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SIMULATION AND ANALYSIS OF A VARIABLE SPEED DRIVE

MATLAB/SIMULINK METHOD

PROJECT INDEX: 109

BY

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DEDICATION

This project is dedicated to my Dear family starting from my father and mother for believing in me and giving me all the support and encouragement throughout the course and my sisters and brothers for being the best supportive people.

ACKNOWLEDGEMENT

First and foremost, I would like to give my thanks to God for the provision of life health and energy to be able to fulfill my dreams to this level.

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An entailed project like this would never have been attempted without reference to and inspiration from the works of others whose details are mentioned in reference section, my acknowledgements extends to them as well. My classmates, I salute you all.

ABSTRACT

Induction motors are widely used in many industrial processes due to their rigid nature, reliability and robustness. However, induction motors have fixed speed limiting them from being used in other processes. Available speed control techniques such as variation of supply voltage, variation of number of poles, variation of motor resistance, constant V/F ratio control and slip recovery method are some of the methods of speed control characterized by low efficiency and high maintenance cost. Improvement in power electronics technology though advancements in semiconductor electronic devices have led to development of variable frequency motor drive, an electronic device used to control speed of an induction motor with increased efficiency, reliability and low cost. This paper seeks to carry out modeling, simulation and performance analysis of a variable frequency drive using MATLAB/SIMULINK model. Control of speed of induction motor was successfully achieved from zero to nominal speed by varying frequency of applied AC voltage using pulse width modulation method.

Contents

List of figures

List of tables

Abbreviations

IGBT-Insulated gate bipolar transistor

PWM-Pulse width modulation

IFOC-Indirect field oriented control

FOC-Field oriented control

VFD-Variable frequency drive

VSD-Variable speed drive

CHAPTER ONE

INTRODUCTION

Background of study

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. A variable frequency drive (VFD) also referred to as a variable speed drive is a type of system through which speed of an induction motor can be varied. A VFD makes use of electrical motor hence referred to as electric drives. This controls speed of electric machine by converting frequency of grid to adjustable value on machine side hence allowing electrical motors to quickly and easily adjust its speed. In these, various sensors and control algorithms is done to control speed using suitable speed control techniques and in this case varying the frequency using the pulse width modulation(PWM) inverter. The basic block diagram of a VFD is shown below in fig 1.1.

Two major functions of the VFD are;

- Provide power conversion from one frequency to another.
- Enable control of output frequency.

Variable frequency drives are used in many applications ranging from smallest to largest of industrial appliances. These include mining industries, compressors, and ventilation systems for large buildings, fans, pumps, conveyors and machine tools. VFDs can be classified as:

- Ac Variable frequency drives
- Current source input VFD
- Pulse width modulated VFD
- Flux vector pulse width VFD

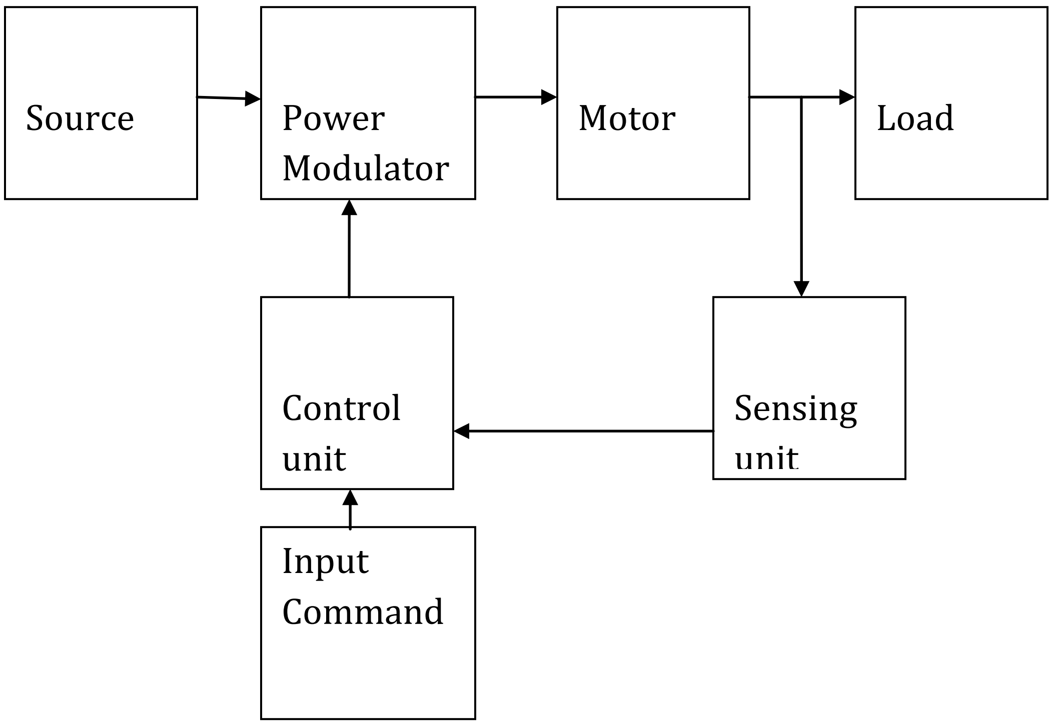


Figure1.1: Block diagram of an electrical drive.

Project Objectives

The main objective is to simulate and analyze a variable speed drive with respect to power consumption in pumping and related activities. Voltage and frequency input to induction motor are to be controlled to achieve desired speed response.
Present methodology used to simulate and analyze a variable frequency drive.

Specific objectives

To determine power consumption reduction in pumping and related activities through use of a variable frequency drive. In doing so

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

Scope of project

Scope of project includes simulating and analyzing a variable speed drive in relating to pumping mechanisms with the aim of power consumption reduction. This is formulated based on approach that speed=120f/p hence using mat lab to analyze power consumption taking into account parameter changes and the best method of speed control implemented in mat lab software.

Problem definition

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.

Justification of the project

- Demand for efficient, steady reliable energy is increasingly high with increasingly high speed requirements to boost economic development of the country.
- Investment, running and maintenance costs need to be kept as minimal as possible in any industrial application enabling future advancements in technology through savings made.

- Kenya is a hub for integration and economic development in East and Central Africa requiring constant supply of energy to keep it afloat with the competing market. This starts with energy savings in industrial applications through power savings. Energy is necessary in any country's economy for it to compete favorably in ever competitive world.

CHAPTER TWO

LITERATURE REVIEW

DRIVE 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

VSDs consist of three basic components;

- Electrical motor-connected directly or indirectly (through gears) to load.
- Power converter-controls power flow from an AC supply to motor by appropriate control of power semiconductor switches.
- Control system-for proper control systems, VSD system variables both electric and mechanical are needed for control and protection.

Advantages of Variable speed Drives

- Improved process control
  VSDs use in process control result in more efficient operating systems due to automation of systems.
- Reduced Mechanical stress
  Motors started on direct- on- line startup are associated with high in-rush current and poor power factor. It also increases stress on mechanical system.
  Use of VSDs improve operating conditions by giving smooth controlled startup and energy saving in running and startup, Benefits of these include; elimination of uncontrolled in-rush current, power wastage is eliminated and life of motor and driver machine are elongated.
- Improved Electrical System Power Factor
  Use of diode Supply Bridge for rectification, electrical VSDs operate at near unity power factor over the whole speed range, which is supply, delivers mostly real power.
  Modern PWM drives convert the three phase AC line voltage to a fixed-level DC voltage regardless of inverter output speed and power hence provide constant power factor regardless of power factor of load machine and controller installation configuration.

Disadvantages of VSDs

These include;

- Acoustic noise
- Motor de-rating
- Supply harmonics

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

- Premature motor insulation failure
- Bearing/earth current
- Electromagnetic compatibility

Acoustic 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.

Motor heating

Inverters used in large drives have limits on switching rates that can cause their output voltage to contain 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.

Supply 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.

Drives Requirements & Specifications

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

Drive 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.

Drive Classifications and Characteristics

Table 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 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 < 1 kW
• Low performance (2Q)	• Transistor	• AC/AC direct (cyclo- and matrix-converter)	• Induction motor (squirrel cage and wound rotor)	• Metal	• Low power (1 < P < 5 kW)
• High performance (4Q)	• Gate Turn-off Thyristor (GTO)	• AC/AC via a DC link Voltage source	• Synchronous motor	• Petrochemical	• Medium Power <500 kW
	• Integrated Gate Commutated Thyristor (IGCT)				
• Servo	• Insulated Gate Bipolar Transistor (IGBT)	• AC/AC via a DC link current source	• *Special motors:* SRM, BDCM, Stepper, Actuators, Linear motor	• Process industry	• High power 1-50 MW
	• MOSFET			• Mining	
				• Marine	

Classification by Applications

Under this classification there are four main groups:
• Appliances (white goods)
• General purpose drives

• System drives
• Servo drives

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. Figure 1 summarizes its key features.
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. The main features of cyclo-converters are listed in table 2 below.
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:

(a) The increased level of silicon employed (bi-directional switches),

(b) Its output voltage is always less than its input voltage

(c) 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.

