

بسم الله الرحمن الرحيم

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**Speed Control of Three Phase Induction Motor Driving
Heavy Duty Dredge Pump**

**التحكم في سرعة المحرك الحثي ثلاثي الطور المستخدم
في تشغيل طلمبة سحب عالية الأداء**

A thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechatronics

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

قال تعالى:

[رَبِّ اجْعَلْنِي مُقِيمَ الصَّلَاةِ وَمِنْ

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صدق الله العظيم

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DEDICATION

I would like to dedicate this research to the soul of my father, who taught me how to pave the life for my future. My dedication should be given to my mother, kindness, and all my feelings towards her say a life. My dedication to my wife, my friends, my family, and anyone who helped me to complete this thesis.

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At the beginning, I would like to extend my gratitude to Allah, who gave me the ability to complete this work successfully. It is honorable to give my acknowledgment to the administration of the university, staff, and all members. My special acknowledgement extends to my dear supervisor, Dr. Abdel Aziz Yousif, who gave me valuable advice, excellent guidance and continuous encouragement throughout my research. His efforts to pass his knowledge to me and his patience when I struggled to understand at times were paramount in my success. Also I will never forget my colleagues encouraged me through all the study period, and those who helped me by all meaning.

ABSTRACT

The main aim of the thesis dealt with the concept of speed control of a three-phase induction motor in pumping application. In recent years, a major issue that effects the electricity generation in Roseires hydro-power station is sedimentation. Dredge Pumps are frequently used there to remove sand and gravel in front of the intakes of the turbines. Three-phase induction motor is the most widely used electric motors in this process to drive these pumps. It runs at essentially constant speed-which is frequency dependant- from no-load to full-load. However, controlling the motor speed is required for optimizing the dredging process by controlling the flow, increasing bearing and pumps seal life and Pump energy savings.

Variable frequency electronics drives are being used to control the speed of induction motor. Direct torque control is a one of the latest drive technology describes the way in which the control of torque and speed are directly based on the electromagnetic state of the motor. It is the first technology to control the real motor control variables of torque and flux.

In this thesis a system of three phase induction motor with Adjustable Speed Drives (ASD) is used to drive heavy-duty dredge pump using direct torque control method. MATLAB/SIMULINK tool is used for simulating the whole system. The results are then obtained in speed and torque control modes to fulfill the requirements of controlling the speed and achieving the objectives.

المستخلص

تقوم الفكرة العامة لهذا البحث علي دراسة التحكم في سرعة المحرك الحثي ثلاثي الطور في تطبيقات طلمبات الشفط.فعلي مدي سنوات عديدة كانت ولاتزال مشكلة الإطماء من أكبر معوقات التوليد الكهربائي بمحطة توليد الروصيرص ، و تعتبر الطلمبات الساحبة من أهم الطرق المستعملة في إزالة هذه الإطماء من أمام مداخل التوربينات بالبحيرة كما يعد المحرك الحثي ثلاثي الطور المشغل الرئيسي لمثل هذه الطلمبات. ونسبة لدوران المحرك الحثي ثلاثي الطور بسرعة ثابتة كان من المهم في مثل هذا النوع من التطبيقات التحكم في سرعة المحرك وبالتالي انسياب الطمي المخلوط وذلك لتحسين عملية ازالة الاطماء والمحافظة علي الاجزاء الميكانيكية وحفظ الطاقة .

تستعمل المشغلات الالكترونية ذات التردد المتغير بصورة كبيرة في التحكم في سرعة المحرك الحثي ثلاثي الطور. وتعتبر تقنية التحكم المباشر في العزم من أحد الطرق المتقدمة المستخدمة في التحكم في العزم والسرعة بصورة مباشرة بمعرفة الحالة الكهرومغناطيسية للمحرك.وتعتبر هذه التقنية أول تقنية تتحكم في القيم الحقيقية لمتغيري العزم والفيض الكهرومغناطيسي للمحرك.

يتم في هذا البحث دراسة نظام يتكون من محرك حثي ثلاثي الطور يرتبط بمشغل تردد متغير باستعمال تقنية التحكم المباشر في العزم وذلك لتشغيل طلمبة سحب عالية الاداء والتحكم فيها.تتم محاكاة هذا النظام في برنامج الماتلاب وتشغيله وقراءة النتائج في حالتي التحكم بالسرعة والعزم للوصول الي المتطلبات والاهداف الاساسية التي انشئ من أجلها.

TABLE OF CONTENTS

	Page
Dedication.....	ii
Acknowledgments.....	Iii
Abstract	iv
المستخلص.....	v
Table of Contents	vi
List of Tables.....	x
List of Figures.....	xi
List of abbreviations.....	Xiii
List of Symbols.....	Xiv
Chapter One	
Introduction	
1.1 General Concepts.....	1
1.2 Problem Statement.....	1
1.3 Objectives.....	2
1.4 Methodology.....	2
1.5 Dissertation Outline.....	3
Chapter Two	
Theories and Literature Reviews	
2.1 Speed and Torque of Three Phase Induction Motor.....	4
2.2 Centrifugal dredge pump.....	5
2.2.1 Working principles.....	6
2.2.2 Effect of speed variation.....	6
2.2.3 Effect of variable speed drives.....	8
2.2.4 Plain suction dredger.....	8
2.3 Variable Speed Drives Basics.....	8
2.3.1 Hydraulic motor drives.....	9
2.3.2 Mechanical motor drives.....	9

