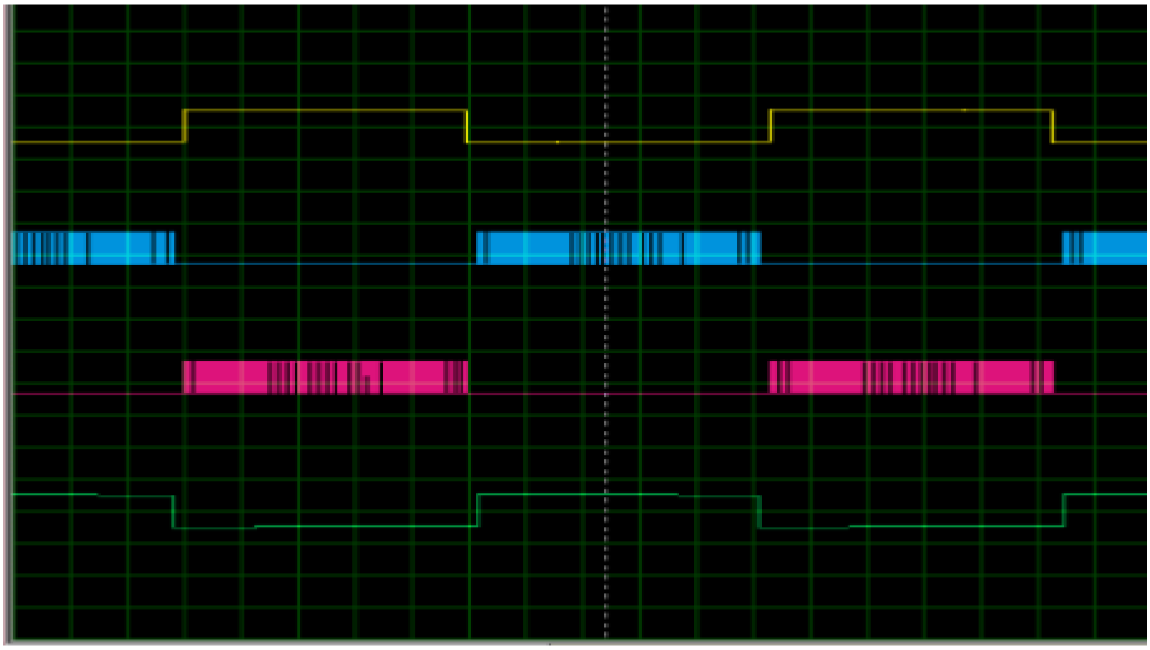

Figure 2.4: Dead time Representation in PWM wave

The reason is quite simple but important that the time to turn off a power device is quite longer than time to turn on that device. For this reason this dead time is inserted switching action of complementary channels.[35]The power transistors turn on at a time when the square wave is feed into them. As the pulse width of this square waveform is varied from microcontroller at a very high switching speed so this square pulse is approximated with a sine wave when it is applied at load. The inductance of the load also helps in shaping this wave form into sine wave. Thus the desired goal is achieved using invertors and PWM.

2.3Advantages of VSD

There are so many benefits associated with this drive. A few of them are listed below.[36]

- Saves energy
- Reduce inrush current
- Easy and simple installation
- Improved power factor
- Reduction in KVA
- High efficiency of motor
- Low thermal and Mechanical losses

very common problem in motors is their low power factor when they don't run at full load this leads to serious damages.[37] So this power factor must be improved. For this purpose capacitors are being used. But there is an extra advantage of using VFD's is the capacitors used in DC bus perform the same action. So without adding extra equipment this power factor correction can be made. These attributes of variable frequency drive tempt the industries to choose it and enjoy extra savings in terms of energy and fewer losses.

2.4 Disadvantages of VSDs

- Acoustic noise
- Motor de-rating
- Supply harmonics
- Problems of fast switching

2.4.1Acoustic Noise

Placing a VSD on a motor increases a motor's acoustic noise level. This occurs when the driver's non-sinusoidal waveform produce vibrations in the motor's laminations which are a result of transistor switching frequency and modulation in DC-to-AC inverter. Switching frequency, fixed or variable, determines audible motor noise. The higher the carrier frequency, the closer the output waveform is to a pure sine wave.

A method of reduction of audible noise is by full spectrum switching achieved by manufacturers by an algorithm within the VSD controller. Traditionally motor noise level is reduced by addition of an LC filter between VSD and motor thus reducing the high frequency component of motor voltage waveform. Modern PWM inverter drives run at very high switching frequency with random switching frequency thus reducing the noise levels.

2.4.2Motor Heating

Inverters used in large drives have limits on switching rates that can cause their output voltage to contain n substantial harmonics of order 5, 7, 11, 13, etc. These cause harmonic currents and additional heating in stator and rotor windings. Modern PWM VSI drives produce a voltage wave with negligible lower- order harmonics. The wave consists of pulses formed by switching at relatively high frequency between the positive and the negative sides of the DC-link voltage supply. For larger motors operating from AC supplies up to 6600v, rapid rate of change of voltage applied to winding may cause deterioration and failure in insulation on the entry turns of standard motors.

For self-ventilated motors, reducing motor shaft speed decreases available cooling air flow. Motor operating at full torque and reduced speed result in inadequate air flow which consequently results in increased motor insulation temperature. This consequently can be damaging and reduce motor’s insulation or cause motor to fail. One solution is to add a constant speed separately driven cooling fan to motor.

2.4.3Supply Harmonics

Current and voltage harmonics are created by VSD connected to power distribution system. Such harmonics pollute the electric plant causing problems if harmonic levels increase beyond a certain level. Effect being overheating of transformers, cables, motors, generators and capacitors connected to the same power supply with devices generating harmonics. The IEEE 519 recommends practices and requirements for harmonic control in electrical power systems. Philosophy being to limit harmonics injection from consumers so as not to cause unacceptable voltage distortion levels for normal system characteristics and to limit the total harmonic distortion of system voltage supplied by the utility. To reduce supply harmonics generated by VSDs equipped with a six pulse converter np6+-1[5, 7, 11, 13, 17, 19, etc] order harmonics are generated. To minimize effect on supply network, recommendations are made by IEEE 519 as to acceptable harmonic limits. For higher drive power, either harmonic filtering or use of a higher converter pulse number is necessary. It is generally true that use of higher pulse number is the cheaper alternative.

2.4.4Problems of fast switching

PWM voltage source inverter (VSI) drives equipped with fast switching devices introduce problems such as;

- Premature motor insulation failure
- Bearing/earth currentElectromagnetic compatibility

2.5 VSD as Energy Saving Device

The biggest advantage of VFD as mentioned previously is its energy saving capabilities.[11] Which not only tempt the costumer but also very helpful in our country where energy consumption needs to be reduced. For this take a simple example of pump and water flow is described to illustrate the working of energy savings.[38] The equations mentioned below show the relationship between power and speed of pump.

Flow2/Flow1=Speed2/Speed1 (2.2)

Head2/Head1= $(\text{Speed2})^2/ (\text{Speed1})^2$ (2.3)

Power2/Power1= $(\text{Speed2})^3/ (\text{Speed1})^3$ (2.4)

The above equation tells us by making use of variable frequency drive approximately 85% energy saving is possible at different operating points of pump.[38]

2.6 VSD Versus Other Techniques

To overcome current inrush problem in induction motors, various methods are used. Soft starter, autotransformer why-delta starter and VFD's are used. The reason behind choosing a VFD is that a VFD reduces the current inrush to the full load current. Soft starters and autotransformer are not that energy efficient. Both these methods operate at a fixed frequency (50 Hz) unlike a VFD which operates a motor at variable frequency. The following table is based on experimental results.

2.7Drive Types And Specifications

Industrial processes require adjustments in some form and VSDs are usually used for such adjustments. These are an important part of automation. VSDs help optimize process, reduce investment costs and energy consumption hence energy costs.

VSDs Are of Three Systems:

- Electrical drives.
- Hydraulic drives .
- Mechanical drives.

2.8Drive Classifications and Characteristics

Table 2.1 illustrates the most commonly used classifications of electric VSDs. In this section, particular emphases will be given to classification by applications and by converter types.
Other classifications, not listed in Table 1, include:

- Working voltage: Low-voltage<690 V or Medium Voltage (MV) 2.4–11 kV Current type: Unipolar or bipolar drive
- Mechanical coupling: Direct (via a gearbox) or indirect mechanical coupling
- Packaging: Integral motors as opposed to separate motor inverter
- Movement: Rotary movement, vertical, or linear
- Drive configuration: Stand-alone, system, DC link bus

- Speed: High speed and low speed
- Regeneration mode: Regenerative or non-regenerative
- Cooling method: Direct and indirect air, direct water (raw water and de-ionized water).

Table 2.1: Classification of electrical VSDs

By application	By devices	By converter	By motors	By industry	By rating
Appliances	Thyristor	AC/DC (chopper)	DC	Power generation	Fraction KW Power <1KW
Low performance (2Q)	Transistor	AC/AC direct (cyclo – and matrix converter)	Induction motor (squirrel cage and wound rotor)	Metal	Low power (1< P < 5KW
High performance (4Q)	Gate Turn-Off Thyristor (GTO)	AC/AC via a DC link voltage source	Synchronous moto	Petrochimical	Medium <500 KW
Servo	Integrated Gate Commutated Thyristor (IGCT)	AC/AC via a DC link current source	Special motors SRM, BDCM,Stepper, Actuator, Linear motor	Process industry	High power 1-50 KW
	Insulated Gate Bipolar Transistor (IGBT)			Mining	
	MOSFET			Marine	

2.8.1 Classification by Applications

Under this classification there are four main groups:

- Appliances (white goods)
- General purpose drives
- System drives
- Servo drives

2.8.2 Classification by Type of Power Device

The Silicon Controlled Rectifier (SCR), also known as the thyristor, is the oldest controllable solid-state power device and still the most widely used power device for MV – AC voltages between 2.4 kV and 11 kV – high power drive applications. Such devices are available at high voltages and currents, but the maximum switching frequency is limited and requires a complex commutation circuit for VSI drive. The SCRs are therefore most popular in applications where natural commutation is possible. The Gate Turn-Off Thyristor (GTO) has made PWM VSI drives viable in LV drive applications. Complex gate drive and limited switching performance, combined with the need for a snubber circuit, limited this device to high performance applications where the SCR-based drives could not give the required performance.

Bipolar/MOSFET type transistors witnessed significant popularity however; they have been replaced by the IGBT which combines the characteristics of both devices – the current handling capability of the bipolar transistor and the ease of drive of the MOSFET. Conversion to IGBT has enabled a 30% to 50% reduction in cost, weight, and volume of the equipment

Classification by the Type of Converter

The power converter is capable of changing both its output voltage magnitude and frequency. However, in many applications these two functions are combined into a single converter by the use of the appropriate switching function; e.g. PWM. By appropriate control of the stator frequency of AC machines, the speed of rotation of the magnetic field in the machine's air gap and thus output speed of the mechanical drive shaft can be adjusted. As the magnetic flux density in the machine must be kept constant under normal operation, the ratio of motor voltage over stator frequency must be kept constant.

The input power of the majority of VSD systems is obtained from sources with constant frequency (e.g. AC supply grid or AC generator). In order to achieve variable frequency output energy an AC/AC converter is needed

1) DC Static Converter

This drive employs the simplest static converter. It is easily configured to be a regenerative drive with a wide speed range.

High torque is available throughout the speed range with excellent dynamic performance. Unfortunately, the motor requires regular maintenance and the top speed often is a limiting factor. Commutator voltage is limited to around 1000 V and this limits the maximum power available. The continuous stall-torque rating is very limited due to the motor's commutator.

2) Direct AC/AC Converters

a) Cyclo-Converter

A typical cyclo-converter comprises the equivalent of 3 anti-parallel 6-pulse bridges (for regenerative converter) whose output may be operated in all four quadrants with natural commutation.

This type of drive is best suited for high performance high power>2 MW drives where the maximum motor frequency is less than 33% of the mains frequency.

b) Matrix-converter

The force-commutated cyclo-converter (better known as a matrix-converter) represents possibly the most advanced state of the art at present, enabling a good input and output current waveform, as well as eliminating the DC link components with very little limitation in input to output frequency ratio. Its main advantage being its ability to convert AC fixed frequency supply input to AC output without DC bus. It is ideal for integrated motor drives with relatively low power ratings. Major drawbacks include:

- The increased level of silicon employed (bi-directional switches)
- Its output voltage is always less than its input voltage
- Complexity of commutation and protection.