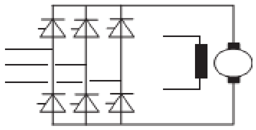
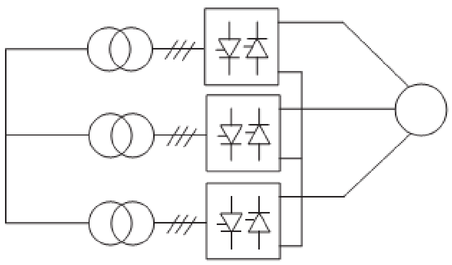
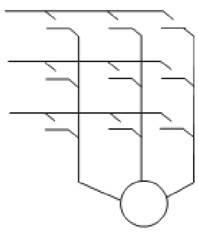
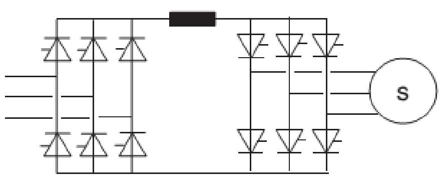
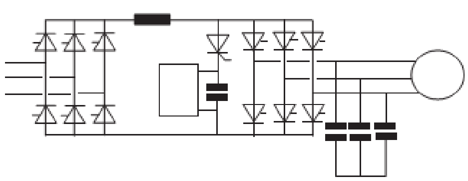
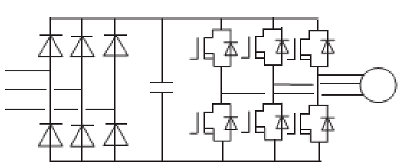
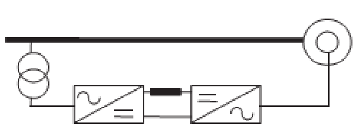
d) Load Commutated Inverter (LCI)

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.

Torque pulsations can be reduced in 12-pulse systems if required.

Table 2: Converter Topologies

Converter	Schematic	Features
(a) Controlled Rectifier		• DC motor • Fully controlled SCR converter • Controlled DC voltage • Simple converter topology • Power factor is a function of speed
(b) Cyclo		• Induction motor & synchronous motor • Direct AC/AC power conversion • 3 × 6-pulse SCR-based fully controlled converters – APT for fully regen • Natural commutation • Low supply harmonics, 18-pulse • Power factor is a function of speed
(c) Matrix		• Squirrel cage induction motor • Synchronous motor • Direct AC/AC power conversion • Forced commutated, reverse conducting switches • Four-quadrant operation inherent PWM in/PWM out • Controlled Power factor
(d) LCI		• Synchronous motor • Simple converter arrangement • Power factor is a function of speed • Load commutated SCRs • Synchronous motor requires excitation • Suffer from torque pulsation at low speeds
(e) FCI		• Squirrel cage induction motor • Similar to LCI • Requires output capacitors for commutation • Requires a diverter commutation circuit for commutation at low speeds • Torque pulsation and resonance
(f) VSI		• Synchronous and squirrel cage induction motors • 6-pulse diode front-end • Good Power factor across speed range • DC link voltage source • PWM output voltage
(g) Kramer		• Wound rotor induction motor with slip rings • Small energy recovery converter • Any type converter may be used between slip ring & AC input

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%.

Load Profiles and Characteristics

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

Load 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)

Motor 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.

Induction Motor Drive

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:

(a**) 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.

(b**) 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.

Within this range, the motor frequency is increased until, at maximum speed.

(c) **Machine Limit (Pullout Torque):**

Once the machine limit has been reached the torque falls off in proportion to the square of motor frequency. Operation at the higher end of this speed range may not be feasible as the motor power factor worsens. This in turn results in a higher stator current than the rated value.

The motor heating may be excessive unless the duty factor is low.

Induction motors are used in applications requiring fast and precise control of torque, speed, and shaft position.

The control method widely used in this type of application is known as Vector control, a transient response at least equivalent to that of a commutator motor can be achieved.

The voltage, current, and flux linkage variables in this circuit are space vectors from which the instantaneous values of the phase quantities can be obtained by projecting the space vector on three radial axes displaced 120 from each other. The real and imaginary components of the space vectors are separated, resulting in separate direct and quadrature axis equivalent circuits but with equal parameters in the two axes.

Changes in the rotor flux linkage can be made to occur only relatively slowly because of the large value of the magnetizing inductance of the induction motor. Vector control is based on keeping the magnitude of the instantaneous magnetizing current space vector constant so that the rotor flux linkage remains constant. The motor is supplied from an inverter that provides an instantaneously controlled set of phase currents that combine to form the space vector, which is controlled to have constant magnitude to maintain constant rotor flux linkage. The second component is a space vector, which is in space quadrature with the instantaneous magnetizing current space vector. This component is instantaneously controlled to be proportional to the demand torque.

To the extent that the inverter can supply instantaneous stator currents meeting these two requirements, the motor is capable of responding without time delay to a demand for torque. This feature, combined with the relatively low inertia of the induction motor rotor, makes this drive attractive for high-performance control systems.

Vector control requires a means of measuring or estimating the instantaneous magnitude and angle of the space vector of the rotor flux linkage. Direct measurement is generally not feasible. Rapid advances are being made in devising control configurations that use measured electrical terminal values for estimation.

MOTOR DRIVES

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.

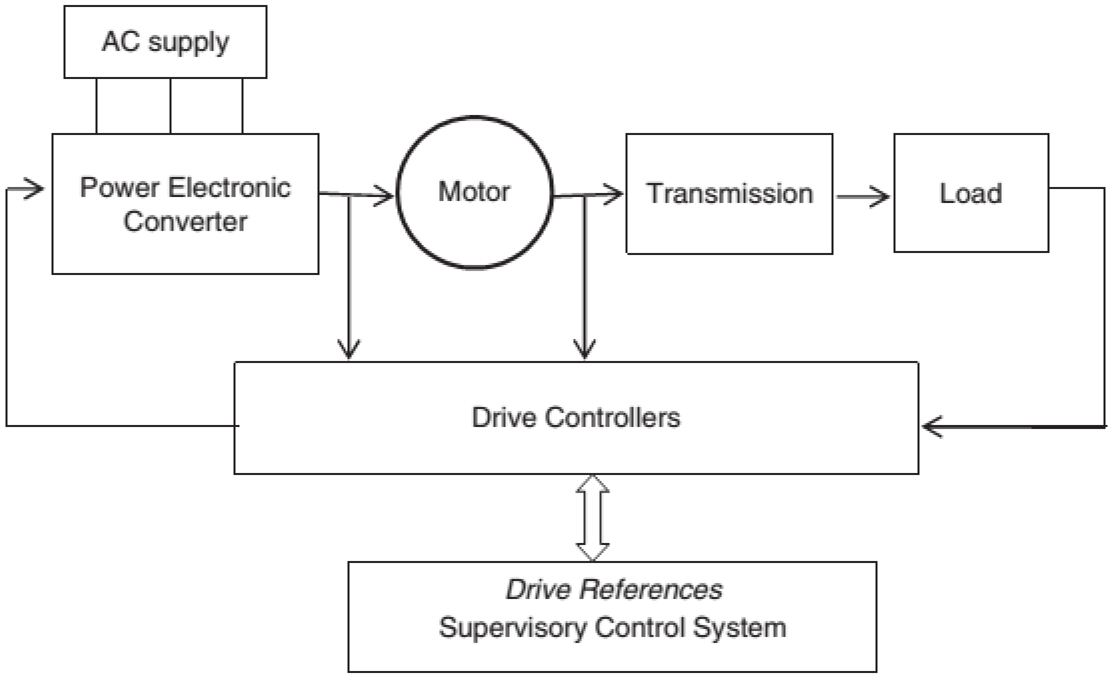


Figure 1: Block diagram of a typical motor-drive system

Steady 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 2 below.

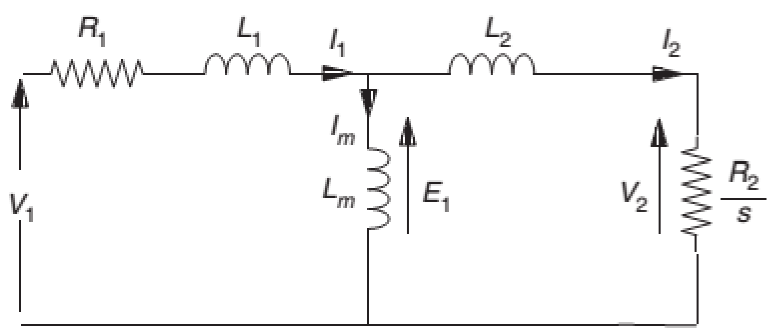


Figure 2; Steady state equivalent circuit of an induction motor

From this representation, the following power relationships in terms of motor parameters and the rotor slip can be found.
Power in rotor circuit,

$$P_2 = 3I_2^2\frac{R_2}{s}$$

$$= \frac{3sR_2E_1^2}{R_2^2 + (s\omega_1 L_2)^2}$$

,

Output power, $P_o = P_2 - 3I_2^2R_2 = (1-s)P_2$

$$= \omega_0 T = \frac{(1-s)\omega_1}{P}T$$

where

slip, $s = \dfrac{\omega_1 - \omega_r}{\omega_1} = \dfrac{\omega_1 - p\omega_o}{\omega_1}$

$P =$ number of pole pairs

$\omega_o = \dfrac{2\pi N}{60}$ rad/s; N is the rotor speed in rev/min,

$\omega_r =$ rotor speed in electrical rad/s,

and

$\omega_1 = 2\pi f_1$ rad/s (electrical), f_1 being the supply frequency.