2.3.3	DC motor drives.....	9
2.3.4	Eddy current drives.....	10
2.3.5	AC motor drives.....	11
2.4	Principles of Induction Motor AC Drives.....	11
2.5	Variable Frequency Drive Components.....	12
2.5.1	Converter stage (rectifier).....	12
2.5.2	Intermediate circuit (DC bus).....	13
2.5.3	Inverter stage.....	13
2.5.4	Inverter control system.....	14
2.6	Inverter Topologies.....	14
2.6.1	Voltage Source Inverter (VSI).....	14
2.6.2	Current Source Inverters (CSI).....	15
2.7	Pulse Width Modulation Technique.....	16
2.7.1	Sinusoidal PWM.....	17
2.7.2	Space vector modulation.....	18
2.7.3	Hysteresis band PWM (HBPWM).....	20
2.8	Induction Motor Control Strategies.....	21
2.8.1	Scalar control.....	22
2.8.2	Vector control.....	25
2.8.3	Sliding mode control.....	27
2.8.4	Direct torque control.....	28
2.9	Motor Load Types.....	29
2.9.1	Constant torque loads.....	30
2.9.2	Constant horsepower loads.....	30
2.9.3	Variable torque loads.....	31
2.10	Ac Drive Operation.....	32
2.10.1	Braking/regeneration.....	33
2.10.2	Harmonics.....	33
2.11	Summary.....	34

Chapter Three

Mathematical Model of Three Phase Induction Motor

3.1	Introduction.....	35
3.2	Induction motor model.....	36
3.2.1	Park's transformation.....	36
3.2.2	Stationary reference frame model equations.....	37
3.2.3	Voltage equations in d, q axes.....	38
3.2.4	Flux equations.....	38
3.2.5	Current equations.....	39
3.2.6	Electromagnetic torque.....	39
3.3	Direct Torque Control.....	40
3.3.1	Switching table.....	42
3.3.2	DTC of IM using space vector modulation.....	42
3.3.3	Stator flux control.....	44
3.3.4	Torque control.....	44
3.4	Summary.....	45

Chapter Four

Simulation of Three Phase Induction Motor Drive

4.1	Introduction.....	46
4.2	Model Description.....	47
4.2.1	Signal selector subsystem.....	50
4.2.2	Dredge pump subsystem.....	50
4.2.3	Speed Controller.....	51
4.2.4	Direct torque control.....	52
4.2.5	Braking Chopper.....	52
4.2.6	Three-Phase Inverter.....	53
4.2.7	Induction motor model.....	54
4.3	Simulation Results.....	54
4.3.1	Variable torque control mode.....	55

4.3.2	Speed Control Mode.....	57
4.4	Summary.....	59

Chapter Five

Conclusion and Recommendations

5.1	Conclusion.....	60
5.2	Recommendations	61
	References.....	62

LIST OF TABLES

Table	Title	Page
Table 3.1	Switching table of inverter voltage vectors	42
Table 4.1	Parameter Values of induction motor used in Simulation	47

.LIST OF FIGURES

Figure	Title	Page
Figure 2.1	Torque – speed curve of the typical 3 phase induction motor	5
Figure 2.2	Main pars of centrifugal pump	5
Figure 2.3	Speed variation effecting centrifugal pump performance	7
Figure 2.4	Basic configuration of an electrical AC drives	11
Figure 2.5	Schematic of the Variable speed Drive connected to an induction Motor	12
Figure 2.6	Rectifier Circuits	12
Figure 2.7	Inverter Circuit	13
Figure 2.8	Typical VSI configuration for induction motor drives	14
Figure 2.9	Current source inverter	15
Figure 2.10	Principle of three phase sinusoidal PWM	16
Figure 2.11	Three phase inverter fed induction motor	17
Figure 2.12	The eight inverter voltage vectors (V_0 to V_7)	18
Figure 2.13	Space vector diagram of the effective vectors	18
Figure2.14	Principle of hysteresis – band current control	19
Figure 2.15	Conventional HBPWM inverter Control Method	20
Figure 2.16	Frequency –voltage –torque curve	22
Figure 2.17	Diagram of open loop V/f control	23
Figure 2.18	Diagram of close loop {V/f control	24
Figure 2.19	Basic Field -oriented control of induct ion motor drive	25
Figure 2.20	Direct field oriented Control Method	26
Figure 2.21	Indirect Vector Control Method	26
Figure 2.22	Idea of sliding mode	27
Figure 2.23	Basic DTC scheme	28
Figure 2.24	Constant Torque load curve	29
Figure 2.25	Constant horsepower load	30

Figure 2.26	Variable torque load	31
Figure 2.27	Electric motor speed – torque chart	32
Figure 3.1	Three phase to two phase transformation scheme	37
Figure 3.2	Conventional DTC scheme	40
Figure 3.3	Inverter output voltage vectors and voltage source inverter	41
Figure 3.4	DTC-SVM	43
Figure 3.5	Stator and rotor flux space vector	44
Figure 4.1	Block diagram module of DTC drive	46
Figure 4.2	DTC model	48
Figure 4.3	Subsystem of DTC induction motor drive (AC4)	49
Figure 4.4	Signal selector subsystem	50
Figure 4.5	Dredge pump subsystem	50
Figure 4.6	Speed controller	51
Figure 4.7	DTC subsystem	52
Figure 4.8	Braking chopper subsystem	53
Figure 4.9	Voltage source inverter	54
Figure 4.10	Induction motor model	54