Matrix-converters provide direct AC/AC power conversion without an intermediate DC link and the associated reactive components. They have substantial benefits for integrated drives as outlined below:

- Reduced volume due to the absence of DC link components
- Ability to operate at the higher thermal limit imposed by the power devices
- Reduced harmonic input current compared to a diode bridge.
- Ability to regenerate into the supply without dumping heat in dynamic braking resistors

c) Current Source Inverter (CSI)

Its output is rectangular blocks of current from the motor bridge supplied from a supply converter whose output is kept at constant current by a DC link reactor and current servo. It is typically based on fast thyristors.

d) Load Commutated Inverter (LCI)

Natural commutations of thyristors is usually achieved with Synchronous Machines at speeds>10%. This is induced as a result of the presence of the motors Electromotive Force (EMF), this is called Load Commutation hence the drives other name of LCI. At low speeds the motor voltage is too low to give motor bridge commutations. This is achieved by using the supply converter. Induction motor LCI drives can be supplied by adding a large capacitor on the motor terminals.

The LCI drive has limited performance at low speeds. It also suffers from torque pulsation at 6 and 12 times motor's frequency and beat frequencies. Critical speeds can excite mechanical resonance. Its AC power factor varies with speed.

e) Forced Commutated Inverter (FCI)

Externally commutated current source converters with an induction motor are also a viable solution. To compensate for the inductive component in the motor current a bank of capacitors is usually used at the motor terminals. The capacitor current is proportional to the motor voltage and frequency. Load commutation at high speed where the compensation current is high enough. Forced commutation at lower speed where the capacitive current is too low for compensation. Modern drives employ forced commutated devices, such as reverse blocking GTOs and IGCTs.

f) Slip Power Recovery (Kramer)

In this, the rotor current of a slip-ring wound-rotor induction motor is rectified and the power then reconverted to AC at fixed frequency and fed back into the supply network. For traditional designs the low frequency slip ring currents are rectified with a diode bridge and the DC power is then inverted into AC power at mains frequency.

The traditional designs had poor AC mains dip immunity, high torque pulsation and high levels of low frequency AC supply harmonics. The latest generation of this type of drive is called the Rotor Drive and uses PWM-VSI inverters for the rotor and AC supply bridges.

g) PWM-VSI Converter

The availability of power electronic switches with turn-off capability; e.g. FETs, BJTs, IGBTs, and GTOs have currently favored drives with voltage-fed PWM converters on induction. The PWM VSI drives offer the highest possible performance of all variable speed drives. Recent improvements in switching technology and the use of micro-controllers have greatly advanced this type of drive. The inverters are now able to operate with an infinite speed range. The supply power factor is always near unity. Additional hardware is easily added if there is a requirement to regenerate power back into the mains supply. Motor ripple current is related to the switching frequency and in large drives the motor may be derated by less than 3%.

2.9Load Profiles and Characteristics

Drive performs is very much dependent on the load characteristics. Here, four load characteristics are described.

2.9.1Load Profile Types

The four different load profiles have been described. These are:

1. Torque proportional to the square of the shaft speed
(Variable torque)
2. Torque linearly proportional to speed (Linear torque)
3. Torque independent of speed (Constant torque)
4. Torque inversely proportional to speed (Inverse torque)

2.9.2Motor Drive Duty

1) Duty Cycle

The size of the driven motors is generally chosen for continuous operation at rated output, yet a considerable proportion of motor drives are used for duties other than continuous. As the output attainable under such deviating conditions may differ from the continuous rating, fairly accurate specification of the duty is an important prerequisite for proper planning. There is hardly a limit to the number of possible duty types.

In high performance applications, such as traction and robotics, the load and speed demands vary with time. The electric, magnetic, and thermal loading of the motor and the electric and thermal loading of the power electronics converter are definite constraints in a drive specification.

2) Mean Output

Variation of the required motor output during the periods of loaded operation is among the most frequent deviations from the duty types defined. In such cases the load (defined as current or torque) is represented by the mean load. This represents the root mean square (RMS) value, calculated from the load versus time characteristics. The maximum torque must not exceed 80% of the breakdown torque of an induction motor.

If the ratio of the peak torque to the minimum power requirements is greater than 2:1, the error associated with using the root mean square (RMS) output becomes excessive and the mean current has to be used instead.

2.10Drives Requirements & Specifications

2.10.1 General Market Requirements

Some of the most common requirements of VSDs are: high reliability, low initial and running costs, high efficiency across speed range, compactness, satisfactory steady-state and dynamic performance, compliance with applicable national and international standards (e.g. EMC, shock, and vibration), durability, high availability, ease of maintenance, and repairs. The order and priority of such requirements may vary from one application to another and from one industry to another. For example, for low performance drives such as fans and pumps, the initial cost and efficiencies are paramount, as the main reason for employing variable speed drives is energy saving. In critical VSD applications, such as Military Marine Propulsion, reliability, availability and physical size are very critical requirements. Cost is relatively less critical. However, achieving these requirements adds to the cost of the basic drive unit. Series and parallel redundancy of components enable the VSD equipment to continue operation even with failed components. This section identifies the VSD requirements in various drive applications in different industries.

a) The Mining Industry

The majority of early generation large mine-winders are DC Drives. Modern plants and retrofits generally employ cyclo-converters with AC motors. However, small mine winders (below 1 MW) tend to remain DC.

The main requirements are:

• High reliability & availability

• Fully regenerative

• Small number requiring single quadrant operation

• High range of speeds

• High starting torque required

• High torque required continuously during slow speed running

- Low torque ripple required
- Low supply harmonics
- Low audible noise emissions
- Flameproof packaging

b) The Process Industries

The main requirements of this market are:

- Initial purchase price (long-term cost of ownership does not generally influence purchasing decision)
- Efficiency in continuous processes
- Reliability
- Ease of maintenance
- Bypass facility
- Two-quadrant operation for fans, pumps, and compressors
- Four-quadrant operation for some Test Benches
- Control must allow additional functions such as temperature protection, motor bearing temperature, flow and pressure control etc.
- There is no requirement, in general, for field weakening
- The harmonics produced by the drive, imposed on the power system should not require a harmonic filter.

c)The Metal Industries

The requirements of this industry are:

- Reliability – high availability
- Efficiency of the equipment – long-term costs of ownership
- Low maintenance costs – (this has been a key factor in the move from DC to AC)
- Power supply system distortion – more onerous regulations from the supply authorities
- Initial purchase cost – very competitive market, and large drive costs have a big impact on total project costs

• Confidence in the supplier and their solution

2.10.2Drive Specifications

Drives need to be produced and supplied according to specifications provides. Failure to specify an electric VSD can result in conflict between the equipments supplier and end user. Often cost can delay a project completion and/or loss of revenue. To avoid such, requirement specifications should reflect the operating and environmental conditions. Equipment supplier and customer need to work as partners.

Identifying applicable national and international standards on issues related to EMC, harmonics, safety, and noise, smoke emissions during faults, dust and vibrations is a major issue. As far as the end user is concerned, they need to specify the drive interfaces-AC input voltage, shaft mechanical power and shaft speed. Harmonic survey needs to be carried out for higher power drives.

CHAPTER THREE

MATHEMATICAL MODEL

3.1 Introduction

Just as power electronic equipment has tremendous variety, depending on power level of application; motors also come in different types depending on requirements of application and power level.

For many years, the brushed DC motor has been the natural choice for applications requiring high dynamic performance. In contrast, induction motor was considered for low performance, adjustable speed applications at low and medium power levels. At very high power levels, the slip-ring induction motor or synchronous motor drives were natural choices but these boundaries are becoming blurred.

Typical motor-drive system is expected to have some of system blocks indicated in figure below. Loads may be conveyor systems, traction system, rolls of a mill drive, cutting tool of numerically controlled machine tool, compressors of an air conditioner, robotic arm, etc.

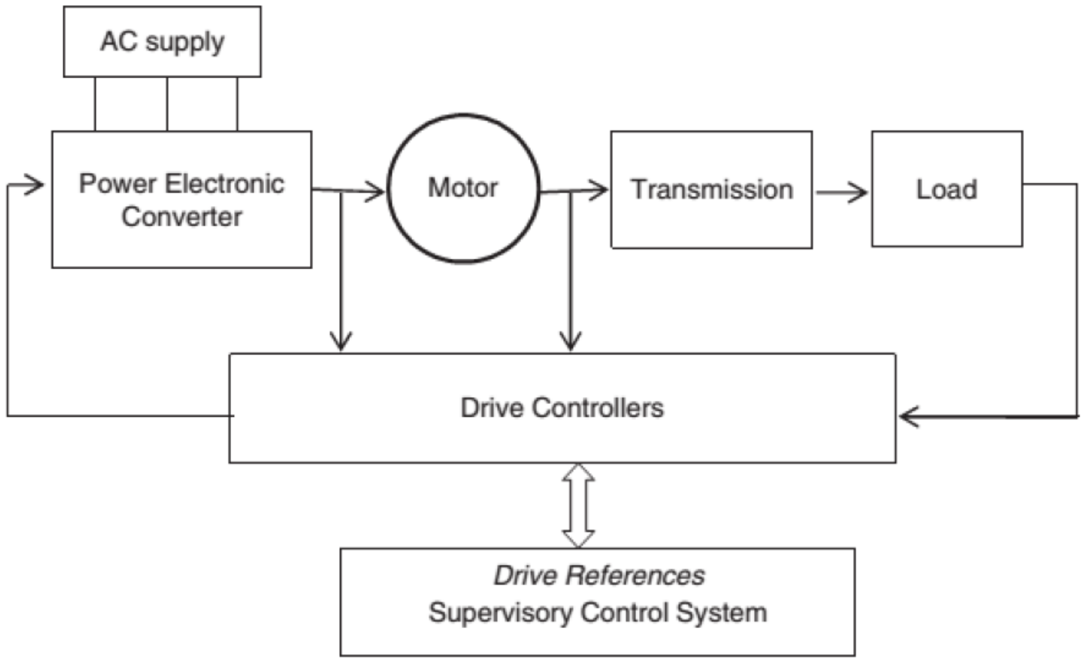

Figure3.1: Block diagram of a typical motor-drive system

3.2Steady state representation of an induction motor

The traditional methods of variable-speed drives are based on the equivalent circuit representation of the motor shown in figure 3.2 below.

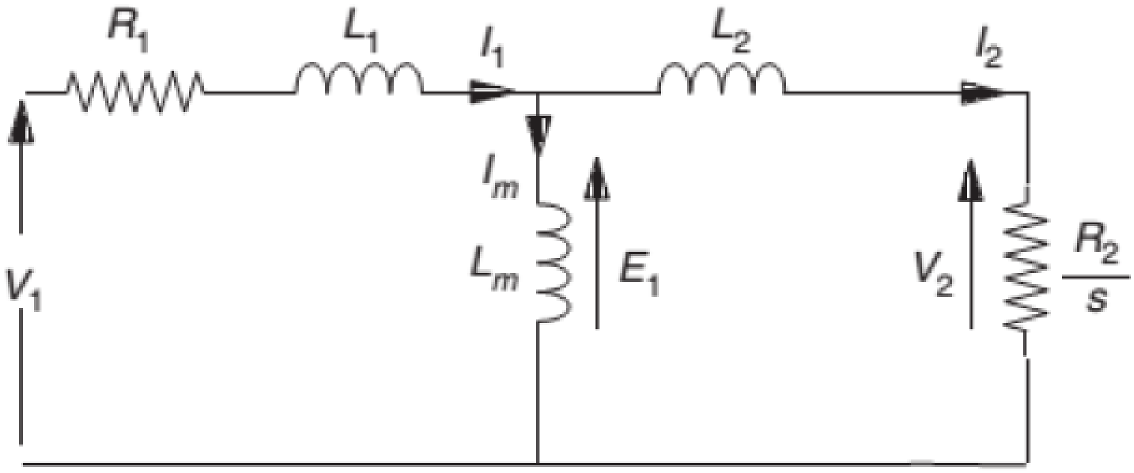

Figure 3.2: Steady state equivalent circuit of an induction motor

From figure 3.2 the following power relationships in terms of motor parameters and the rotor slip can be found

Power in rotor circuit

$P=3I^2{}_2\frac{R2}{s}$ (3.1)

$P= 3sR^2{}_2E^2{}_1/ R^2{}_2+ (s\omega_1L_2)^2$ (3.2)