The developed torque, $T = \dfrac{P_2}{\omega_1/P}$ Nm

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;

1. Rectifier unit
2. Dc bus link
3. Inverter unit
4. Control stage

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

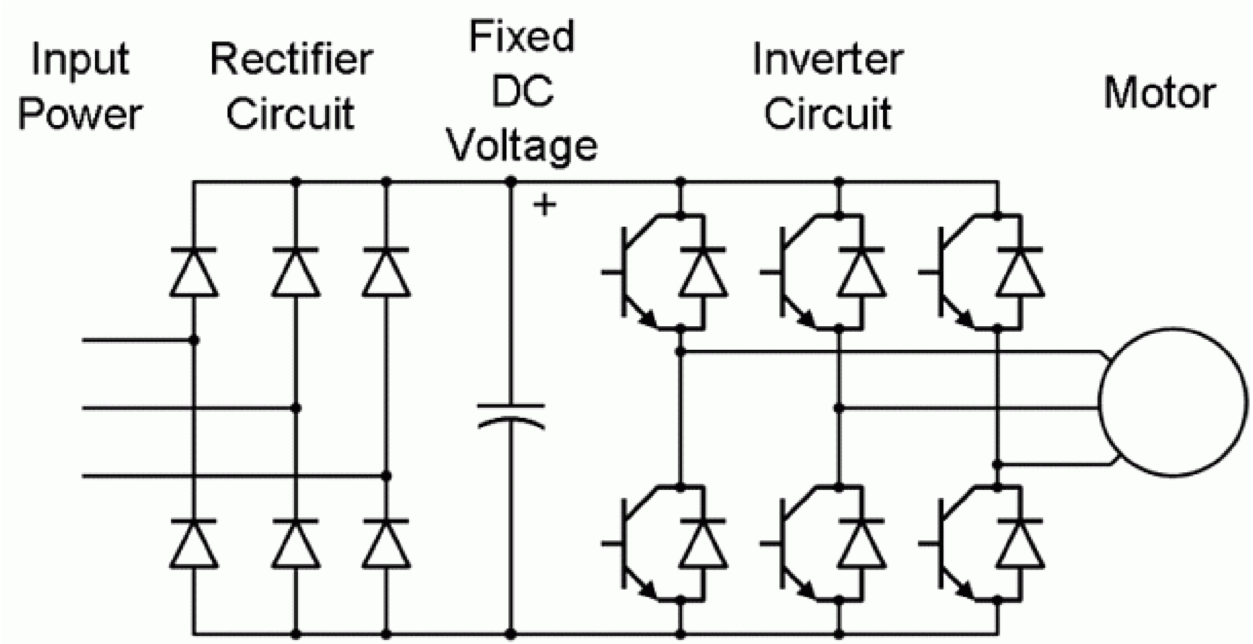


Figure 3: VFD circuit diagram

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.

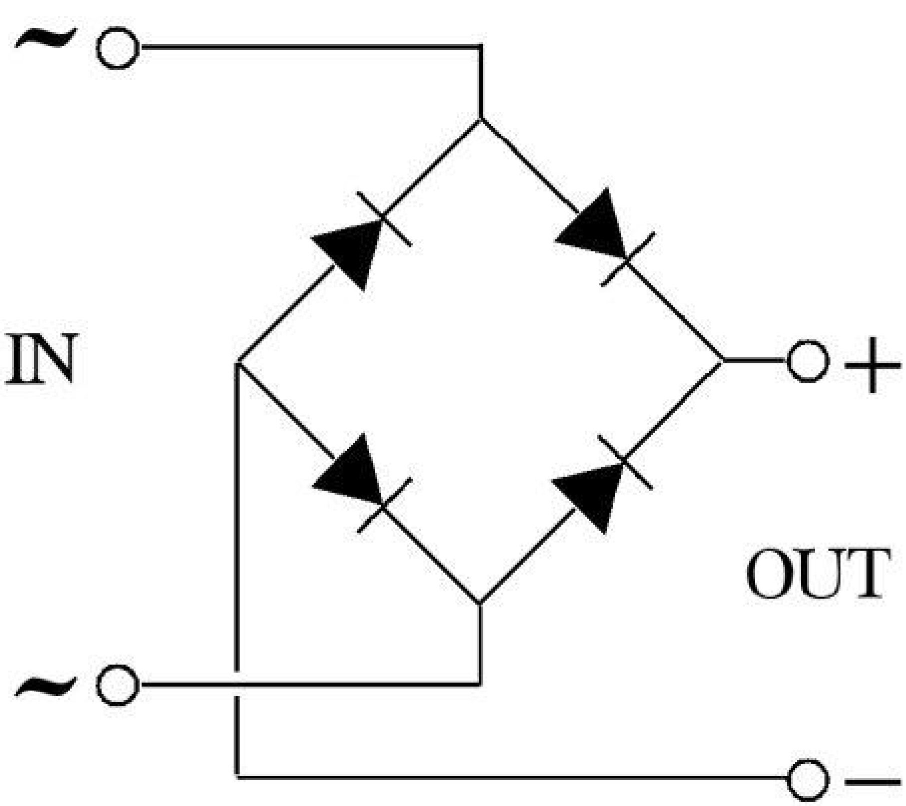


Figure 4: Diode bridge rectifier

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.

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.Arrangment 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. 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 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.

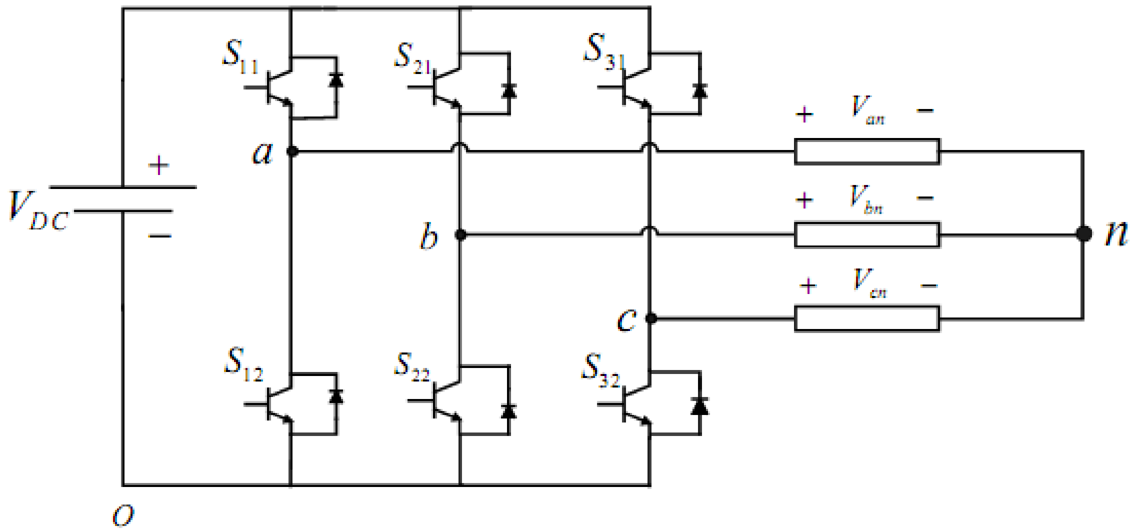


Figure 5: Full-Bridge inverter

The inverter model shown in Figure 5 has eight switch states given in Table 2. 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.

$S_{11} + S_{12}$ (1)

$S_{21+}S_{22}$ (2)

$S_{31}+S_{32}$ (3)

Table 3: Switching States in a three phase inverter

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

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.

$$\frac{V_{DC}}{2}(S_{11} - S_{12}) = V_{an} + V_{no} \qquad (4)$$

$$\frac{V_{DC}}{2}(S_{21} - S_{22}) = V_{bn} + V_{no} \qquad (5)$$

$$\frac{V_{DC}}{2}(S_{31} - S_{32}) = V_{cn} + V_{no} \qquad (6)$$

Expressing (4) to (6) in terms of modulation signals and making use of conditions from (1) to (3) gives:

$$\frac{V_{DC}}{2}(M_{11}) = V_{an} + V_{no} \qquad (7)$$

$$\frac{V_{DC}}{2}(M_{21}) = V_{bn} + V_{no} \qquad (8)$$

$$\frac{V_{DC}}{2}(M_{31}) = V_{cn} + V_{no} \qquad (9)$$

Adding equation (7), (8), (9) gives equation (10).

$$\frac{V_{DC}}{2}(S_{11} + S_{21} + S_{31} - S_{12} - S_{22} - S_{32}) = V_{an} + V_{bn} + V_{cn} + V_{no} \qquad (10)$$

As we are dealing with balanced voltages,

$V_{an} + V_{bn} + V_{cn}$=0, equation (10) becomes,

$$\frac{V_{DC}}{6}(2S_{11} + 2S_{21} + 2S_{31} - 3) = V_{no} \qquad (11)$$

Substituting for V_{no} in equations (4) to (6) gives:

$$\frac{V_{DC}}{3}(2S_{11} - S_{21} - S_{31}) = V_{an} \qquad (12)$$

$$\frac{V_{DC}}{3}(2S_{21} - S_{21} - S_{31} = V_{bn} \qquad (13)$$

$$\frac{V_{DC}}{3}(2S_{31} - S_{21} - S_{11} = V_{cn} \qquad (14)$$

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.

- Current 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).

- **Voltage 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. 1. 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.

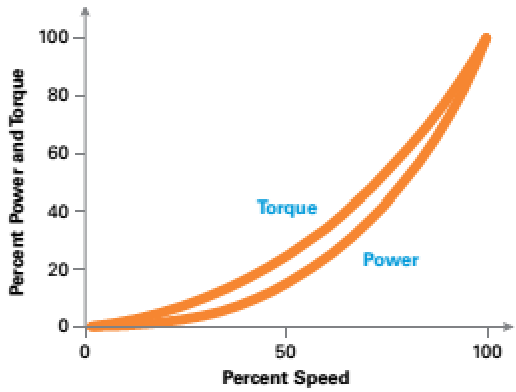


Figure 6: Variable torque load

2. **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.