LIST OF ABBREVIATIONS

AC	Alternating Current
ASD	Adjustable Speed Drives
DC	Direct Current
VC	Vector Control
FOC	Field Oriented Control
DVC	Direct Vector Control
IDVC	Indirect Vector Control
IM	Induction Motor
DTC	Direct Torque Control
PWM	Pulse Width-Modulated
SVPWM	Space Vector Pulse Width-Modulation
V/f	Voltage-by-frequency
VSD	Variable Speed Drive
VFD	Variable Frequency Drive
VSI-Fed	Voltage Source Inverter-fed
PI	Proportional Integral
PID	Proportional Integral Derivative
CSI	Current Source Inverter
IGBT	Insulate Gate Bipolar Transistor
m.m.f	magneto motive force
e.m.f	electro motive force
MATLAB	MATrix LABoratory
Q	Flow rate of centrifugal pump
H	Head of centrifugal pump
P	Power absorbed by centrifugal pump
N	Rotating speed of centrifugal pump

LIST OF SYMBOLS

ω_s	Synchronous speed in rad/sec
ω_r	Rotor speed in rad/sec
V_{ds}	d-axis stator voltage component expressed in Stationary Reference Frame
V_{qs}	q-axis stator voltage component expressed in Stationary Reference Frame
V_{dr}	d-axis rotor voltage component expressed in Stationary Reference Frame
V_{qr}	q-axis rotor voltage component expressed in Stationary Reference Frame
λ_{qs}	q-axis stator flux linkages
λ_{ds}	d-axis stator flux linkages
λ_{qr}	q-axis rotor flux linkages
λ_{dr}	d-axis rotor flux linkages
R_s	Stator resistance
R_r	Rotor resistance
L_s	Self inductance of the stator
L_r	Self inductance of the rotor
L_m	Magnetizing inductance
T_e	Electromagnetic torque
T_ℓ	Load torque reflected on the motor shaft
I_{ds}	d- axis stator current component expressed in Stationary Reference Frame
I_{qs}	q-axis stator current component expressed in Stationary Reference Frame
P	Number of poles
p	The differential operator d/dt
B_m	Flux Density
J	Inertia
K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gain

E	Error = SP-PV
t	Time or instantaneous time (the present)
γ	Angle between fluxes

CHAPTER ONE

INTRODUCTION

1.1 General Concepts

Induction motor drives with cage-type machines have been the work-horses in the industry for variable speed applications in a wide power range that covers fractional horse-power to megawatts. These applications include pumps and fans, paper and textile mills, subway and locomotive propulsions, electric and hybrid vehicles, machine tools and robotics, home appliances, heat pumps and air-conditioners, rolling mills, wind generation systems, etc. In addition to the process control, the energy saving aspect of variable frequency drives is getting a lot of applications nowadays. During the last few years, the significance of the squirrel cage induction motors in speed and position controlled drives have grown drastically. In recent years due to the advances in the development of high speed computers and power electronics technology with associated high speed microcontrollers, Alternating Current (AC) drive systems have been a viable alternative to Direct Current (DC) machines for variable speed applications. This increased interest in induction motors is because of its merits over the other types of industrial motors .These merits include: lightness, simplicity, ruggedness less initial cost, high torque-inertia ratio, capability of much higher speed, ease of maintenance etc [1].

Generally, an Induction Motor (IM) can run only at its rated speed when it is connected directly to the main supply. However, many applications need variable speed operations. In most of the applications the input power is directly proportional to the cube of motor speed. In certain applications like induction motor-based centrifugal pump, a speed reduction of 20% results in an energy saving of approximately 50% [2].

1.2 Problem Statement

In Roseires hydropower station sedimentation is one of the major problems that affects the total generation of electricity especially during the low level seasons .The transportation of materials such as sand and gravel block partly or totally the area in

front of the intakes of turbines that lead to decrease the amount of generated power. It also chemically affects some mechanical parts of the turbine (erosion problems). Dredgers are used to solve this problem. A dredger is a piece of equipment which can dig, transport and dump a certain amount of underwater laying soil in a certain time. A floating cutter suction dredger is employed to remove accumulated sediment in front of the intakes of power station turbines.

1.3 Objectives

This research deals Speed control of three phase induction motor driving heavy duty dredge pump. The main objectives of this research are:

- To optimize the dredging process by using a system of three phase induction motor and variable frequency drive to control the main heavy duty dredge pump.
- To control the pump speed to meet the variable requirements of the dredging areas.
- To Increase the bearing and pump seal life by maintaining only pressure needed in pump to satisfy system requirements.
- To save power and decrease maintenance cost.

1.4 Methodology

Centrifugal pumps are generally sized to operate at or near the best efficiency point at maximum flow. The maximum flow requirements, however, frequently occur for a very short period during the operating cycle with the result that some method of flow control is required. The traditional approach to flow control has used valves; which increase system pressure, inherently waste energy, and generally cause the pump to operate at lower efficiencies. Adjustable speed drives can achieve reduced flow by providing adjustable speed pump operation. This results in reduced system pressure and operation near the pump's best efficiency point. In addition, maintenance costs might be reduced.

Variable Frequency Drives (VFDs) are commonly used today in conjunction with large three phase induction motors to drive pumps. The VFD application can provide many operational and energy conservation advantages. However, the VFD and the motor must be designed as a system to realize the benefits and to avoid the potential pitfall. In this research speed control of induction motor connected to heavy duty dredge pump using variable frequency drive will be analyzed and discussed. MATLAB software is used to simulate the whole system. The MATLAB /SIMULINK is developed to perform DTC under torque and speed modes and the results will be discussed and compared.

1.5 Dissertation Outline

An introduction of this research gives a brief description about three phase induction motor and speed control methods. Pump motor application regarding dredge centrifugal pump using as a good solution for sedimentation problem in rosieres reservoir. The rest of the thesis is divided into the following chapters:

In chapter two, the basic concept of variable speed drives is briefly reviewed. The principles of induction motor drives are discussed. Also, the variable frequency drive components are addressed. Furthermore, the inverter topologies are discussed. Different induction motor control methods are then presented. Finally, the motor load types are discussed.