Output power, $P_0=P_2-3I^2{}_2R_2=(1-s)P_2$ (3.3)

$= \omega_0T = ((1-s)\omega_1/P)*T$ (3.4)

Where

Slip $s= (\omega_1- \omega_r) / \omega_1= (\omega_1-p\omega_0) / \omega_1$ (3.5)

P = number of poles pairs

$\omega_0= 2\pi N/ 60$ rad/s ; (3.6)

N is the rotor speed in rev/min

ω_r =rotor speed in electrical rad/s

and$\omega_1= 2\pi f_1$rad/s (electrical) (3.7)

f_1= the supply frequency

the developed torque,

$T = P_2 / (\omega_1/P)$ (3.8)

3.3 Variable Frequency drive principles of operation

A variable frequency drive is a device used to control speed by varying the frequency. Speed (rpm) $\boldsymbol{nr}=\mathbf{120}\boldsymbol{f}/\boldsymbol{P}$ It consists of four units:

- Rectifier unit
- Dc bus link
- Inverter unit
- Control stage

The basic block diagram of a variable speed drive is shown below

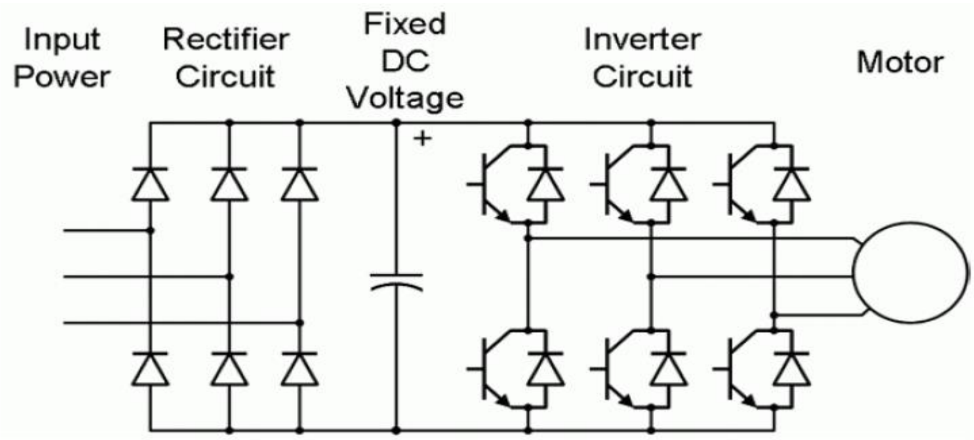

Figure 3.3: VFD circuit diagram

3.3.1 Rectifier stage

Rectifiers can be controlled or uncontrolled voltage source or current source derived based on DC power stage to either buck or boost. Can also have active front-ends that use pulse width modulation (PWM) to control the rectifier in order to minimize harmonics and in turn improve the power factor of motor automatically through backing off the voltage potential, a technique referred to as high-quality rectification. A full wave bridge rectifier converts single phase or three phase 50 Hz power from standard utility supply to either fixed or adjustable Dc voltage.

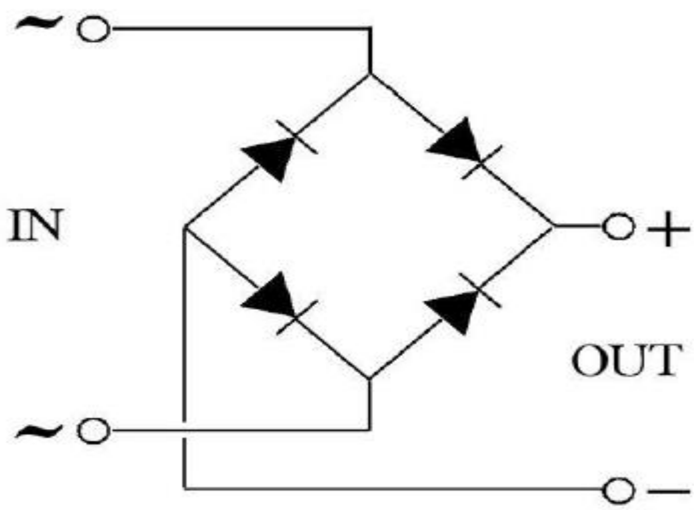

Figure 3.4: Diode bridge rectifier

One diagonal pair of rectifier will allow power to pass through only when the voltage is positive. A second diagonal pair of rectifier will allow power to pass through only when the voltage is negative. Two diagonal pair of rectifiers is required for each phase of power. This comprises of 6 diodes which converts AC power supply voltage to DC power supply voltage to be supplied to the inverter. This is done in order to vary frequency of induction motor as it is easier to convert AC supply to DC supply as AC can be easily rectified to DC .DC supply has no hard or soft frequencies generated as DC supply is a continuous flow of current hence can be easily controlled to be able to generate different frequencies as compared to Ac supply which has fixed frequency.

3.3.2 DC bus link

This comprises of a single link inductor or shunt capacitor or a combination of the two. At this stage, the converted AC supply to DC supply is then stored as energy and later on released. It also reduces ripple current and voltage. This is done through volt-second balance in inductors and charge(amp-second) balance in capacitors Arrangement of DC storage elements depend on how the DC energy conversion function, buck, boost, buck/boost, regenerative, non-regenerative, etc. A regenerative system can give power back to the system while still absorbing power.

3.3.3 Inverter stage

This section of the VFD is referred to as an "inverter." The inverter contains transistors that deliver power to the motor. The "Insulated Gate Bipolar Transistor" (IGBT) is a common choice in modern VFDs. The IGBT can switch on and off several thousand 19 times per second and precisely control the power delivered to the motor.

The IGBT uses a method named "pulse width modulation" (PWM) to simulate a current sine wave at the desired frequency to the motor. Motor speed (rpm) is dependent upon frequency. Varying the frequency output of the VFD controls motor speed: Speed (rpm) = frequency (hertz) x 120/no. of poles.

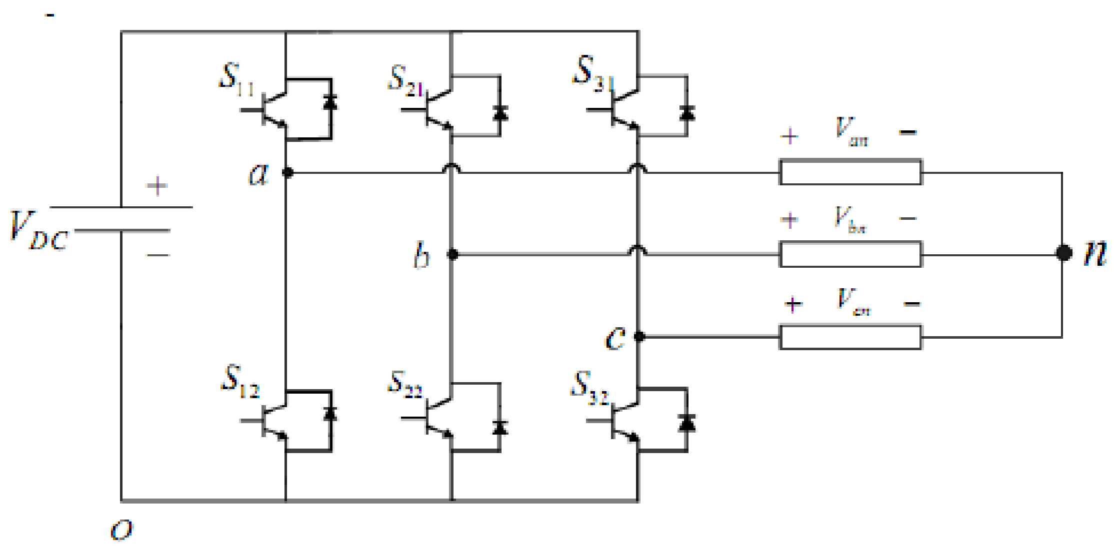

Figure 3.5: Full-Bridge inverter

The inverter model shown in Figure 3.5 has eight switch states given in Table 3.1 In order that the circuit satisfies the KVL and the KCL, both of the switches in the same leg cannot be turned ON at the same time, as it would short the input voltage violating the KVL. Thus, the nature of the two switches in the same leg is complementary.

S_{11}+ S_{12}

S_{21} + S_{22}

S_{31} + S_{32}

S_{11}	S_{12}	S_{31}	V_{ab}	V_{bc}	V_{ca}
0	0	0	0	0	0
0	0	1	0	V_{DC}	V_{DC}
0	1	0	$-V_{DC}$	V_{DC}	0
0	1	1	$-V_{DC}$	0	$-V_{DC}$
1	0	0	$-V_{DC}$	0	$-V_{DC}$
1	0	1	$-V_{DC}$	$-V_{DC}$	0
1	1	0	0	V_{DC}	$-V_{DC}$
1	1	1	0	0	0

Table 3.1 : switching states in a three phase inverter

The selection of the states in order to generate the given waveform in a three-phase inverter is done by the modulating technique that ensures the use of only the valid states.

$$\frac{VDC}{2}(S_{11} - S_{12}) = V_{an} + V_{no} \qquad (3.9)$$

$$\frac{VDC}{2}(S_{21} - S_{22}) = V_{bn} + V_{no} \qquad (3.10)$$

$$\frac{VDC}{2}(S_{31} - S_{32}) = V_{cn} + V_{no} \qquad (3.11)$$

Expressing (3.4) to (3.6) in terms of modulation signals and making use of conditions from (3.1) to (3.3) gives:

$$\frac{VDC}{2}(M_{11}) = V_{an} + V_{no} \qquad (3.12)$$

$$\frac{VDC}{2}(M_{21}) = V_{bn} + V_{no} \qquad (3.13)$$

$$\frac{VDC}{2}(M_{31}) = V_{cn} + V_{no} \qquad (3.14)$$

Adding equation (3.7), (3.8), (3.9) gives equation (3.10).

$$\frac{VDC}{2}(S_{11} + S_{21} + S_{31} - S_{12} - S_{22} - S_{32}) = V_{an} + V_{bn} + V_{cn} + 3V_{no} \quad (3.15)$$

As we are dealing with balanced voltages,

V_{an}+V_{bn}+V_{cn}=0, equation (3.10) becomes,

$$\frac{VDC}{6}(2S_{11} + 2S_{21} + 2S_{31} - 3) = V_{no} \quad (3.16)$$

Substituting for Vno in equations (3.4) to (3.6) gives:

$$\frac{VDC}{3}(2\,S_{11} - S_{21} - S_{31}) = V_{an} \quad (3.17)$$

$$\frac{VDC}{3}(2\,S_{21} - S_{11} - S_{31}) = V_{bn} \quad (3.18)$$

$$\frac{VDC}{3}(2\,S_{31} - S_{21} - S_{11}) = V_{cn} \quad (3.19)$$

The switches are a combination of power diodes, MOSFET and IGBT transistors arranged in three basic combinations: single quadrant, two quadrants and four quadrants. The two quadrant switches can be current-bidirectional or voltage-bidirectional. The four quadrant switches are developed using two quadrant types as building blocks. MOSFET transistors tend to be used for high current, bidirectional switch applications; and IGBT transistors tend to be used for high voltage bidirectional applications. Also, all switching is done in such a way that the device is only operated in its linear active region for a very short time. It is either turned on or turned off. To get these devices to switch fast (in the kilo-hertz range), it is necessary to use driver circuits and snubbers to optimize the switching speed and minimize losses. Also, faster switching translates directly to smaller energy storage elements. The inverter of the VSD (variable speed drive) can be a voltage inverter source (VSI) or current inverter source (CSI). In industrial markets, the VSI design has proven to be more efficient, have higher reliability and faster dynamic response, and be capable of running motors without de-rating.

VSI fully integrated designs save money with higher efficiencies, minimizing install time, eliminating interconnect power cabling costs and reducing building floor space. Efficiencies are 97% with high power factor through all load and speed ranges.

3.3.3.1Current source inverter

The way each of the drive building blocks operates defines the type of drive topology. The first topology that will be investigated is the current source inverter (CSI). The converter section uses silicon-controlled rectifiers (SCRs), gate commutated thyristors (GCTs), or symmetrical gate commutated thyristors (SGCTs). This converter is known as an active rectifier or active front end (AFE). The CSI design requires input and output filters due to high harmonic content. The input is similar to a low voltage (LV) drive six-pulse input. At higher horsepower, a six-pulse active front end (AFE) input creates harmonics in the power system and poor power factor. To mitigate this issue, drive manufacturers combine either input transformers or reactors and harmonic filters to reduce the detrimental effects of the drive on the power system at the point of common coupling (PCC).