3. **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

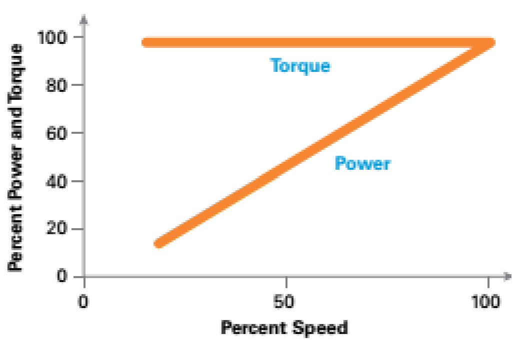


Figure 7: Constant Torque Load

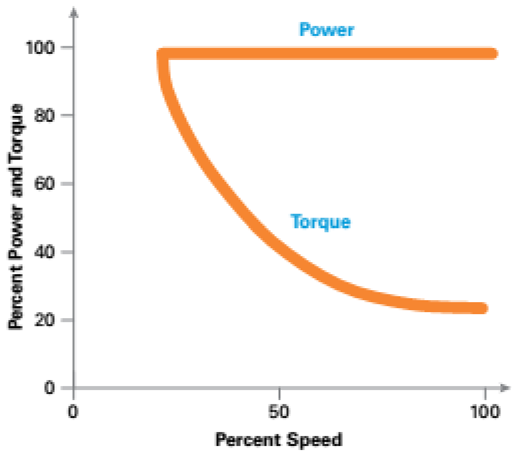


Figure 8; Constant Power load profile

Variable 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.

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: $V = 4.444\ f\ N\Phi m$

Or $V/f = 4.444 N\Phi m$

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.

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 as shown in Figure 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.

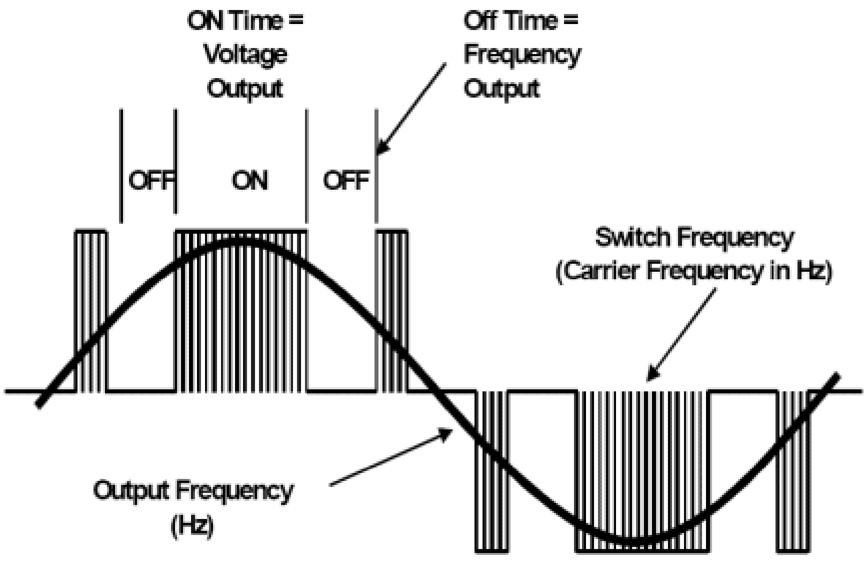


Figure 9: Drive output waveform of pulse width modulator

Mathematical modeling of a 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 (2) to (4)

$V_{as} = V_m cos w_e t$ (1)

$V_{bs} = V_m \cos(w_e t+\theta)$ (2)

$V_{bs} = V_m \cos(w_e t-\theta)$ (3)

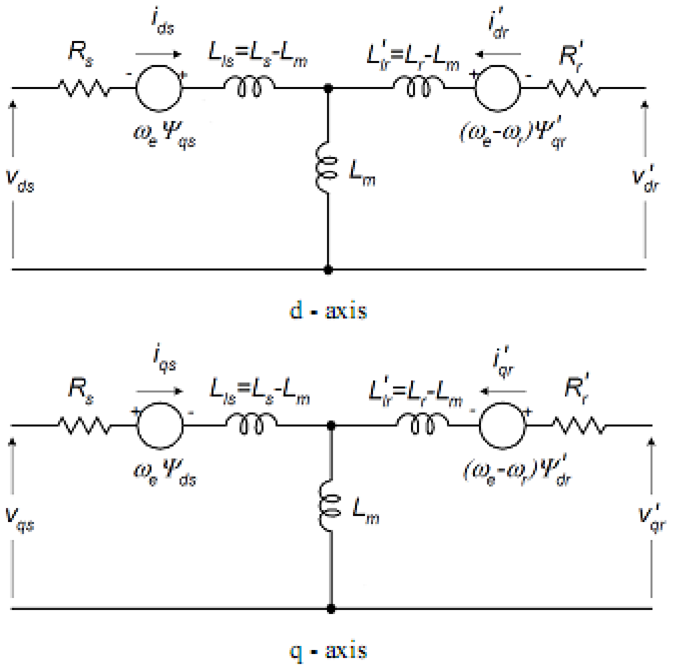


Figure 10: Induction motor equivalent d-q-o circuit diagram

Model 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 equivalent circuit diagram of d-q-o coordination is shown in Fig.4. 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;

$$\varphi_{qs} + L_s i_{qs} + L_m i'_{qr} \qquad (4)$$

$$\varphi_{ds} + L_s i_{ds} + L_m i'_{dr} \qquad (5)$$

$$\varphi_{qr} + L'_r i_{qr} + L_m i_{qs} \qquad (6)$$

$$\varphi'_{dr} + L'_r i'_{dr} + L_m i_{ds} \qquad (7)$$

Where $L_s = L_{is} + L_m$ (8)

For the stator side;

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_e \varphi_{ds} \qquad (9)$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_e \varphi_{qs} \qquad (10)$$

CHAPTER THREE

METHODOLOGY

Tools overview

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

1**) Mat lab**

Mat lab is a high- level language and interactive environment for numerical computation, visualization, and programming. Using Mat lab you can analyze data, develop algorithms, and create models and applications. The language, tools and build-in math functions enable you to explore multiple approaches and reach a solution faster than with spreadsheets or traditional programming languages, such as c/c++ or Java [16].

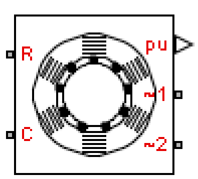
Key Features

- High-level language for numerical computation, visualization and application development
- Interactive for iterative exploration, design and problem solving
- Mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, numerical integration and solving ordinary differential equations
- Built in graphics for visualizing data and tools for creating custom plots
- Development tools for improving code quality and maintainability and maximizing performance
- Functions for integrating MATLAB based algorithms with external applications and language such as C, java.NET, and Microsoft Excel.

Simulink

Simulink, developed by Math Works, is a data flow graphical programming language tool for modeling, simulating and analyzing multi-domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for multi-domain simulation and Model-Based Design.

Asynchronous machine (squirrel cage)



The Asynchronous Machine Squirrel Cage (fundamental) block models a squirrel-cage-rotor asynchronous machine with parameterization using fundamental parameters. A squirrel-cage-rotor asynchronous machine is a type of induction machine. All stator connections are accessible on the block. Connect port ~1 to a three-phase circuit. To connect the stator in delta configuration, connect a Phase Permute block between ports ~1 and ~2. To connect the stator in wye configuration, connect port ~2 to a Grounded Neutral or a Floating Neutral block.

Electrical Defining Equations

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

$$\theta_e(t) = \int_0^t 2\pi f_{rated} dt,$$

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

$$P_s = \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\ -\sin\theta_e & -\sin(\theta_e - \frac{2\pi}{3}) & -\sin(\theta_e + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix},$$

,

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

$$v_{ds} = \frac{1}{\omega_{base}}\frac{d\psi_{ds}}{dt} - \omega\psi_{qs} + R_s i_{ds},$$

$$v_{qs} = \frac{1}{\omega_{base}}\frac{d\psi_{qs}}{dt} + \omega\psi_{ds} + R_s i_{qs},$$

And

$$v_{0s} = \frac{1}{\omega_{base}}\frac{d\psi_{0s}}{dt} + R_s i_{0s},$$

Where:

- v_{ds}, v_{qs}, and v_{0s} are the d-axis, q-axis, and zero-sequence stator voltages, defined by

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} = P_s \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix},$$

Where v_a, v_b, and v_c are the stator voltages across ports ~1 and ~2.

- ω_{base} is the per-unit base electrical speed.
- Ψds, ψ_{ds}, and ψ_{0s} are the d-axis, q-axis, and zero-sequence stator flux linkages.
- R_s are the stator resistance.
- i_{ds}, i_{qs}, and i_{0s} are the d-axis, q-axis, and zero-sequence stator currents defined by

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{0s} \end{bmatrix} = P_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix},$$

Wherei_a,i_b and$i_c$are the stator currents flowing from port ~1 to port ~2.

The rotor voltage equations are defined by

$$v_{dr} = \frac{1}{\omega_{base}} \frac{d\psi_{dr}}{dt} - (\omega - \omega_r)\psi_{qr} + R_{rd} i_{dr} = 0$$

And

$$v_{qr} = \frac{1}{\omega_{base}} \frac{d\psi_{qr}}{dt} + (\omega - \omega_r)\psi_{dr} + R_{rd} i_{qr} = 0,$$

Where:

- v_{dr} and v_{qr} are the d-axis and q-axis rotor voltages.
- φ_{dr} and ψ_{qr} 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.
- ω_r is the per-unit mechanical rotational speed.
- R_{rd} is the rotor resistance referred to the stator.
- i_{dr} and i_{qr} are the d-axis and q-axis rotor currents.