In chapter three, the mathematical model of the induction motor is introduced. The concepts of park's transformation and stationary reference frame equations are discussed. Finally, the theory of Direct Torque Control (DTC) is presented in details.

In chapter four, a simulation model in MATLAB /SIMULINK for a three phase induction motor driving heavy duty dredge pump using DTC method is carried out. A detailed description of the components of the model is illustrated and the results of simulation are shown and discussed.

Chapter five contains conclusion and recommendations.

CHAPTER TWO

THEORIES AND LITERATURE REVIEWS

2.1 Speed and Torque of Three Phase Induction Motor

The relationship between rotor speed, frequency, and slip is given by:

$$N_m = \frac{120f}{P}(1-S) \quad (2.1)$$

The rotational speed of an induction machine depends on the supply frequency, pole-pair number and slip of the motor. Since the AC power available from the mains ought to maintain constant voltage and frequency at all times, a power converter is required to modify the power flow appropriately [3].

For drives with constant inertia, the mechanical system of the motor and its load can be described by a fundamental torque equation:

$$T = T_\ell + J \frac{d}{dt} (\omega_m) \quad (2.2)$$

Where

T is the instantaneous value of the developed motor torque

T_ℓ is the instantaneous value of the load torque,

ω_m is the instantaneous angular velocity of the motor shaft and

J is the moment of inertia of the motor and its load.

Equation (1.2) shows that the torque developed by the motor is counter-balanced by a load torque, and a dynamic torque $J \frac{d}{dt} (\omega_m)$ which is present only during transient operation. The drive accelerates or decelerates depending on whether T is greater or less than T_ℓ . During deceleration, the dynamic torque has a negative sign. Therefore, it assists the motor developed torque T and maintains the drive motion by extracting energy from the stored kinetic energy. It is very important to control the torque and the

speed for drives for different applications. Figure 2.1 shows the typical Torque-Speed curve of the typical three-phase induction motor [4].

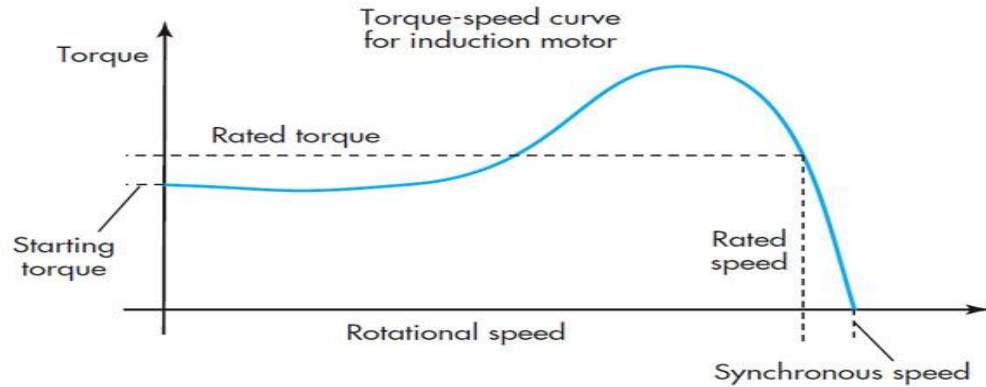


Figure 2.1: Torque-Speed curve of the typical three-phase induction motor

2.2 Centrifugal Dredge Pump

Centrifugal Pump can be defined as a mechanical device used to transfer liquid of various types. As the name suggests, it relies on the principal of Centrifugal force. It converts the energy provided by a prime mover, such as an electric motor, steam turbine, or gasoline engine, to energy within the liquid being pumped [5]. The main parts of centrifugal pump are shown in figure 2.2.

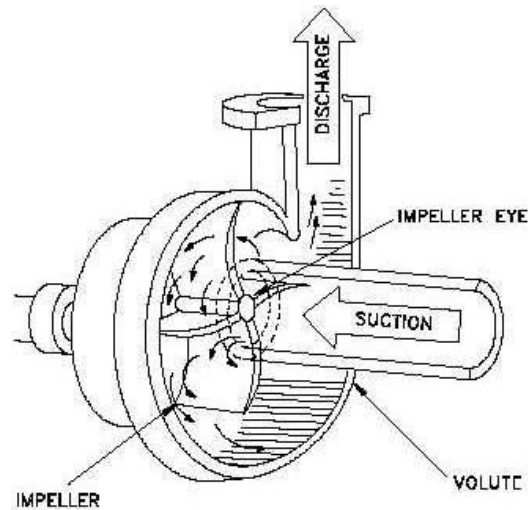


Figure 2.2: Main Parts of Centrifugal Pump

2.2.1 Working principles

Water enters the center (eye) of the impeller and exits the impeller with the help of centrifugal force. As water leaves the eye of the impeller a low-pressure area is created, causing more water to flow into the eye. Atmospheric pressure and centrifugal force cause this to happen. Velocity is developed as the water flows through the impeller spinning at high speed. The water velocity is collected by the diffuser and converted to pressure by specially designed passageways that direct the flow to the discharge of the pump, or to the next impeller should the pump have a multi-stage configuration. A centrifugal pump is not positive acting; it will not pump the same volume always. The greater the depth of the water, the lesser is the flow from the pump. Also, when it pumps against increasing pressure, the less it will pump. For these reasons it is important to select a centrifugal pump that is designed to do a particular job [5, 6].

2.2.2 Effect of speed variation

There is a relationship between impeller peripheral velocity and generated head. Peripheral velocity is directly related to shaft rotational speed, for a fixed impeller diameter and so varying the rotational speed has a direct effect on the performance of the pump. All the parameters will change if the speed is varied and it is important to have an appreciation of how these parameters vary in order to safely control a pump at different speeds [6].