3.3.3.2Voltage source inverter

This topology uses a diode rectifier that converts utility/line AC voltage (50Hz) to DC. The DC link is parallel capacitors, which regulate the DC bus voltage ripple and store energy for the system. The inverter is composed of insulated gate bipolar transistor (IGBT) semiconductor switches. There are other options to the IGBT. Insulated gate commutated thyristors (IGCTs) and injection enhanced gate transistors (IEGTs).

Depending on the load type, variable speed drives have different applications.

- Variable torque load

These are typical of centrifugal fans and pumps and have the highest and largest energy saving capability. They are governed by the Affinity Laws which describe the relationship between the speed and other variables: The change in flow varies in proportion to the change in speed:

Q1/Q2 = (N1/N2) the change in head (pressure) varies in proportion to the change in speed squared:

$H1/H2 = (N1/N2)^2$

The change in power varies in proportion to the change in speed cubed:

$P1/P2 = (N1/N2)^3$

Where Q = volumetric flow, H = head (pressure), P = power, N = speed (rpm). The power – speed relationship is also referred to as the 'Cube Law'. When controlling the flow by reducing the speed of the fan or pump a relatively small speed change will result in a large reduction in power absorbed.

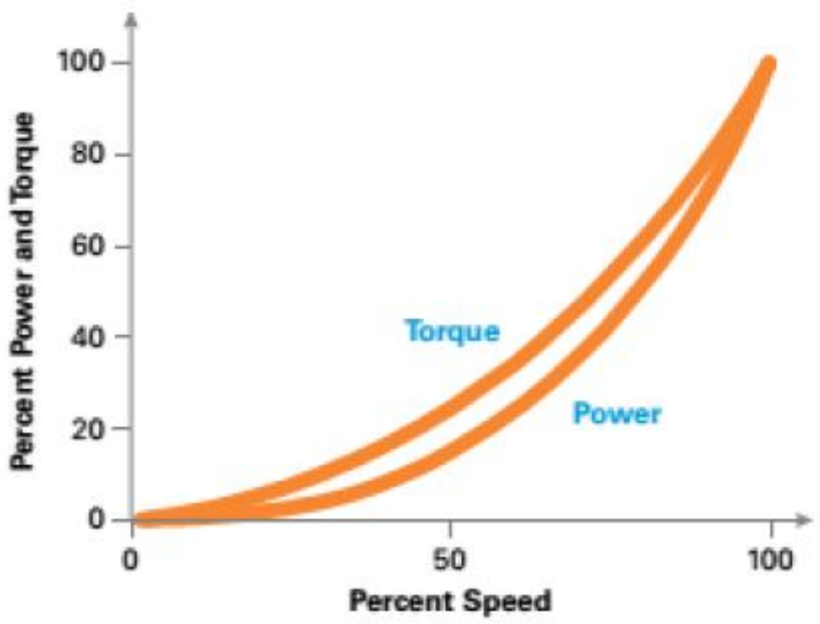

Figure 3.6: Variable torque load

- **Constant torque load**

Typical constant torque applications include conveyors, agitators, crushers, surface winders and positive displacement pumps and air compressors. On constant torque loads the torque does not vary with speed and the power absorbed is directly proportional to the speed, this means that the power consumed will be in direct proportion to the useful work done, for example, a 50% speed reduction will result in 50% less power being consumed.

- **Constant power load**

On constant power loads the power absorbed is constant whilst the torque is inversely proportional to the speed. There are rarely any energy savings opportunities from a reduction in speed. Examples of constant power

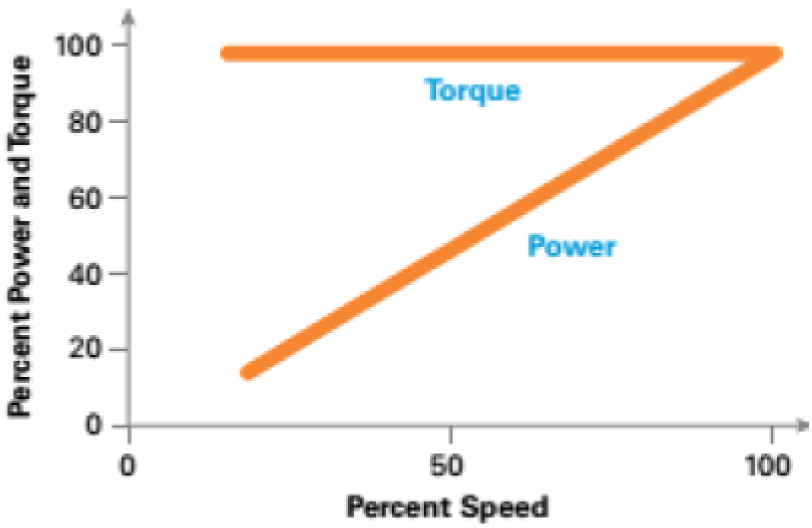

Figure3.7: Constant Torque Load

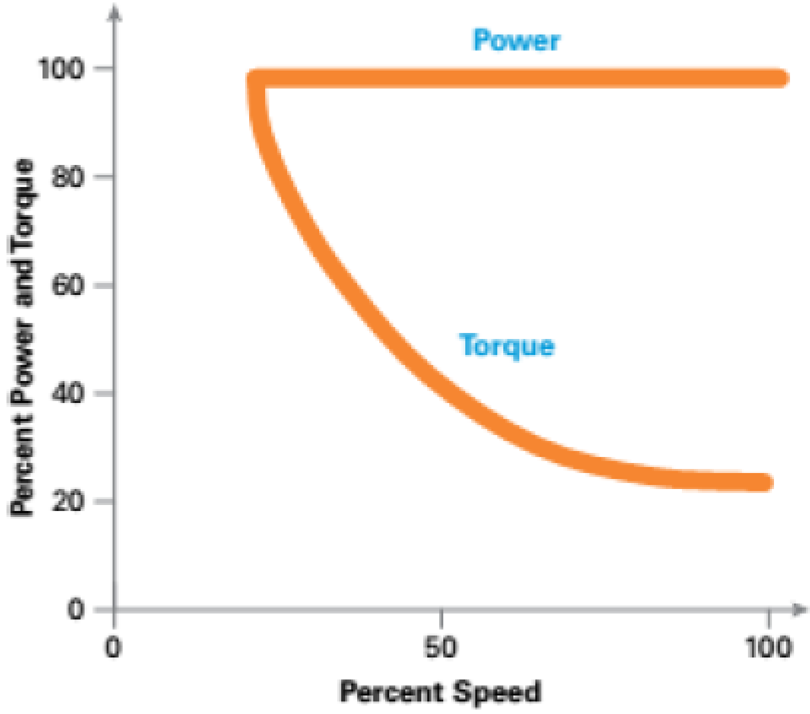

Figure 3.8: Constant Power load profile

3.4Variable frequency drive operation

The basic principle behind VFD operation requires an understanding of the three basic sections: the Rectifier unit, DC Bus and the Inverter unit, as shown in figure 3. The supply voltage is first passed through a Rectifier unit where it gets converted from AC to DC supply; the three phase supply is fed with three phase full wave diode where it gets converted into DC supply. The DC bus comprises a filter section where the harmonics generated during the AC to DC conversion are filtered out. The last section consists of an inverter section which comprises six insulated gate bipolar transistors (IGBT) where the filtered DC supply is being converted into quasi-sinusoidal wave of AC supply which is supplied to the induction motor connected to it. It is known that the synchronous speed of an electric motor is dependent on the frequency. Therefore by varying the frequency of the power supply through VFD the speed of the motor can be controlled applications include centre winders and machine tools.

3.4.1 Constant V/F Ratio Operation

All Variable Frequency Drives 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 Φ of the motor are related by the equation:

$$V = 4.444\, f\, N\Phi m \qquad (3.20)$$

Or

$$V/f = 4.444 N\Phi m \qquad (3.21)$$

Where N = number of stator turns per phase.

Φm = magnetic flux

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 Φm 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.

3.5How 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 as shown in Figure 3.9 below. Diode Bridge is used in some converters to reduce harmonics. PWM produces a current waveform that more closely matches the line source, which reduces undesired heating. PWM drive has almost constant power factor at all speeds which is close to unity. PWM units can also operate multiple motor on a single drive. Thus the carrier frequency is derived from the speed of the power device switch remains ON and OFF drive. It is also called switch frequency. The higher the carrier frequency of the power line, the higher the resolution of the pulse width modulation. The typical carrier frequency ranges from 3 to 4 KHz or 3000 to 4000 cycles per second as compared with older SCR based carrier frequency which ranges from 250 to 500 cycles per second. Thus it is clear that the higher the carrier frequency the higher will be the resolution of output waveform.

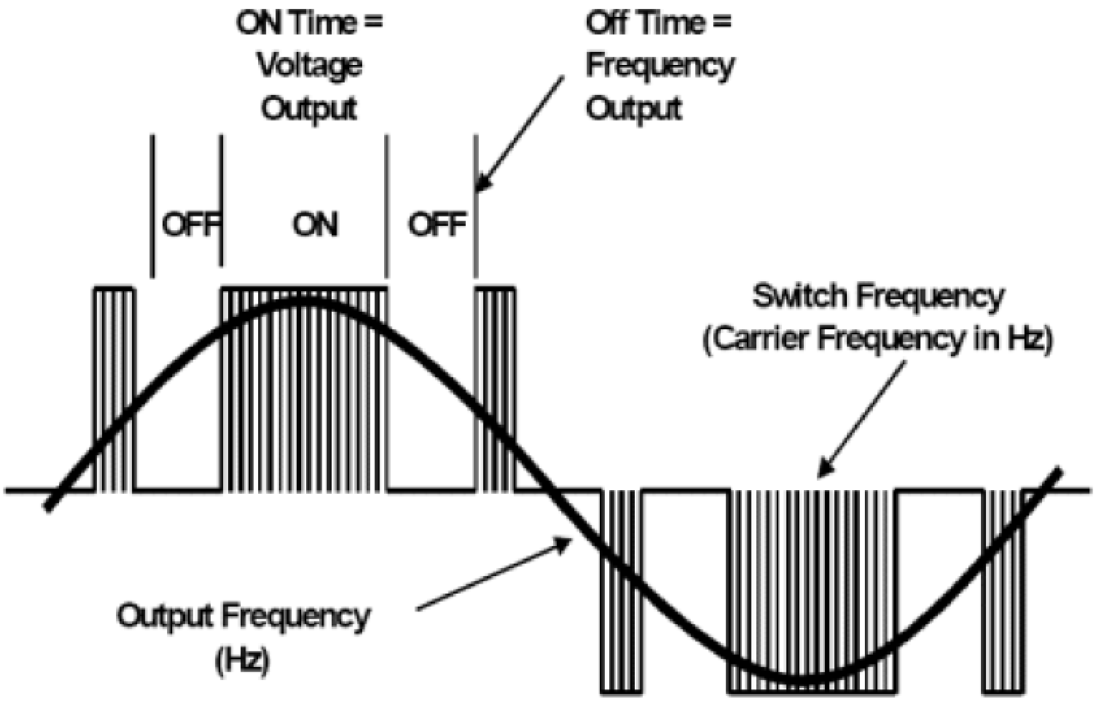

Figure 3.9: Drive output waveform of pulse width modulator

3.6Mathematicalmodeling of three phase voltage source

The three phase voltage source is the provider of AC three phase voltages with constant frequency of ωe which puts LC filtered three phase voltages on induction motor stator and is modeled using (3.18) to (3.20)