The stator flux linkage equations are defined by

$$\psi_{ds} = L_{ss} i_{ds} + L_m i_{dr},$$

$$\psi_{qs} = L_{ss} i_{qs} + L_m i_{qr},$$

And

$$\psi_{0s} = L_{ss} i_{0s},$$

Where L_{ss} is the stator self-inductance and L_m is the magnetizing inductance. The rotor flux linkage equations are defined by

$$\psi_{dr} = L_{rrd} i_{dr} + L_m i_{ds}$$

The stator self-inductance L_{ss}, stator leakage inductance L_{ls}, and magnetizing inductance L_m are related by

$$L_{ss} = L_{ls} + L_m.$$

The rotor self-inductance L_{rrd}, rotor leakage inductance L_{lrd}, and magnetizing inductance L_m are related by

$$L_{rrd} = L_{lrd} + L_m.$$

Asynchronous machine parameters (initial values)

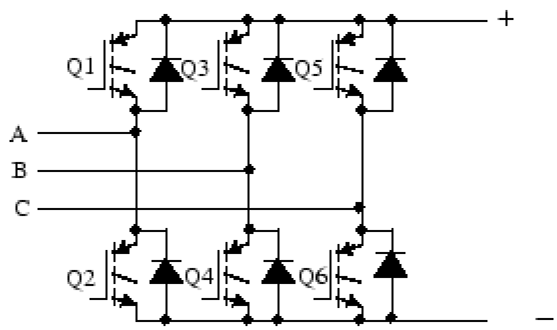
Nominal power, voltage (line-line), and frequency	[3*746, 220, 60]
Stator resistance and Inductance	[1.115 0.005974]
Rotor resistance and Inductance	[1.083 0.005974]
Mutual inductance	0.2037
Inertia constant, friction factor, and pole pairs	[0.02 0.005752 2]

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 Vn to 220 Vrms implements a 3 HP, 60 Hz machine with two pairs of poles. Its nominal speed is therefore slightly lower than the synchronous speed of 1800 rpm, or w_s= 188.5 rad/s. These are the initial conditions on starting of motor load.

Universal 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:

IGBT-Diode Bridge:



Number 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.
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
Snubber 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,

$$Rs > 2\frac{T_s}{Cs}$$

$$Cs < \frac{P_n}{1000(2\pi f)V_n^2},$$

Where

p_n =nominal power of single or three phase converter (VA)
V_n = nominal line-to-line AC voltage (V_{rms})
f = fundamental frequency (Hz)
T_s = 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.

Power 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

Ron

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

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.

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: Universal bridge parameters

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

	Vf	0 V
	Vfd	0 V
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 asynchronous machine). The high resistance value of the snubber does not affect the circuit performance.

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.

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.
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.

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 (F_c) of the triangular carrier signal.

$$F_c = SwitchingRatio \times OutputVoltageFrequency$$

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

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.

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.

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.

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 5: Pulse width generator parameters (initial)

Generator type	Three-phase bridge (6 pulses)
Mode of operation	Unsynchronized
Carrier frequency	18*60Hz (1080 Hz)
Internal generation of modulating signals	Selected
Modulation index m	0.9
Output voltage frequency	60 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 (60 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:

$$V_{LLrms} = \frac{m}{2} \times \frac{\sqrt{3}}{\sqrt{2}} Vdc = m \times 0.612 \times VDC$$

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 asynchronous 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.

Loading 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.

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

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 below.

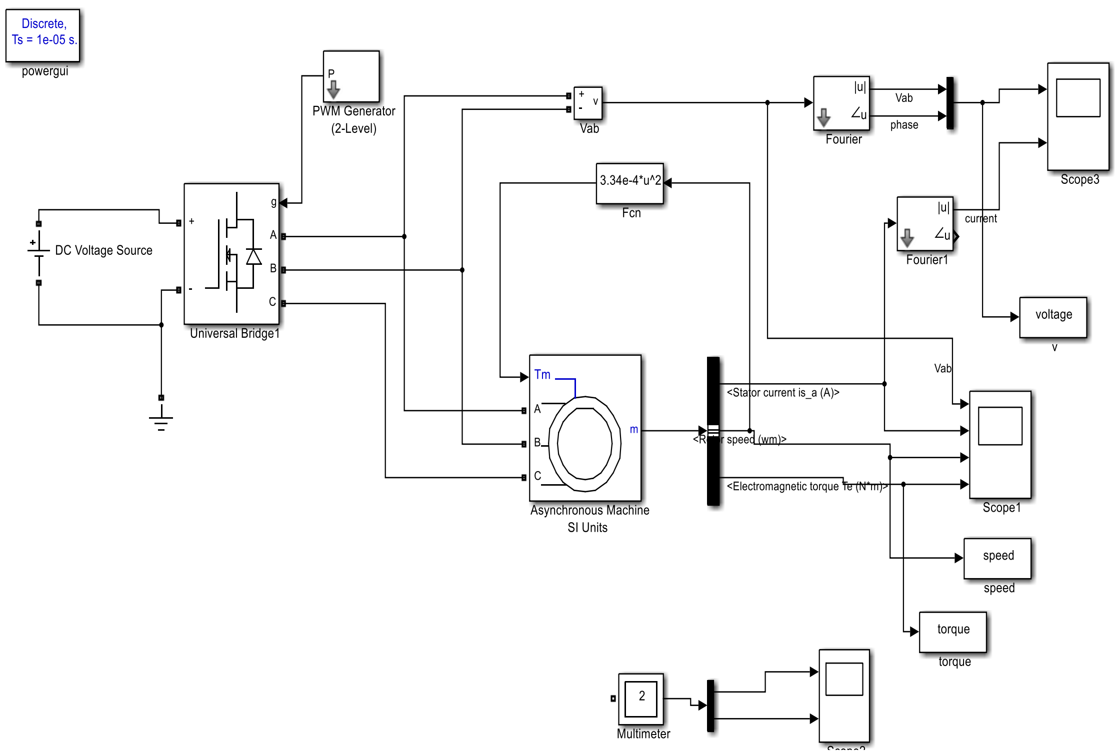


Figure 11: Simulation and analysis of variable speed drive circuit

CHAPTER FOUR

RESULTS AND ANALYSIS

For a 220v(rms),60Hz, 3HP,1080 rpm motor, the initial results obtained for torque. Speed and power are as shown below.

For 400v, 1080 carrier frequency the results are as shown below.

Table 6; Torque for a 400v.1080Hz input

Time	Torque
0.999720000000000	10.2155313227259
0.999740000000000	9.87057767153302
0.999760000000000	9.39347116179305
0.999780000000000	8.91782722710348
0.999800000000000	8.44366069240089
0.999820000000000	7.97098614950335
0.999840000000000	7.49981800599869
0.999860000000000	7.44557092845490
0.999880000000000	7.53401217437970
0.999900000000000	7.62720925302681
0.999920000000000	7.72509253335500
0.999940000000000	7.82759224671599
0.999960000000000	7.93463844479750
0.999980000000000	8.04616100757170
1	8.16208965116576

Table 7: Speed output for a 400v, 1080Hz input

Time	Speed
0.999720000000000	151.768128978712
0.999740000000000	151.769738482508
0.999760000000000	151.770837024171
0.999780000000000	151.771425696366
0.999800000000000	151.771539422022
0.999820000000000	151.771179735811
0.999840000000000	151.770348187625
0.999860000000000	151.769115517630
0.999880000000000	151.768003115336
0.999900000000000	151.767016131385
0.999920000000000	151.766124809225
0.999940000000000	151.765333790641
0.999960000000000	151.764647646155
0.999980000000000	151.764070875766
1	151.763607908791

Power=speed times torque

Power=speed cubed for variable torque load

Table 8: Power, speed output for a 400v, 1080Hz input

Time	Speed	Power
0.999720000000000	151.768128978712	3495761
0.999740000000000	151.769738482508	3495872
0.999760000000000	151.770837024171	3495948
0.999780000000000	151.771425696366	3495989
0.999800000000000	151.771539422022	3495997
0.999820000000000	151.771179735811	3495972
0.999840000000000	151.770348187625	3495914
0.999860000000000	151.769115517630	3495829
0.999880000000000	151.768003115336	3495752
0.999900000000000	151.767016131385	3495684
0.999920000000000	151.766124809225	3495623
0.999940000000000	151.765333790641	3495568
0.999960000000000	151.764647646155	3495521
0.999980000000000	151.764070875766	3495481
1	151.763607908791	3495435

For the second simulation, voltage =400v and carrier frequency=2000Hz, results are as shown below.