The performance characteristic of a pump when operating at different speeds than the speed at which it has been tested is predicted by using Affinity Laws .the mathematical relationships for this law is given below ,constant size of impeller is assumed:

Flow: Flow is proportional to the speed

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \quad (2.3)$$

Head: Head is proportional to the square of speed

$$\frac{H_1}{H_2} = \frac{(N_1^2)}{(N_2^2)} \quad (2.4)$$

Power (kw): Power is proportional to the cube of speed

$$\frac{P_1}{P_2} = \frac{(N_1^3)}{(N_2^3)} \quad (2.5)$$

The subscript 1 denotes the original value and the subscript 2 denotes a new value. As can be seen from the above laws, doubling the speed of the centrifugal pump will increase the power consumption by 8 times. Conversely a small reduction in speed will result in drastic reduction in power consumption. This forms the basis for energy conservation in centrifugal pumps with varying flow requirements. The implication of this can be better understood as shown in an example of a centrifugal pump Figure 2.3 below [6, 7].

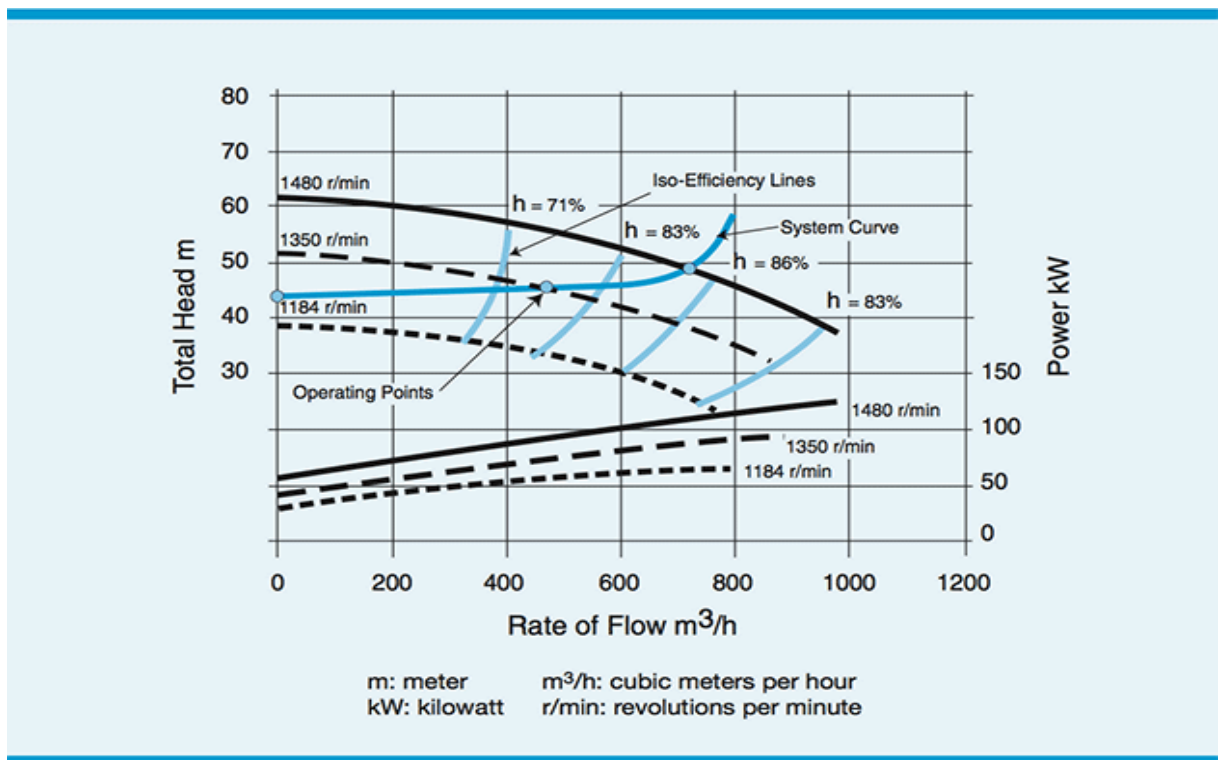


Figure 2.3: Speed Variations Effecting Centrifugal Pump curve Performance

2.2.3 Effect of variable speed drives

Pump speed adjustments provide the most efficient means of controlling pump flow. By reducing pump speed, less energy is imparted to the fluid and less energy needs to be throttled or bypassed. Variable speed drives (VSDs) control pump speeds using several different types of mechanical and electrical systems. Mechanical VSDs include hydraulic clutches, fluid couplings, and adjustable belts and pulleys. Electrical VSDs include eddy current clutches, wound rotor motor controllers, and variable frequency drives (VFDs). VFDs adjust the electrical frequency of the power supplied to a motor to change the motor's rotational speed. VFDs are by far the most popular type of VSDs

2.2.4 Plain suction dredger

A plain suction dredger is a stationary dredger that position on one or more wires, with at least one dredge pump, which is connected to the suction pipe and the delivery pipe. The suction pipe is situated in a well in front of the pontoon. Good production can only achieved by this kind of dredgers either the soil is free running sand or the cut or breach height is sufficient (at least 10 m). Dredge pump is simply a centrifugal pump with some special characteristics. The discharge of the soil sucked is done either by pipeline or by barges. Most suction dredgers are equipped with jet water pump(s) to assist either the beaching process or to improve the mixture forming process near the suction mouth [8].