$V_{as} = V_m COS \omega_e t$ (3.22)

$$V_{bs} = V_m COS(\omega_e t + \theta) \tag{3.23}$$

$$V_{cs} = V_m COS(\omega_e t - \theta) \tag{3.24}$$

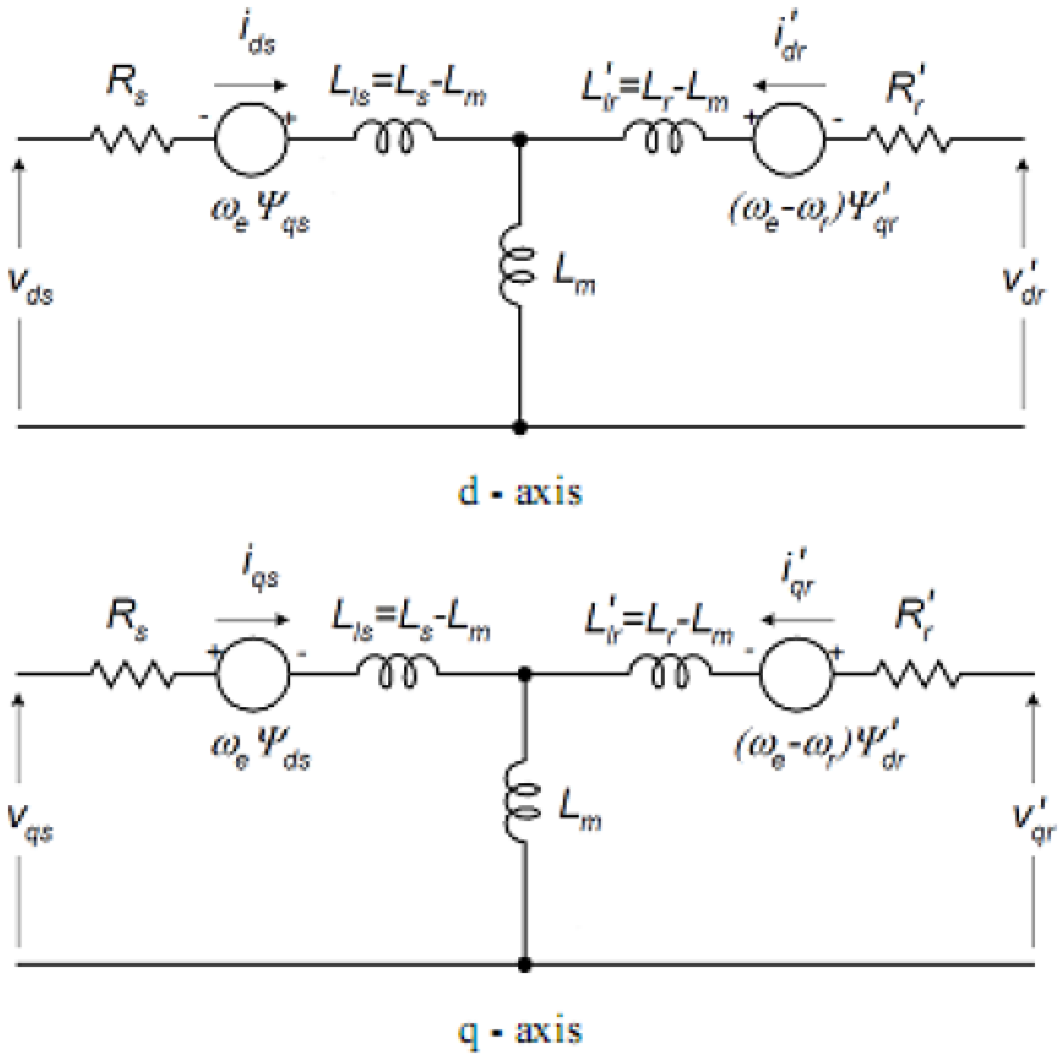

Figure 3.10: Induction motor equivalent d-q-o circuit diagram

3.6.1Model of the induction motor

The three phase induction motor works as a converter of electrical energy to mechanical energy that exerts the electromagnetic torque to the load. The induction motor is modeled using transformation of fixed ABC coordinates to rotating d-q-o coordinates. The three phase induction motor model maybe formulated as mentioned in the equations below. From the above diagram the following equations are obtained for the flux;

$$\varphi_{qs} = L_s i_{qs} + L_m i'_{qr} \quad (3.25)$$

$$\varphi_{ds} = L_s i_{ds} + L_m i'_{dr} \quad (3.26)$$

$$\varphi_{qr} = L'_r i_{qr} + L_m i_{qs} \quad (3.27)$$

$$\varphi_{dr} = L'_r i_{dr} + L_m i_{ds} \quad (3.28)$$

Where $L_s = L_{is} + L_m$ (3.29)

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_e \varphi_{ds} \quad (3.30)$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_e \varphi_{qs} \quad (3.31)$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1Introduction

The simulation and analysis for the variable speed drive done via Matlab-simulink ,Voltage and frequency input to induction motor are to be controlled to achieve desired speed response.

From the collected data all parameters were entered for the simulation.

Analysis results of voltage, stator current, electromagnetic torque , rotor speed and total harmonic distortion (THD) For a 220v(RMS),50Hz, 3HP,1080 rpm induction motor are showed in graphs.

4.2Induction machine (squirrel cage)

The induction Machine Squirrel Cage (fundamental) block models a squirrel-cage-rotor induction machine with parameterization using fundamental parameters. A squirrel-cage-rotor is a type of induction machine.

4.2.1Electrical Defining Equations

The induction machine equations are expressed with respect to a synchronous reference frame, defined by

$$\theta_e(t) = \int_0^t 2\pi frated dt (4.1)$$

*Where frated*is the value of the Rated electrical frequency. Park's transformation maps stator equations to a reference frame that is stationary with respect to the rated electrical frequency. Park's transformation is defined by

$$p_s = \frac{2}{3}\begin{bmatrix} cos\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos(\theta_e + \frac{2\pi}{3}) \\ -sin\theta_e & -\sin\left(\theta_e - \frac{2\pi}{3}\right) & -\sin(\theta_e + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (4.2)$$

The electrical angle is θe .Park's transformation is used to define the per-unit induction machine equations. The stator voltage equations are defined by

$$v_{ds} = \frac{1}{\omega_{base}}\frac{d\Psi_{ds}}{dt} - \omega\Psi_{qs} + R_s i_{ds} \quad (4.3)$$

$$v_{qs} = \frac{1}{\omega_{base}}\frac{d\Psi_{ds}}{dt} - \omega\Psi_{ds} + R_s i_{qs} \quad (4.4)$$

And

$$v_{0s} = \frac{1}{\omega_{base}}\frac{d\Psi_{ds}}{dt} + R_s i_{0s} \quad (4.5)$$

Where:

vds, *vqs*, and *v0s* are the d-axis, q-axis, and zero-sequence stator voltages, defined by

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} = p_s \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (4.6)$$

Where$i$, and$ic$are the stator currents.

The rotor voltage equations are defined by

$$v_{dr} = \frac{1}{\omega_{base}}\frac{\alpha\Psi_{\mathrm{dr}}}{dt} - (\omega - \omega_r)\Psi_{\mathrm{qr}} + \mathrm{R_{rd}}\mathrm{i_{dr}} = 0 \quad (4.7)$$

And

$$v_{qr} = \frac{1}{\omega_{base}}\frac{\alpha\Psi_{\mathrm{dr}}}{dt} - (\omega - \omega_r)\Psi_{\mathrm{dr}} + \mathrm{R_{rd}}\mathrm{i_{dr}} = 0 \quad (4.8)$$

Where:

- vdr and *vqr* are the d-axis and q-axis rotor voltages.
- φdr and *ψqr* are the d-axis and q-axis rotor flux linkages.
- *ω* is the per-unit synchronous speed. For a synchronous reference frame, the value is 1.
- *ωr* is the per-unit mechanical rotational speed.
- *Rrd* is the rotor resistance referred to the stator.
- *Idr* and *iqr* are the d-axis and q-axis rotor currents.

The stator flux linkage equations are defined by

$$\Psi_{ds} = L_{ss}i_{ds} + L_m i_{dr} \quad (4.9)$$

$$\Psi_{qs} = L_{ss}i_{qs} + L_m i_{qr} \quad (4.10)$$

And

$$\Psi_{0s} = L_{ss}i_{0s} \quad (4.11)$$

And

Where *Lss*is the stator self-inductance and*Lm*is the magnetizing inductance. The rotor flux linkage equations are defined by

$$\Psi_{dr} = L_{rrd}i_{dr} + L_m i_{ds} \quad (4.12)$$

The stator self-inductance Lss, stator leakage inductance Lls, and magnetizing inductance Lm are related by

$$L_{ss} = L_{ls} + L_m \quad (4.13)$$

The rotor self-inductance Lrrd, rotor leakage inductance Llrd, and magnetizing inductance Lm are related by

$$L_{rrd} = L_{lrd} + L_m \quad (4.14)$$

Table 4.1 induction machine parameters (initial values)

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

Stator resistance and inductance, rotor resistance and inductance are chosen to have smallest values possible to minimize current mitigation. The number of pole pairs is chosen to be two to implement a 4 pole motor. Setting the nominal power to 3*746 VA and the nominal line-to-line voltage Vnto 220 Vrms implements a 3 HP, 50 Hz machine with two pairs of poles. Its nominal speed is therefore slightly lower than the synchronous speed of 1800 rpm, or ws= 188.5 rad/s. These are the initial conditions on starting of motor load.

4.3Universal bridge

The Universal Bridge block implements a universal three-phase power converter that consists of up to six power switches connected in a bridge configuration. The Universal Bridge block allows simulation of converters using both naturally commutated (and line-commutated) power electronic devices (diodes or thyristors) and forced-commutated devices (GTO, IGBT, and MOSFET).The Universal Bridge block is the basic block for building two-level voltage-sourced converters (VSC).The device numbering is different if the power electronic devices are naturally commutated or forced-commutated. For a naturally commutated three- phase converter (diode and thyristor), numbering follows the natural order of commutation

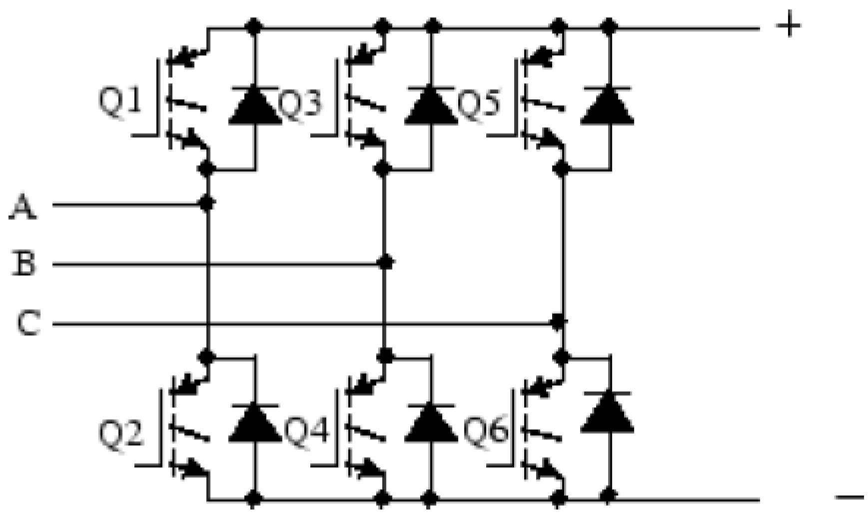

Figure4.1:IGBT-Diode Bridge

4.3.1Number of bridge arms

Set to 1 or 2 to get a single-phase converter (two or four switching devices). Set to 3 to get a three-phase converter connected in Graetz bridge configuration (six switching devices).For our case, this is set to 3 as three phase supply voltage is being fed into the converter.

4.3.2 Snubber resistance Rs

The snubber resistance is in ohms (Ω). Set the Snubber resistance Rs parameter to inf to eliminate the snubbers from the model. Snubber is eliminated to

4.3.3Snubber capacitance Cs

The snubber capacitance is in farads (F). Set the Snubber capacitance Cs parameter to 0 to eliminate the snubbers, or to inf to get a resistive snubber.In order to avoid numerical oscillations when your system is discretized, you need to specify Rs and Cs snubber values for diode and thyristor bridges. For forced-commutated devices (GTO, IGBT, or MOSFET), the bridge operates satisfactorily with purely resistive snubbers as long as firing pulses are sent to switching devices. If firing pulses to forced-commutated devices are blocked, only ant parallel diodes operate, and the bridge operates as a diode rectifier.

In this condition appropriate values of Rs and Cs must also be used. For a discretized system,

$$R_s > 2\frac{T_s}{C_s}$$

$$C_s < \frac{P_s}{1000(2\pi f)V_n^2}$$

Where

- pn =nominal power of single or three phase converter (VA) Vn= nominal line-to-line AC voltage (*V*rms) f = fundamental frequency (Hz) Ts = sample time (s)
- These Rs and Cs values are derived from the following two criteria:
- The snubber leakage current at fundamental frequency is less than 0.1% of nominal current when power electronic devices are not conducting.

- The RC time constant of snubbers is higher than two times the sample time Ts. These Rs and Cs values that guarantee numerical stability of the discretized bridge can be different from actual values used in a physical circuit.