Table 9: Speed output for a 400v, 2000Hz input

Time	Speed
0.999720000000000	151.755762519272
0.999740000000000	151.755499629429
0.999760000000000	151.755419023001
0.999780000000000	151.755516800124
0.999800000000000	151.755722756785
0.999820000000000	151.755965874111
0.999840000000000	151.756274633940
0.999860000000000	151.756653994283
0.999880000000000	151.757039020563
0.999900000000000	151.756909863620
0.999920000000000	151.756267720261
0.999940000000000	151.755219803040
0.999960000000000	151.754299934135
0.999980000000000	151.753513077475
1	151.752828473351

Torque results were as shown below

Table 10: Torque output for a 400v, 2000Hz input

Time	Torque
0.999720000000000	151.755762519272
0.999740000000000	151.755499629429
0.999760000000000	151.755419023001
0.999780000000000	151.755516800124
0.999800000000000	151.755722756785
0.999820000000000	151.755965874111
0.999840000000000	151.756274633940
0.999860000000000	151.756653994283
0.999880000000000	151.757039020563
0.999900000000000	151.756909863620
0.999920000000000	151.756267720261
0.999940000000000	151.755219803040
0.999960000000000	151.754299934135
0.999980000000000	151.753513077475
1	151.752828473351

Power values were as shown below

Table 11: Power, speed input for a 400v, 2000Hz input

Time	Speed	Power
0.999720000000000	151.755762519272	3494907
0.999740000000000	151.755499629429	3494888
0.999760000000000	151.755419023001	3494883
0.999780000000000	151.755516800124	3494890
0.999800000000000	151.755722756785	3494904
0.999820000000000	151.755965874111	3494921
0.999840000000000	151.756274633940	3494942
0.999860000000000	151.756653994283	3494968
0.999880000000000	151.757039020563	3494995
0.999900000000000	151.756909863620	3494986
0.999920000000000	151.756267720261	3494942
0.999940000000000	151.755219803040	3494869
0.999960000000000	151.754299934135	3494806
0.999980000000000	151.753513077475	3494751
1	151.752828473351	3494705

Graphs obtained from mat lab are as shown below

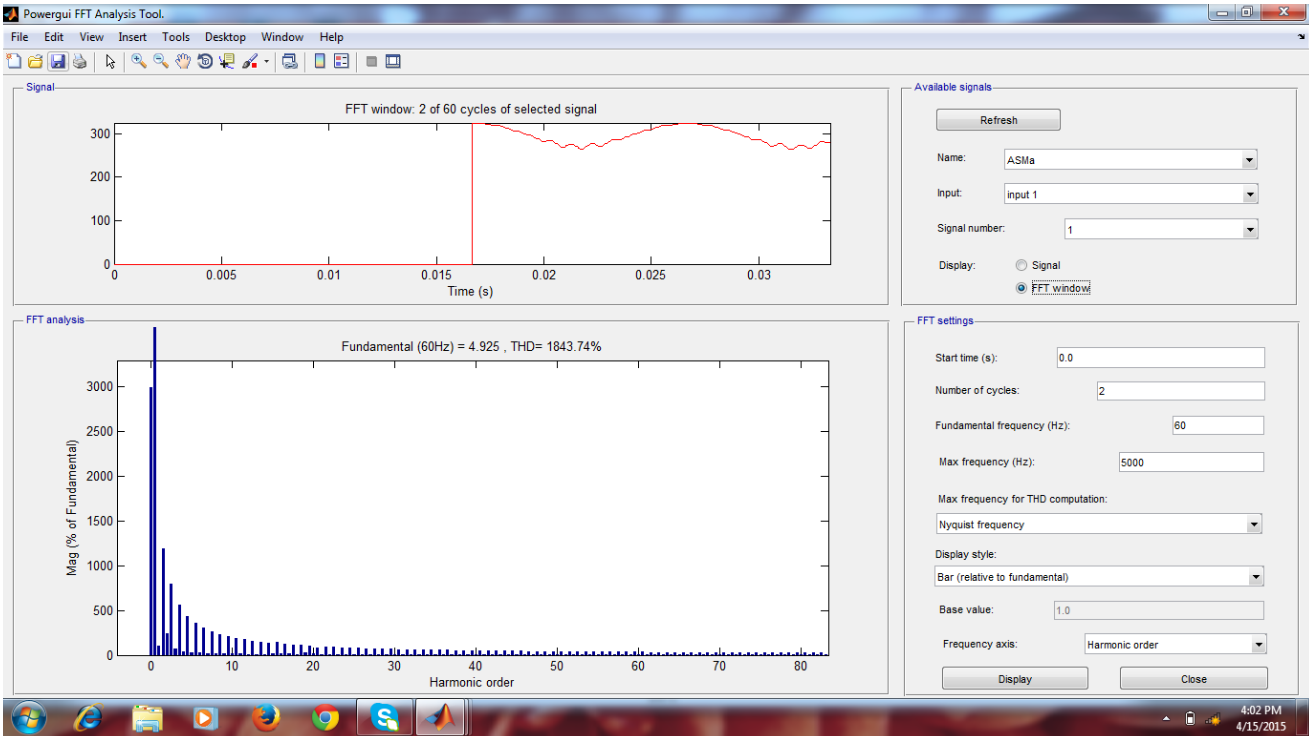


Figure 12: Fft analysis and total harmonic distortion display for 400v, 1080Hz

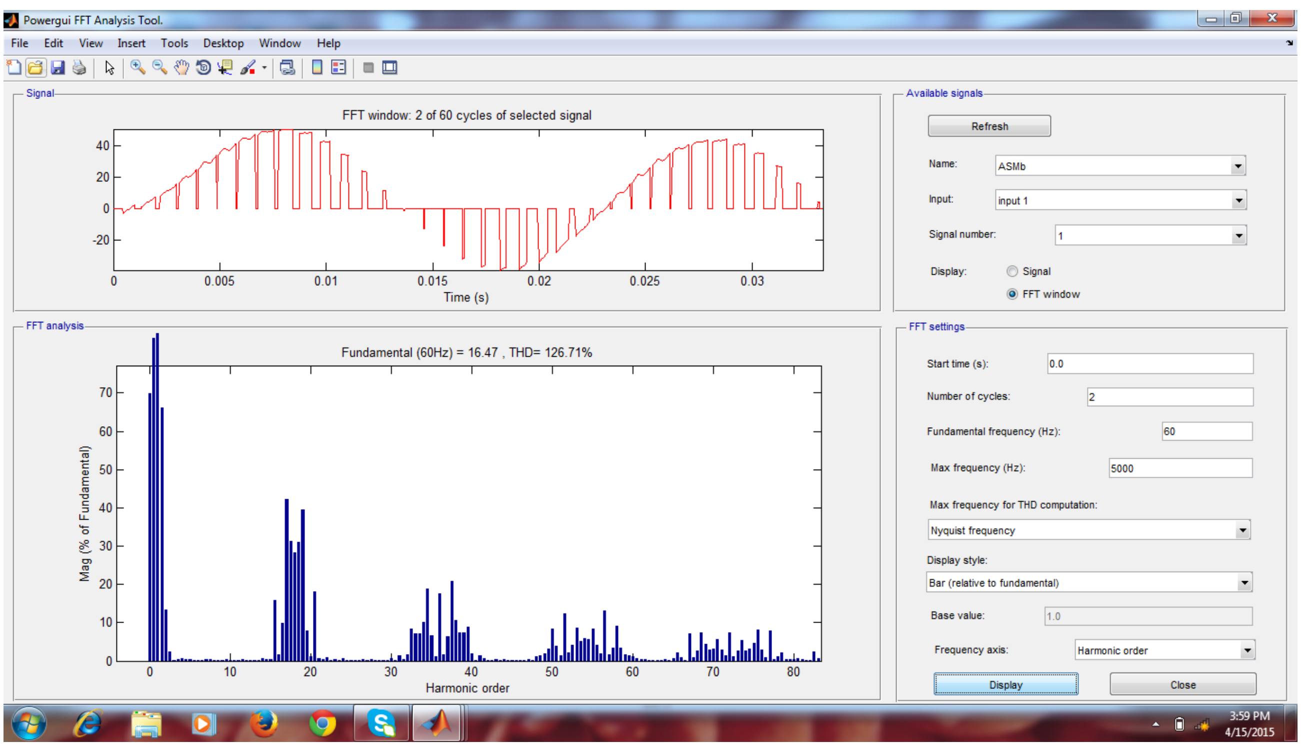


Figure 13: Fft analysis and total harmonic distortion

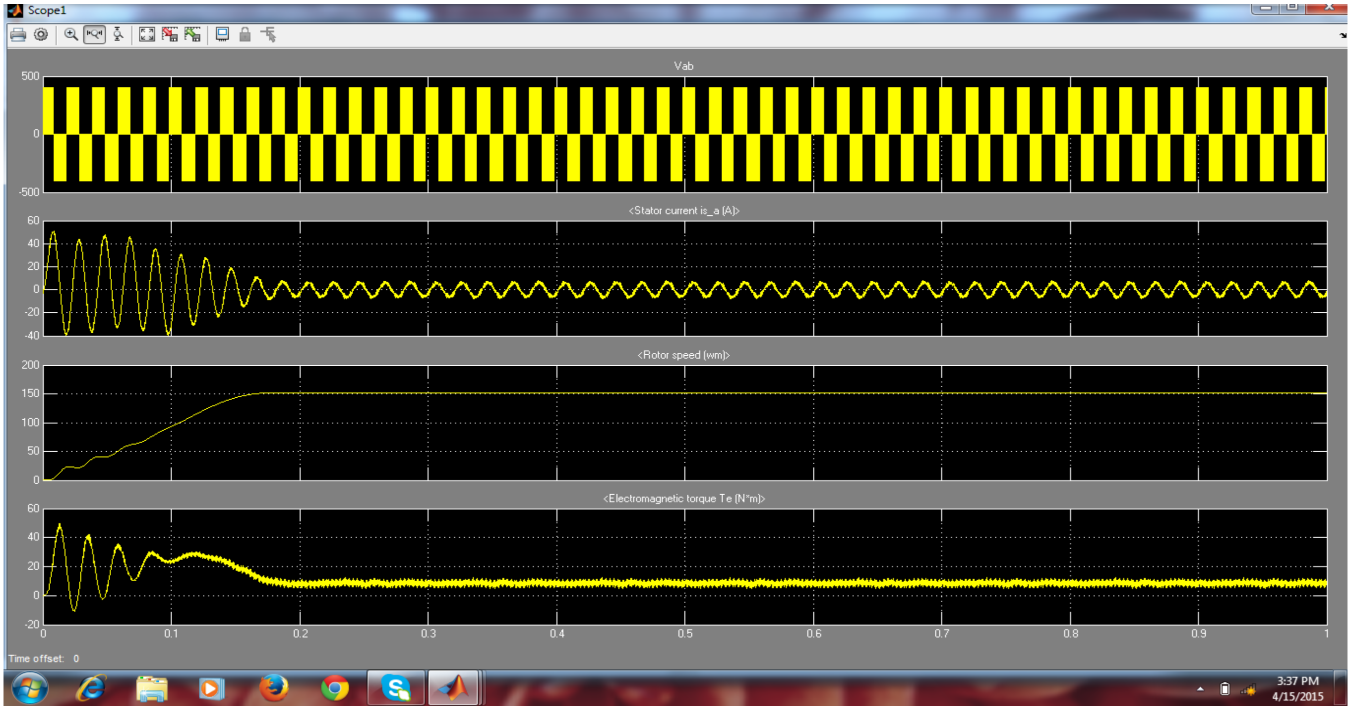


Figure 14: scope 1 showing voltage, stator current, electromagnetic torque and rotor speed