2.3 Variable Speed Drives Basics

For many years, the application of variable speed controls in industry is dictated by the process requirements, and limited by the available technology. Performance requirements took precedence over considerations of first cost, maintenance, and efficiency. The constant speed AC motor was usually used as the prime conversion from electrical to mechanical energy. To obtain variable speeds for machine operations, the motor required a secondary energy conversion using mechanical, hydraulic, or variable voltage DC generating equipment. While it was possible to develop very sophisticated control systems, every step in the conversion, including

signal-amplifying exciters, added power losses, making the total installation relatively inefficient. For the purpose of this research, a drive can be defined as a method of providing variable speed and/or torque to a machine input shaft. The most common source of power is the electric induction motor, which has a constant speed characteristic when connected directly to the power source. Generally there are five categories of electric drives [9]:

2.3.1 Hydraulic motor drives

Hydraulic motors convert hydraulic power to mechanical rotating force. Their rotating speed can be steplessly adjusted by controlling the supply flow, while their output torque depends on the difference between the motor inlet and outlet pressure. The motors are available in gear, vane and piston types, as are the hydraulic pumps. Piston motors with variable displacement are also available.

2.3.2 Mechanical motor drives

Mechanical motor drives consist of a power source, actuators, a system of mechanisms and a controller with sensors. They are less costly than competing electrical drives and their control is much simpler. They are used in industries ranging from aerospace to mining and heavy industry. The mechanical motor drive converts electrical energy into mechanical energy. Mechanical speed control products include gearing, mechanical transmissions and belt drives with variable pitch pulleys. They are the traditional adjustable speed drives and used in a large variety of machinery.

2.3.3 DC motor drives

DC motor consists of magnetic field flux (excitation) circuit placed on the stator, armature circuit placed on the rotor and a commutator which inverts the current in an armature coil whenever it passes through the neutral zone that is perpendicular to the stator field axis. The power is transferred to the armature through brushes that are fixed in the neutral zone and lean to the commutator. The excitation and armature circuit can be connected separately from each other, or a series or parallel connection

can utilize instead. The separately excited DC motors are mostly used in controlled drives, owing the possibility independent field and armature current control and related superior control features in wide range of speed. The speed of a DC motor is inversely proportional to motor flux and directly proportional to armature voltage. Both motor flux and armature voltage can be used to control the motor speed. There are electronic devices that control DC motors by changing the voltage applied to the motor. Traditional Variable Speed Drives (VSDs) device are used almost exclusively for constant load (cranes, elevators, hoists) and close speed control or positioning (plastic calendaring, metal rolling processes and machine tools).

2.3.4 Eddy current drives

Electromagnetic drives, or eddy-current couplings, have more in common with mechanical adjustable speed drives than they do with other electrical drives. These drives use a speed adjustment mechanism located between a constant-speed motor and the load rather than an adjustable voltage or frequency power supply controlling the speed of DC or AC motors. Another aspect in common with mechanical drives is that they are inherently single-motor units. The drive unit consists of a constant-speed AC induction motor and a magnetic clutch or eddy-current coupling. The variable-speed output shaft is rotated for the constant-speed ac motor through the action of the eddy-current coupling [10].

2.3.5 AC motor drives

AC motor drives are much more complex than the DC system. It is necessary to convert AC power to DC, and then invert it back to a variable frequency system. Often the AC system has to be larger to provide the equivalent torque at certain operation speeds. AC VSDs are electronic devices that control the speed of the motor by controlling the frequency of the voltage at the motor. These devices are used in a wide range of the applications and are able to provide constant-torque and variable-torque operation, and in the last few years have been developed to achieve position control. They are used in virtually every type of motor system from pumps and fans to web roll

control, machine tools, and many others. This thesis is mainly about AC induction motor drives.

2.4 Principles of Induction Motor AC Drives

Induction motor control is implemented through what is commonly known as an electrical drive. Though definitions may vary, the electrical drive consists of electronic control systems, measurement systems, power electronic devices and often the motor itself. The term frequency converter is commonly used when dealing with AC drives, based on the principle of speed control through variation of electrical supply frequency; other more generic terms used in flow control applications include Adjustable Speed Drive (ASD), VSD and VFD [11].

In this chapter, the main components of a typical AC drive, the frequency converter and its control schemes are illustrated in figure 2.4.

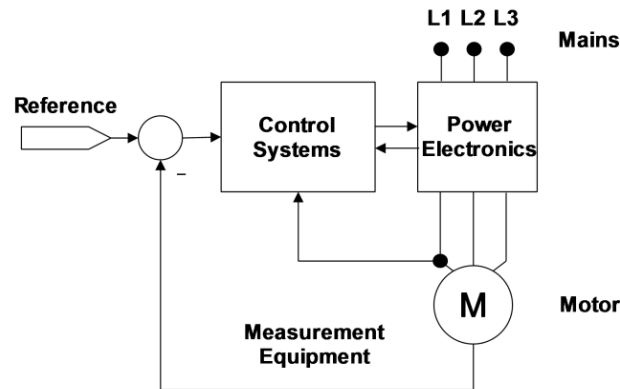


Figure 2.4: Basic configuration of an electrical AC drives

2.5 Variable Frequency Drive components

Variable Frequency Drive (VFD) can be used to control the speed of three-phase induction motor. A variable frequency drive is a system equipped for controlling the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electrical power supplied to the motor. The basic components of the VFD are explained as shown in figure 2.5.