4.4Power electronic device

When you select Switching-function based VSC, a switching-function voltage source converter type equivalent model is used, where switches are replaced by two voltage sources on the AC side and a current source on the DC side. This model uses the same firing pulses as for other power electronic devices and it correctly represents harmonics normally generated by the bridge

1) Ron

It is the internal resistance of the selected device, in ohms (Ω).

2) Lon

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

3) Forward voltage Vf

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

Forward voltages [Device Vf, Diode Vfd]

This parameter is available when the selected Power electronic device is GTO/Diodes or IGBT/Diodes. Forward voltages which are in volts (V), of the forced-commutated devices (GTO, MOSFET, or IGBT) and of the anti-parallel diodes.

[Tf (s) Tt (s)]

Fall time Tf and tail time Tt are in seconds (s), for the GTO or the IGBT devices.

Measurements

Select Device voltages to measure the voltages across the six power electronic device terminals. Select Device currents to measure the currents flowing through the six power electronic devices. If anti parallel diodes are used, the measured current is the total current in the forced-commutated device (GTO, MOSFET, or IGBT) and in the anti parallel diode.

Table 4.2: Universal bridge parameters

Power electronic device	IGBT/Diodes	
Snubber		
	Rs	1e5 Ω
	Cs	inf
	Ron	1e-3 Ω
Forward voltages		

	Vf	0V
	Vfd	0V
Tail		
	Tf	1e-6 s
	Tt	1e-6 s

Notice that the snubber circuit is integral to the Universal Bridge dialog box. As the Cs capacitor value of the snubber is set to Inf (short-circuit), we are using a purely resistive snubber. Generally, IGBT bridges do not use snubbers; however, because each nonlinear element in SimPowerSystems™ software is modeled as a current source, you have to provide a parallel path across each IGBT to allow connection to an inductive circuit (stator of the induction machine). The high resistance value of the snubber does not affect the circuit performance.

4) Pulse Width Generator

The PWM Generator (2-Level) block generates pulses for carrier-based pulse width modulation (PWM) converters using two-level topology. The block can control switching devices (FETs, GTOs, or IGBTs) of three different converter types: single-phase half-bridge (1 arm), single-phase full-bridge (2 arms), or three-phase bridge (3 arms).The reference signals (Uref input), also called modulating signal, is naturally sampled and compared with a symmetrical triangle carrier. When the reference signal is greater than the carrier, the pulse for the upper switching device is high (1) and the pulse for the lower device is low (0).The figure shown below shows the pulse generation for a single-phase half-bridge converter. In this case, one reference signal is required to generate the two pulses. For a single-phase full-bridge, a second reference signal is required to generate the two pulses of the second arm. This signal is internally generated by phase-shifting the original reference signal by180 degrees. For a three-phase bridge, three reference signals are required to generate the six pulses. The reference signals can also be internally generated by the PWM generator. In this case, specify a modulation index, a voltage output frequency, and phase.

5) Generator type

Specify the number of pulses to generate. The number of pulses generated by the block is proportional to the number of bridge arms to fire. Select Single-phase half-bridge (2 pulses) to fire the self-commutated devices of a single-phase half-bridge converter. Pulse 1 fires the upper device, and pulse 2 fires the lower device.

Select Single-phase full-bridge (4 pulses) to fire the self-commutated devices of a single-phase full-bridge converter. Four pulses are then generated. Pulses used are 1 and 3and this fire the upper devices of the first and second arm. Pulses 2 and 4 fire the lower devices.

Select Three-phase-bridge (6 pulses) to fire the self-commutated devices of a three-phase bridge converter. Pulses 1, 3, and 5 fire the upper devices of the first, second, and third arms. Pulses 2, 4, and 6 fire the lower devices.

6) Mode of operation

When set to Unsynchronized, the frequency of the unsynchronized carrier signal is determined by the Carrier frequency parameter.

When this is set to Synchronized, the carrier signal is synchronized to an external reference signal (input wt) and the carrier frequency is determined by the Switching ratio parameter.

7) Carrier frequency (Hz)

Specify the frequency, in hertz, of the triangular carrier signal. This parameter is visible only if the Mode of operation parameter is set to Un-synchronized.

Switching ratio (carrier frequency/output frequency)

Specify the frequency (Fc) of the triangular carrier signal.

$$F_c = SwitchingRatio \times Output\ Voltage\ Frequency \tag{4.15}$$

This parameter is visible only if the Mode of operation parameter is set to Synchronized.

8) Internal generation of modulating signal (s)

When selected, the reference signal is generated by the block.

When not selected, the external reference signals are used for pulse generation.

The parameter is visible only if the Mode of operation parameter is set to Unsynchronized.

9) Modulation index

Specify the modulation index to control the amplitude of the fundamental component of the output voltage of the converter. The modulation index must be greater than 0 and lower than or equal to 1. The parameter is visible only when the internal generation of modulating signal (s) parameter is selected.

10) Output voltage frequency (Hz)

Specify the output voltage frequency used to control the frequency of the fundamental component of the output voltage of the converter. The parameter is visible only when the internal generation of modulating signal (s) parameter is selected.

Output voltage phase (degrees)

Specify this parameter to control the phase of the fundamental component of the output voltage of the converter. The parameter is visible only when the internal generation of modulating signal (s) parameter is selected.

Sample time

Specify the sample time of the block, in seconds. Set to 0 to implement a continuous block.

11) Inputs and Outputs

Uref

The vectorized reference signal used to generate the output pulses. The input is visible only when the internal generation of modulating signal (s) is not selected. Connect this input to a single-phase sinusoidal signal when the block is used to control a single-phase half- or full-bridge converter or to a three-phase sinusoidal signal when the PWM Generator block is controlling a three-phase bridge converter. For linear operation of this block, the magnitude of Uref must be between −1 and +1.

The output contains the two, four, or six pulse signals used to fire the self-commutated devices (MOSFETs, GTOs, or IGBTs) of a one-, two- or three-arm converter.

Table 4.3: Pulse width generator parameters (initial)

Generator type	Three-phase bridge (6 pulses)
Mode of operation	Unsynchronized
Carrier frequency	1080 Hz
Internal generation of modulating signals	Selected
Modulation index m	0.9
Output voltage frequency	50 HZ
Output voltage phase	
Sample time	10e-6 s

The block has been discretized so that the pulses change at multiples of the specified time step. A time step of 10 μs corresponds to +/- 0.54% of the switching period at 1080 Hz.

One common method of generating the PWM pulses uses comparison of the output voltage to synthesize (50 Hz in this case) with a triangular wave at the switching frequency (1080 Hz in this case). The line-to-line RMS output voltage is a function of the DC input voltage and of the modulation index *m* as given by the following equation:

$$V_{LLrms} = \frac{m}{2} \times \frac{\sqrt{3}}{\sqrt{2}}\, Vdc = m \times 0.612 \times VDC \qquad (4.16)$$

Therefore, a DC voltage of 400 V and a modulation factor of 0.90 yield the 220 VRMS output line-to-line voltage, which is the nominal voltage of the induction motor (these are initial conditions).

The PWM generator is used to control the inverter bridge. In this case, the converter operates in an open loop and the three PWM modulating signals are generated internally.

4.5Loading and Driving the Motor

You now implement the torque-speed characteristic of the motor load. Assume a quadratic torque-speed characteristic (fan or pump type load). The torque *T* is then proportional to the square of the speed ω.

$T = k \times \omega^2$(4.17)

The nominal torque of the motor is

$$T_n = \frac{3 \times 746}{188.5} = 11.87\ Nm$$

Therefore, the constant *k* should be

$$k = \frac{T_n}{\omega^2} = \frac{11.87}{188.5} = 3.34 \times 10^{-4}$$

A function bock is added to the circuit to show the relationship between speed and torque. The input of the function block is connected to the torque input of the motor. The expression of torque as a function of speed: 3.34e-4*u^2 is entered into the function block (initial conditions).

A dc voltage source of magnitude 400v is connected to the circuit to supply voltage to the circuit. A voltage measurement is also added to measure the output voltage. The circuit used for simulation and analysis of a variable speed drive is as shown Figure 4.2 below.

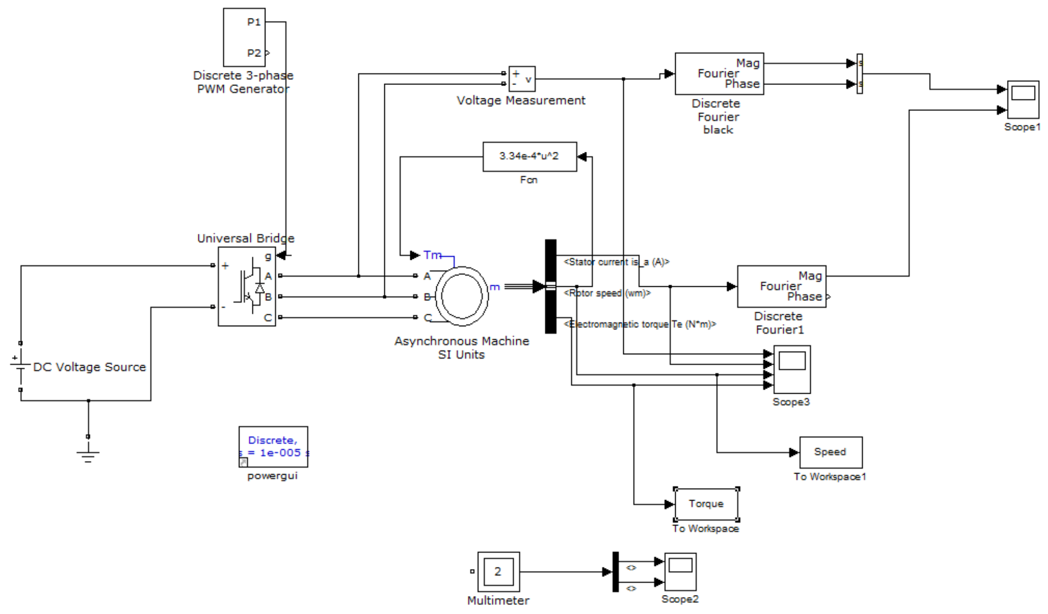

Figure 4.2: Simulation and analysis of variable speed drive circuit

4.6Simulation results

The results from MATLAB software are shown in tables and figures below

Table 4.4: Torque for a 400v.1050Hz input

Time	Torque
0.999730000000000	10.007232736903400
0.999760000000000	9.291072220521810
0.999790000000000	8.578196386658170
0.999820000000000	7.868655068124060
0.999850000000000	7.439017408130450
0.999880000000000	7.570809354487260
0.999910000000000	7.713297536565450
0.999940000000000	7.866246715416920
0.999970000000000	8.029420720703640
1	8.202582511256510

Table 4.5: Speed output for a 400v, 1050Hz input

Time	Speed
0.999730000000000	1.517671390513560e+02
0.999760000000000	1.517689422362604e+02
0.999790000000000	1.517696725848997e+02
0.999820000000000	1.517693352214486e+02
0.999850000000000	1.517679353435381e+02
0.999880000000000	1.517663094131860e+02
0.999910000000000	1.517648867955396e+02
0.999940000000000	1.517636833839105e+02
0.999970000000000	1.517627147157452e+02
1	1.517619959713156e+02

Table 4.6: Torque for a 400v.3000Hz input

Time	Torque
0.999730000000000	10.499005857717590
0.999760000000000	10.447950008945808
0.999790000000000	10.064286788922900
0.999820000000000	10.334611876661333
0.999850000000000	10.595737872477885
0.999880000000000	10.697301162778754
0.999910000000000	10.809575687539521
0.999940000000000	10.094275443158406
0.999970000000000	9.945414775734694
1	10.087128201166658

For input 400v, 6000HZ carrier input , 60HZ output figures is shown below

Figure 4.3 shows the stator current signal in first graph , fundamental frequency (60HZ) and total harmonic distortion (THD) in the second graph.(for 400v, 6000HZ carrier input, 60HZ output)