Figure 15: Scope 3

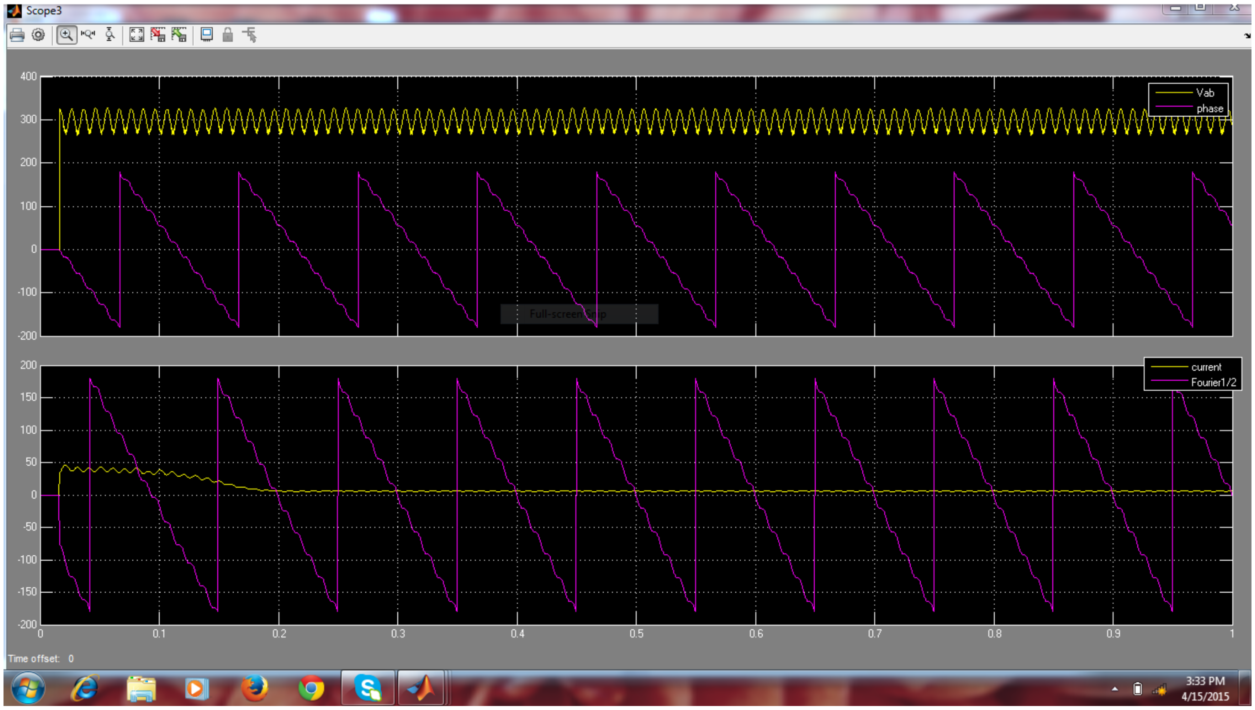


Figure 16: Scope showing voltage and current magnitude and phase respectively

For 400v, 2000Hz carrier frequency, results are as shown below.