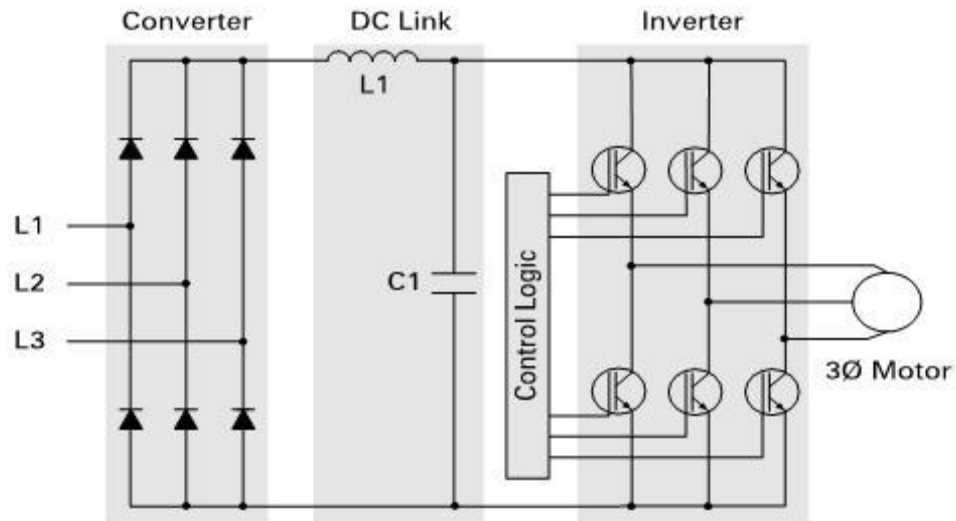


Figure 2.5: Schematic of the variable speed drive connected to an induction motor

2.5.1 Converter stage (rectifier)

The rectifier in a VFD is used to convert incoming AC power into direct current power. There are three pairs of rectifier combination is used for converting three phase AC into DC. Rectifiers can be built using diodes, Silicon Controlled Rectifiers (SCR), or transistors to rectify power. The three-phase AC voltage is converted into a rippling DC voltage in this stage. Figure 2.6 shows the rectifier circuit.

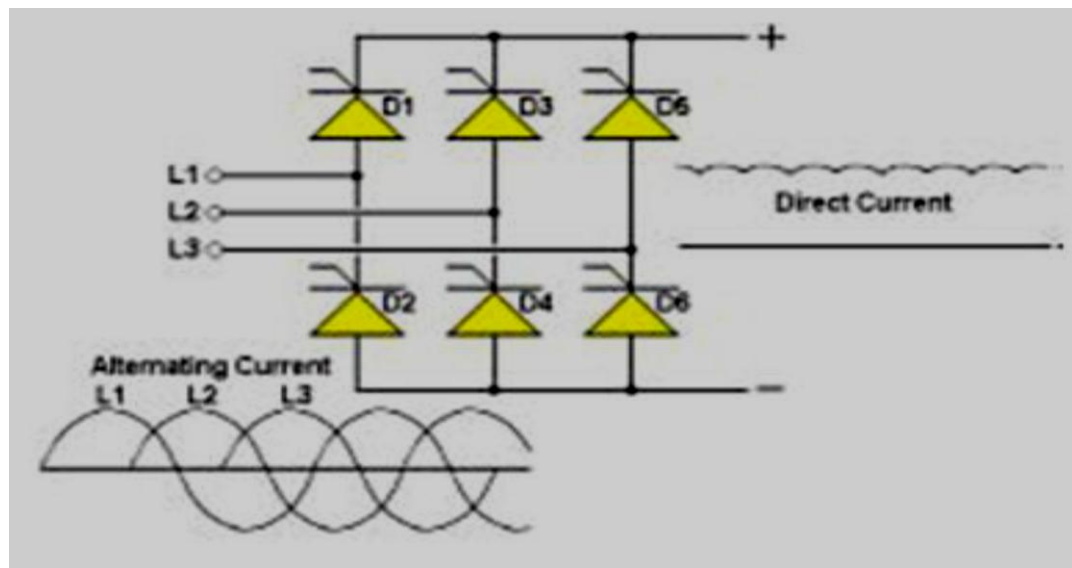


Figure 2.6: rectifier circuits

2.5.2 Intermediate circuit (DC bus)

The intermediate circuit also known as a DC link can be seen as a power storage facility for the inverters. The intermediate circuits smooths and holds the DC voltage at a constant level or energy source for the inverter. There are two major components to the DC link section, capacitors and coils.

2.5.3 Inverter stage

The final section of the VFD is referred as an inverter. The inverter contains transistors that deliver power to the motor. The Insulated Gate Bipolar Transistor (IGBT) is a commonly used one in modern VFDs. The IGBT can switch on and off several thousand times per second and precisely control the power delivered to the motor. Figure 2.7 shows the inverter circuit.