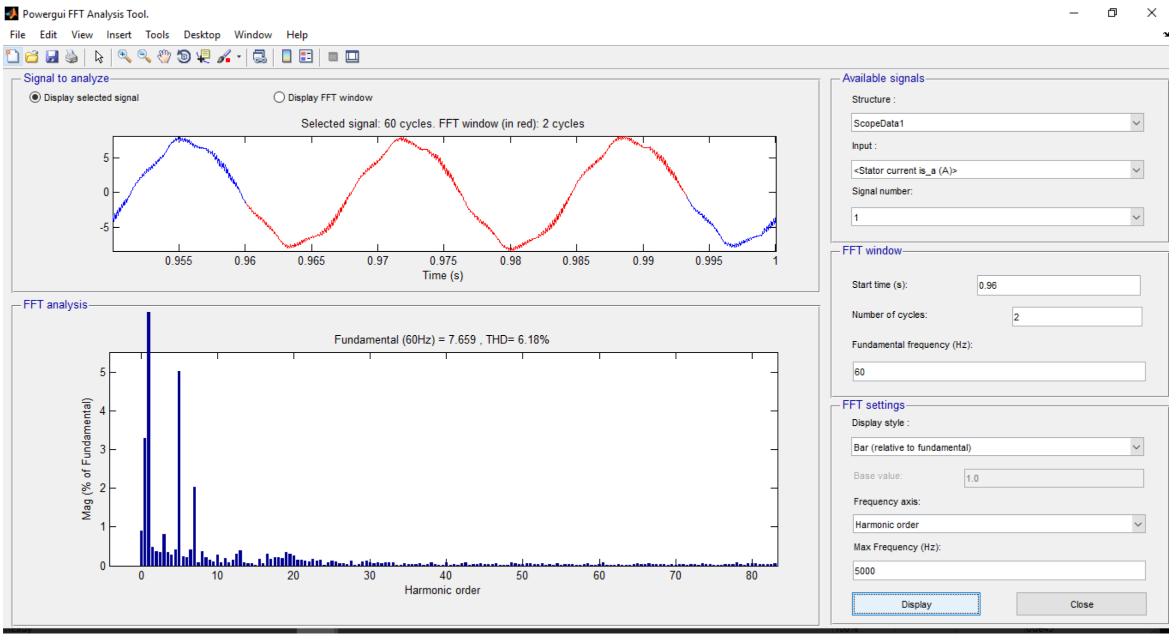

Figure 4.3: Present the FFT analysis and total harmonic distortion

Figure 4.4 shows the bridge current signal in first graph, fundamental frequency (60HZ) and THD in second one.(for 400v, 6000HZ carrier input, 60HZ output)

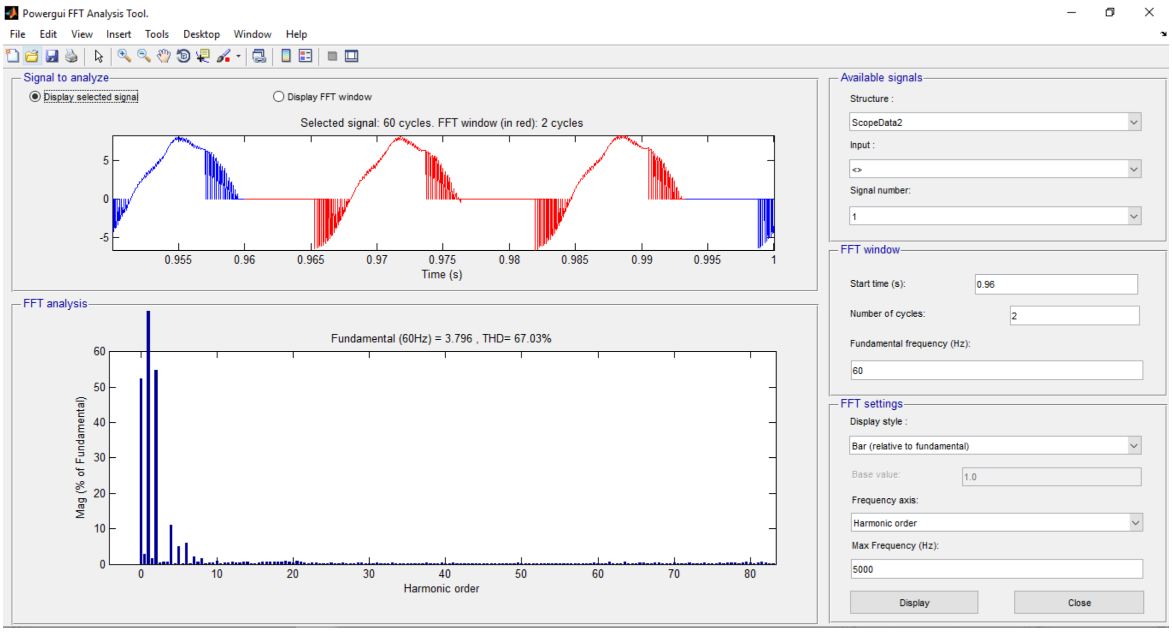

Figure 4.4: FFT analysis and total harmonic distortion

Figure 4.5 shows the voltage , stator current , electromagnetic torque and rotor speed.(for 400v, 6000HZ carrier input, 60HZ output)

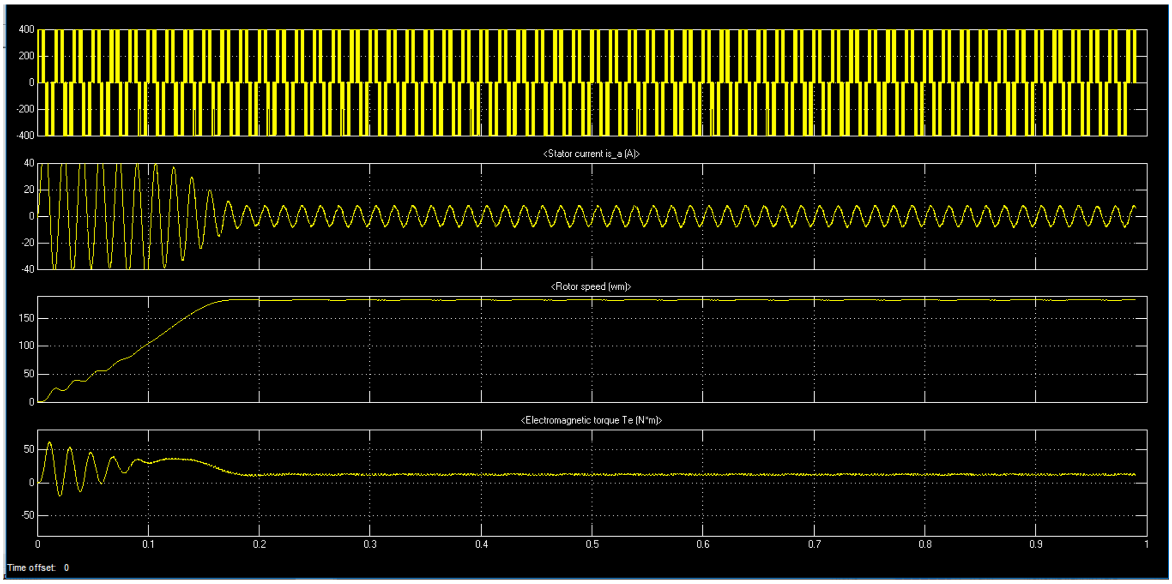

Figure 4.5:Present scope 3

Figure 4.6 shows the full bridge inverter currents for two switches.(for 400v, 6000HZ input, 60HZ)

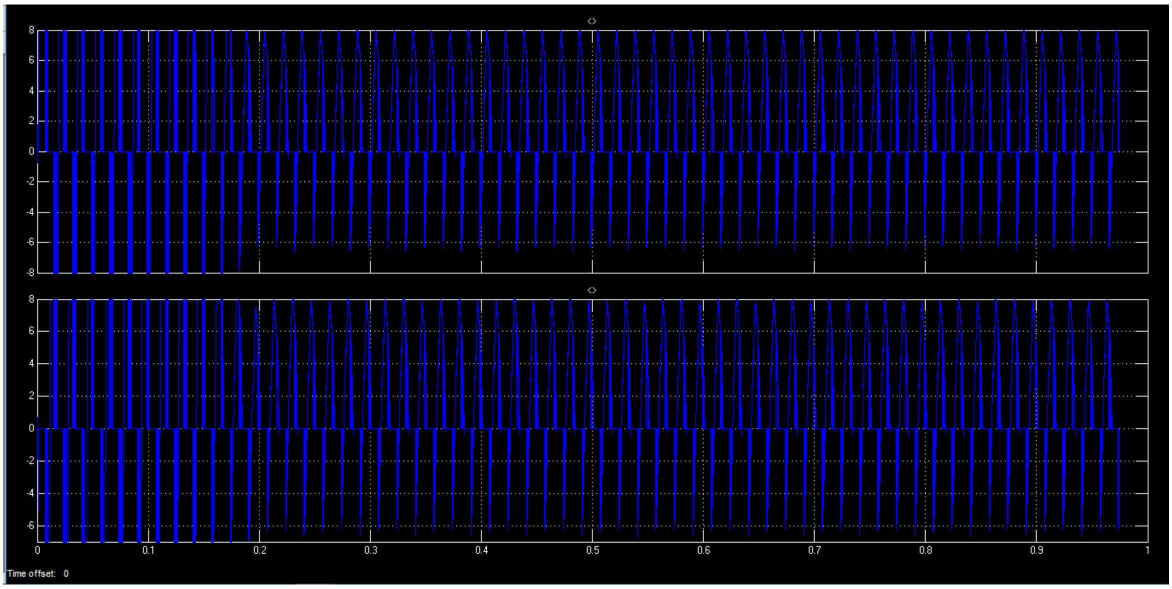

Figure 4.6: Present Scope 2

Figure 4.7 shows voltage , current magnitude and phase respectively

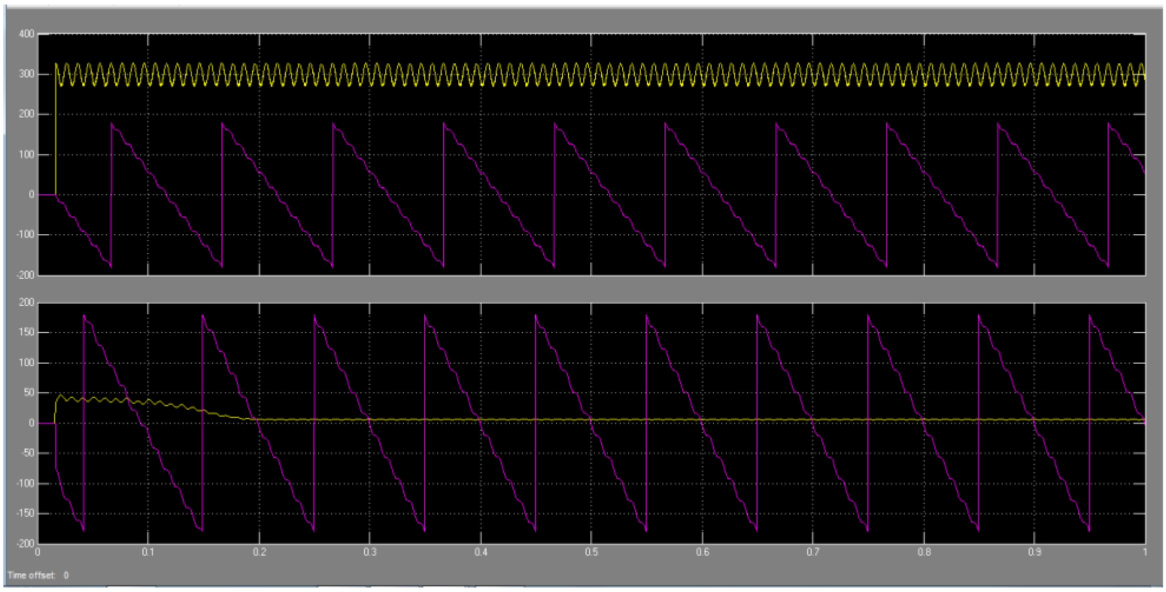

Figure 4.7:Present Scope 1

For input 200v, 6000HZ carrier input , 30HZ output figures is shown below

Figure 4.8 shows the stator current signal in first graph , fundamental frequency (60HZ) and total harmonic distortion (THD) in the second graph.(for 200v, 6000HZ carrier input, 30HZ output)