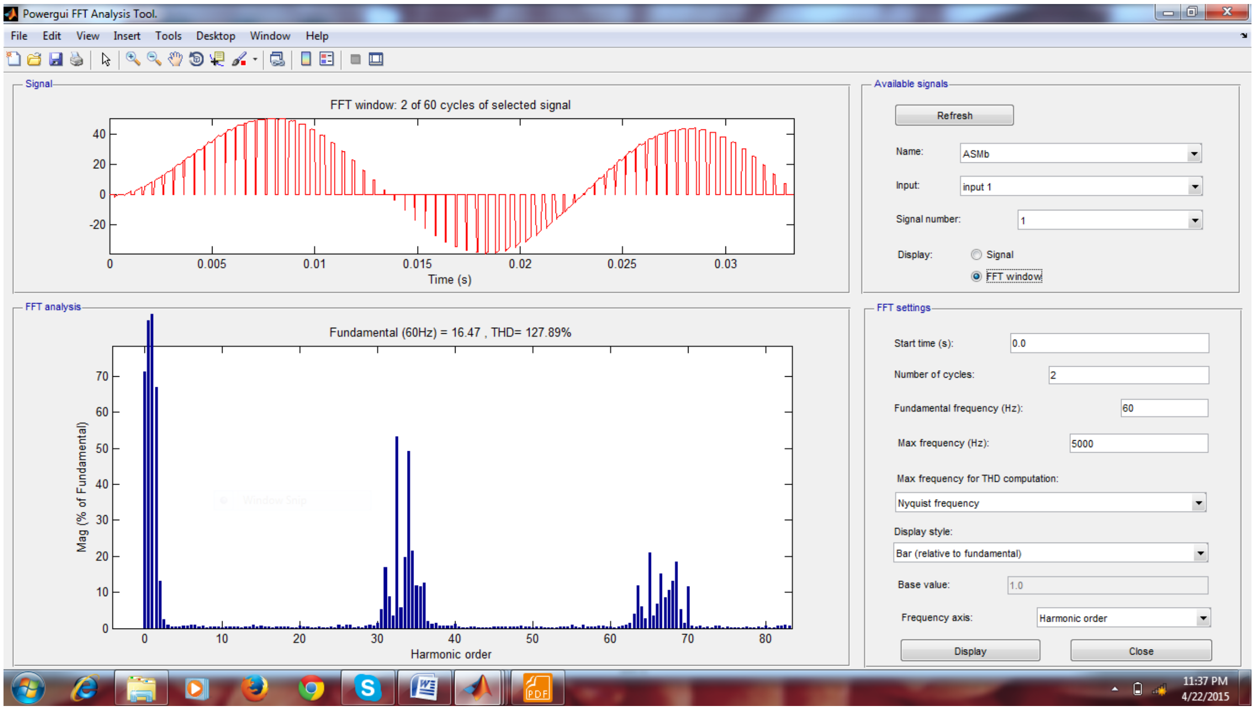


Figure 17: scope showing Fft and total harmonic distortion analysis

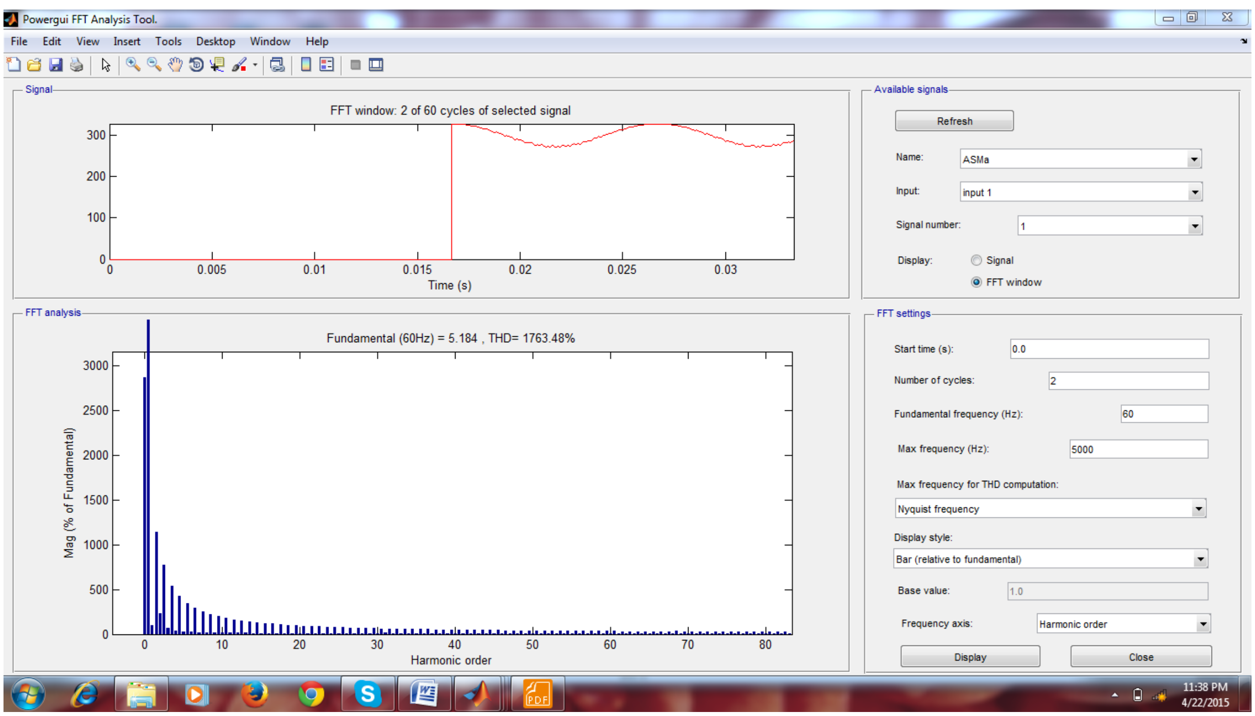


Figure 18: Scope showing Fft and total harmonic distortion analysis

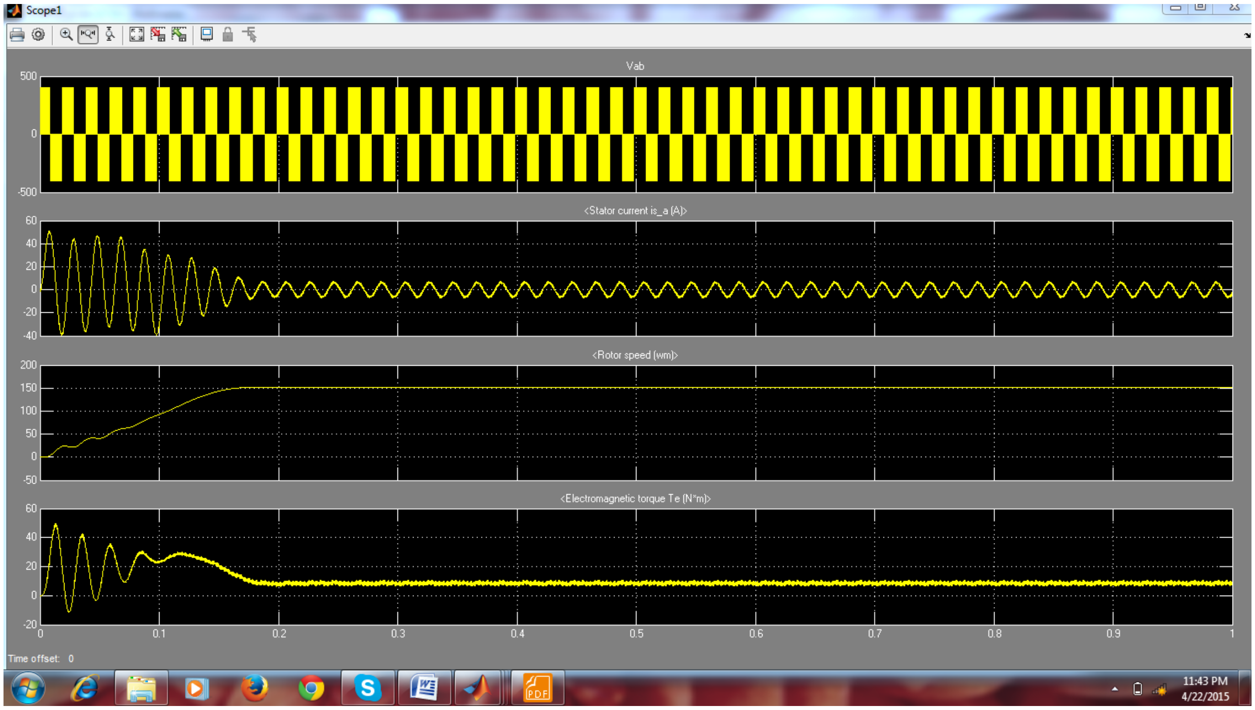


Figure 19: Scope 1 showing electromagnetic torque. Rotor speed, voltage and current

Figure 20: Scope 3

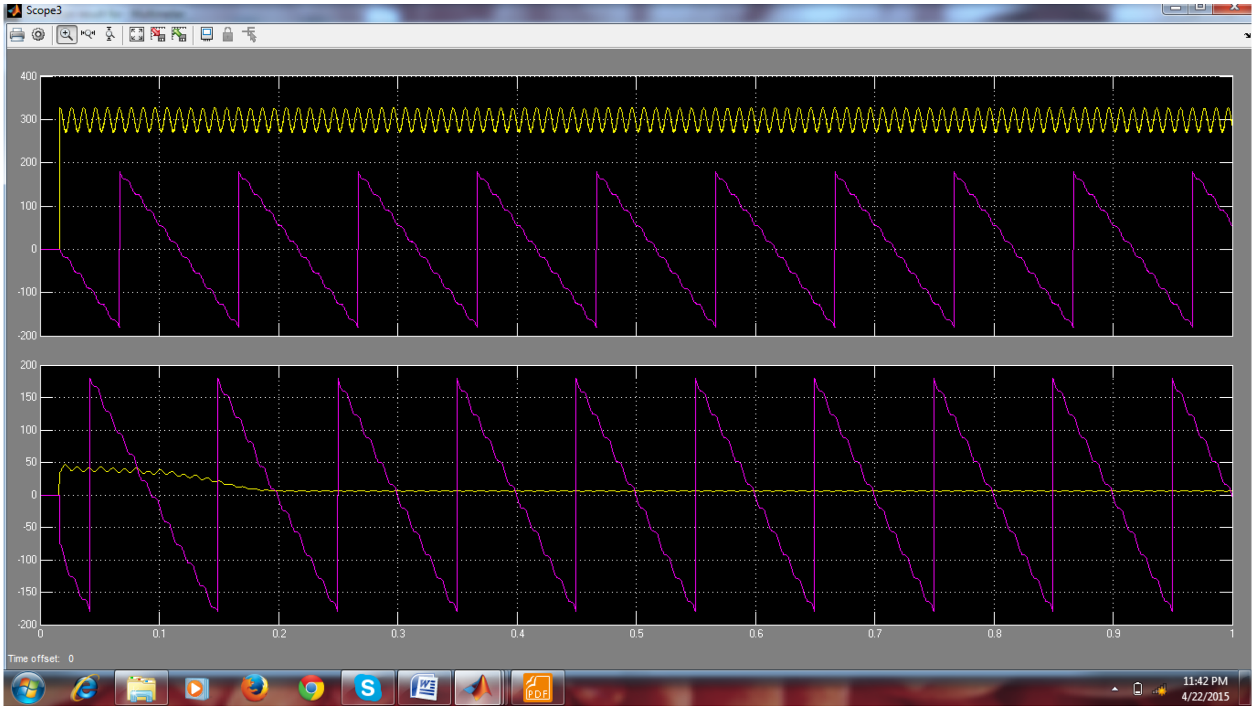


Figure 21: Scope 3 showing voltage and current magnitude and phase

The voltage is increased by increasing modulation index and speed also increases when frequency increases. Due to inherent control from inverter and using pwm techniques voltage is sinusoidal so harmonics are eliminated without using any sought of filter circuit for suppressing harmonics. As frequency increases, speed also increases. Power being equal to speed cubed for variable torque load, reduces total power consumption of motor. Voltage and current levels are high during starting of motor to be able to supply enough torque needed by the motor. These then reduce in magnitude to a certain point where they become constant. 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 little variation between the first and second simulation. Torque ripples are reduced as motor moves from starting to running state. The parameters are initially ramping in nature till they got settled at the peak value. It is seen that the VFD has succeeded in increasing the nominal speed of the motor from using the nominal frequency of 60Hz. Initially the speed of the motor rises from zero and increases above the nominal speed; it experiences some transients and then settles to a stable level within few milliseconds.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

Conclusion

Speed control is a major issue in any industrial process. Induction motors are widely used in many processes due to their rugged nature, low cost and reliability to meet load demands. This is however limited by the fact that induction motors tend to have fixed speed. Variable speed drives, devices which employ different speed control techniques according to their circuitry, control speed through variation of frequency by employing these techniques such as PWM, SVPWM, IFOC and FOC.A formulation of this problem is proposed in this project with the main aim being reduction in total running costs, power consumption reduction and overall efficiency improvement while still meeting load demands. Variable speed drives PWM speed control is proposed as a solution to speed control of induction motors. Results indicate that the objectives of the project are met as speed of induction is varied with a PWM variable speed drive hence

- Optimum speed control of induction motors is achieved.
- Power consumption reduction has been achieved due to power, speed and torque relations.
- Total overall cost reduction was achieved.

Recommendations

Proposed speed control technique is based on variable speed drives techniques to speed control. This works under certain conditions which if not met, the variable speed drive will not be able to work efficiently hence not achieve set objectives. A recommendation to this is being able to work into reducing the constraints rendering the variable speed drive inefficient.

Variable speed drive control circuitry and ratings with regards to motor and load ratings are have not been fully understood. This makes production and installation of variable speed drives ineffective. Hence another major recommendation being to do more research on improving the circuitry of the variable speed drive.

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Appendix

Useful formulas

Rated motor horse power=Motor efficiency*100%/Available HP

Power=speed*torque

$$Rs > 2\frac{T_s}{Cs}$$

$$Cs < \frac{P_n}{1000(2\pi f)V_n^2},$$

p_n =nominal power of single or three phase converter (VA)
V_n = nominal line-to-line AC voltage (V_{rms})
f = fundamental frequency (Hz)
T_s = sample time (s)

$$V_{LLrms} = \frac{m}{2} \times \frac{\sqrt{3}}{\sqrt{2}} Vdc = m \times 0.612 \times VDC$$

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

The nominal torque of the motor is

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