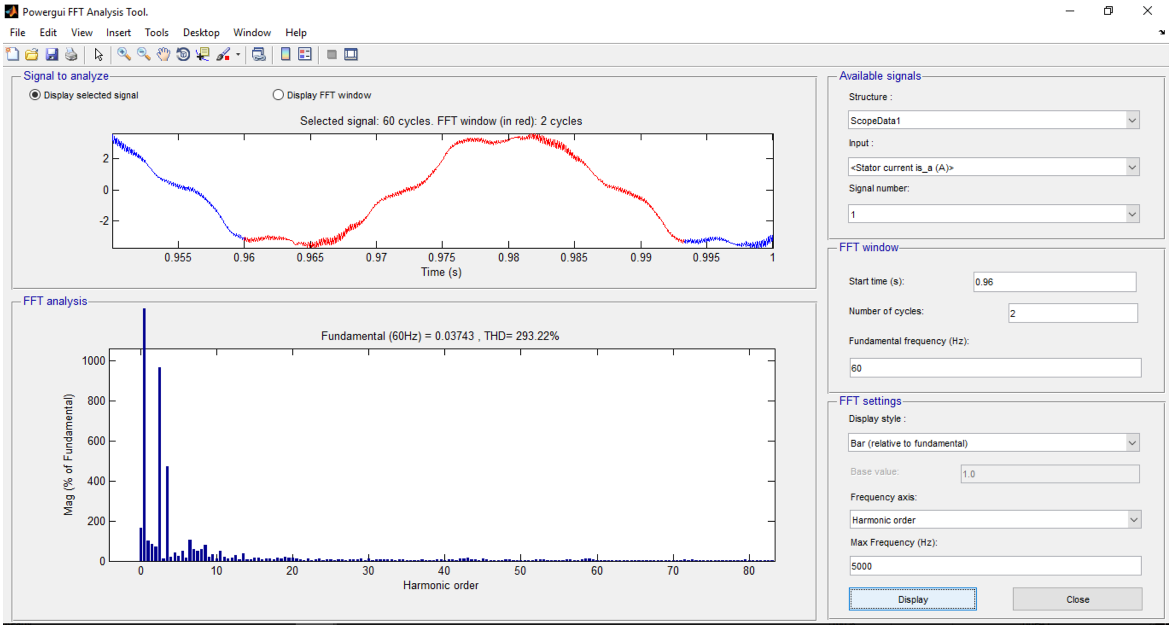

Figure 4.8: Present the FFT analysis and total harmonic distortion

Figure 4.9 shows the bridge current signal in first graph, fundamental frequency (60HZ) and THD in second one.(for 200v, 6000HZ carrier input, 30HZ output)

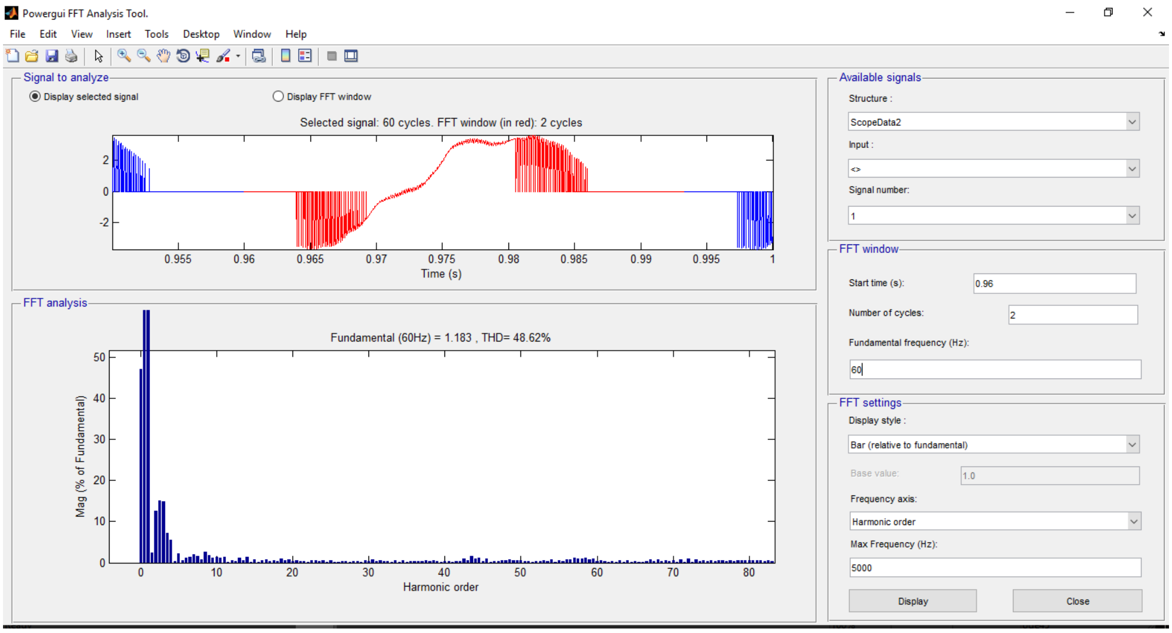

Figure 4.9: FFT analysis and total harmonic distortion

Figure 4.10 shows the voltage , stator current , electromagnetic torque and rotor speed.for(400v, 3000HZ input)

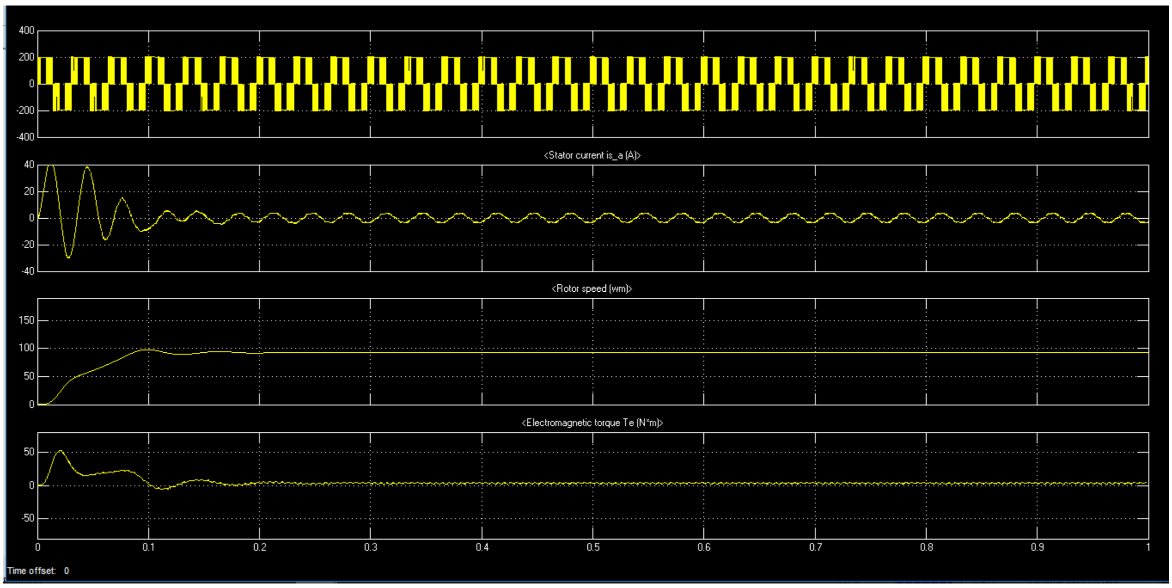

Figure 4.10:Present scope 3

Figure 4.11 shows the full bridge inverter currents for two switches, (for 200v, 6000HZ carrier input, 30HZ output)

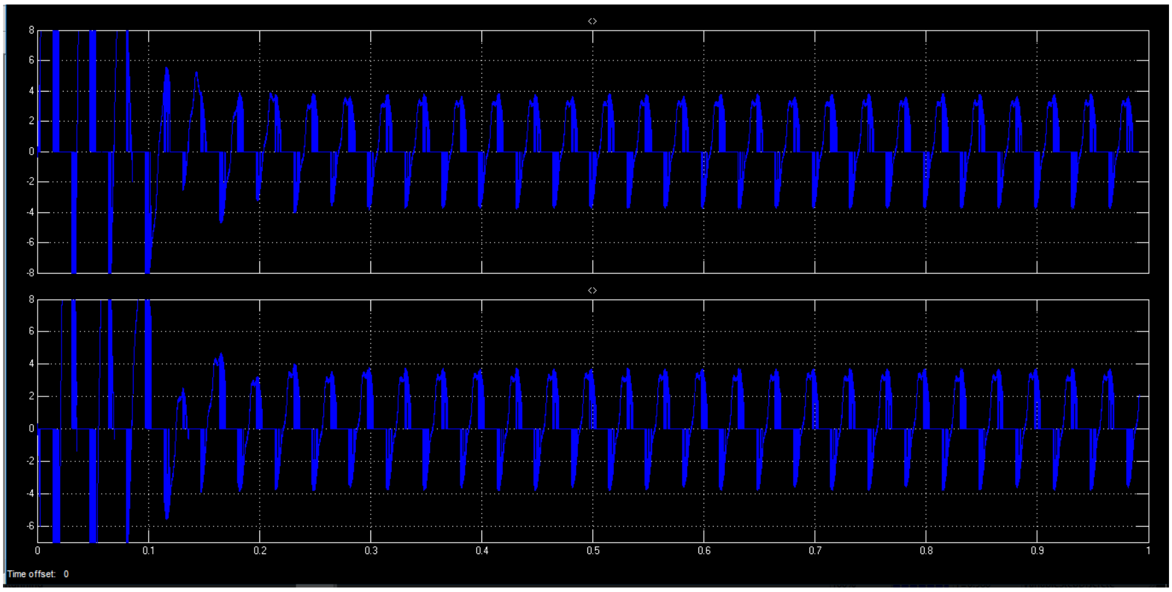

Figure 4.11: Present Scope 2

From analysis result it is obvious that, increase frequency result in speed increase.The voltage is increased by increasing modulation index.Power being equal to speed cubed for variable torque load, reduces total power consumption of motor.

Electromagnetic torque, rotor speed and stator current are high and sinusoidal during starting of motor. They then maintain a certain magnitude after a few seconds. There is a variation between the first(1080HZ) and second(3000Hz) simulation. Torque ripples are reduced as motor moves from starting to running state

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1Conclusion

The speed and frequency control of AC three phase induction motor using variable speed drive is designed and simulated , the effect of frequency on the induction motor for the torque and power consumption is analyzed.

It is obvious that variable frequency drive is the best solution for fixing inherent motor issues and energy saving can be best tackled by this drive. Other techniques like Soft starter does not prove as much efficient as does variable frequency drive because there are many benefits of variable frequency drive like it provides a control over motor starting and stopping, Likewise it gives versatility to motor action. Over load protection, power reduction when not needed and dynamic torque control are other key features of variable frequency drives.

5.2Recommendations

We can suggest that in a country like Sudan this device is of great use because we strongly need energy consumption minimization and for that matter VFD should be used with HVAC systems in industries and house hold appliances. The only drawback associated with this device is cost. It’s quite costly and maintenance is also required. But still the importance of variable frequency drive cannot be denied.

5.3 Reference

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APPENDIXS

APPENDIX (A.1)

VSD with optional control panels

Image courtesy of Siemens

APPENDIX (A.2)

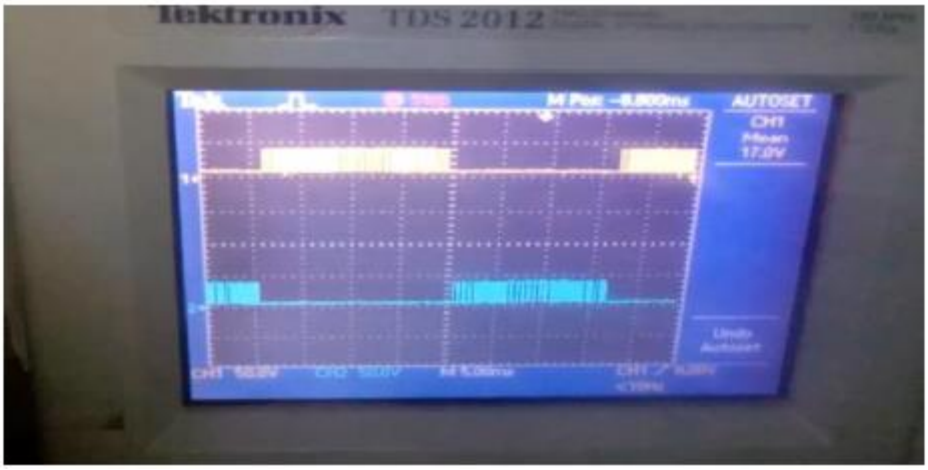
Large VSD mounted in ventilated enclosure

APPENDIX (B.1)

Hardware Results of PWM

APPENDIX (B.2)

Dead time Representation in PWM wave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