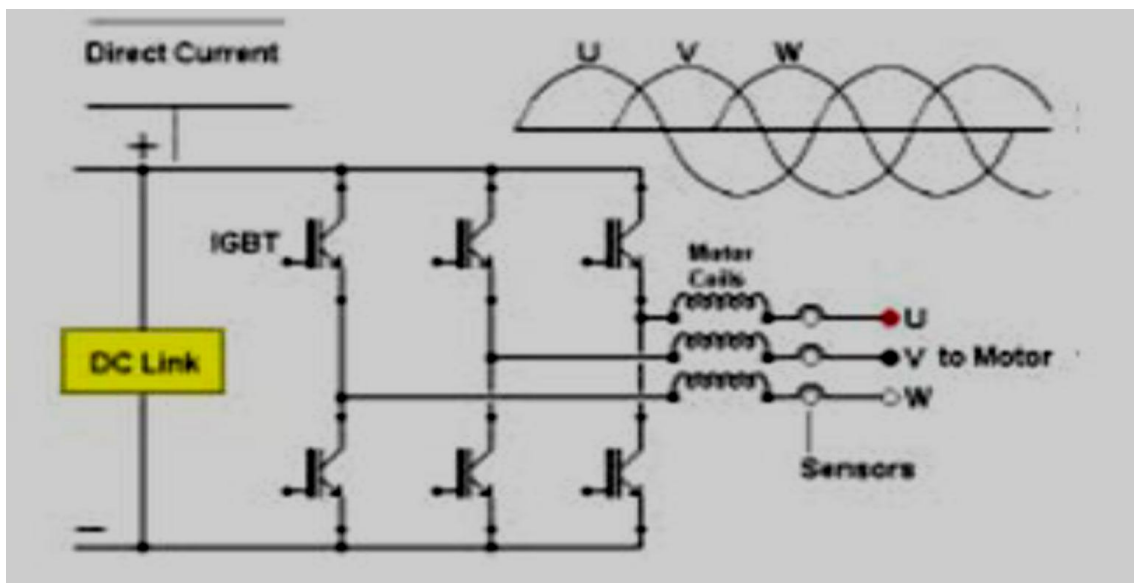


Figure 2.7: Inverter Circuit

2.5.4 Inverter control system

An electronic circuit receives feedback information from the driven motor and adjusts the output voltage or frequency to the selected values. Usually the output voltage is regulated to produce a constant ratio of voltage to frequency. Controllers may incorporate many complex control functions.

2.6 Inverter topologies

The energy storage element can be either an inductor or a capacitor, creating a current source or a voltage source respectively. Even though the inverter stage is usually at the end of the power processing chain, it is commonplace to name the whole system an inverter. When the energy storage element is an inductor, the unit is called a Current Source Inverter (CSI); in the case of a capacitor, the term Voltage Source Inverter (VSI) is used instead.

2.6.1 Voltage Source Inverter (VSI)

A voltage source inverter uses a fixed DC voltage (shunt capacitors) supplied by the converter stage via passive rectification and recreates an output sine wave. The voltage output is fixed and independent of load impedance and using pulse width modulation, consists of a modulated series of voltage pulses which alternate in polarity. The voltage pulse waveform is supplied to the motor stator windings and the inductance acts as a filter to re-create a close approximation of a current sine wave. By varying the voltage pulse width and frequency, the current sine wave amplitude and frequency can be varied to provide speed and torque control of the motor. Figure 2.8 shows the typical VSI configuration for induction motor drives [12].

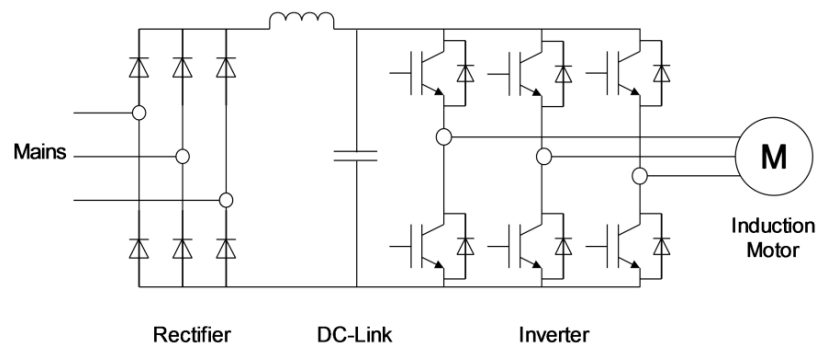


Figure 2.8: Typical VSI configuration for induction motor drives

However, at the expense of higher harmonic content and control requirements, the size of a capacitor of VSI can be reduced significantly. A VSI can also be suitable for multi-motor applications and a wide degree of design variations can be found.

Therefore, a VSI yields a degree of versatility not commonly found in other configurations, making it one of the most widely used converters in industry.

2.6.2 Current Source Inverters (CSI)

A current source inverter is the dual of a voltage source inverter. It uses a fixed DC current (series reactors) supplied by the converter stage via passive rectification. The current output is fixed, independent of load impedance and using pulse width modulation and consists of a modulated series of current pulses which alternate in polarity. The current pulse waveform is supplied to the motor stator windings and the inductance acts as a filter to re-create a close approximation of a voltage sine wave. By varying the current pulse width and frequency, the voltage sine wave amplitude and frequency can be varied to provide speed and torque control of the motor. Figure 2.9 shows the current source inverter [12].

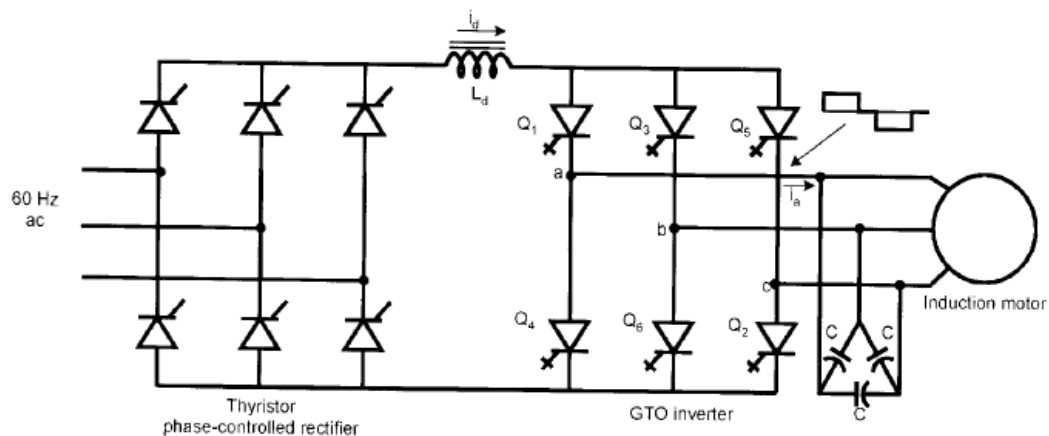


Figure 2.9: Current source inverter

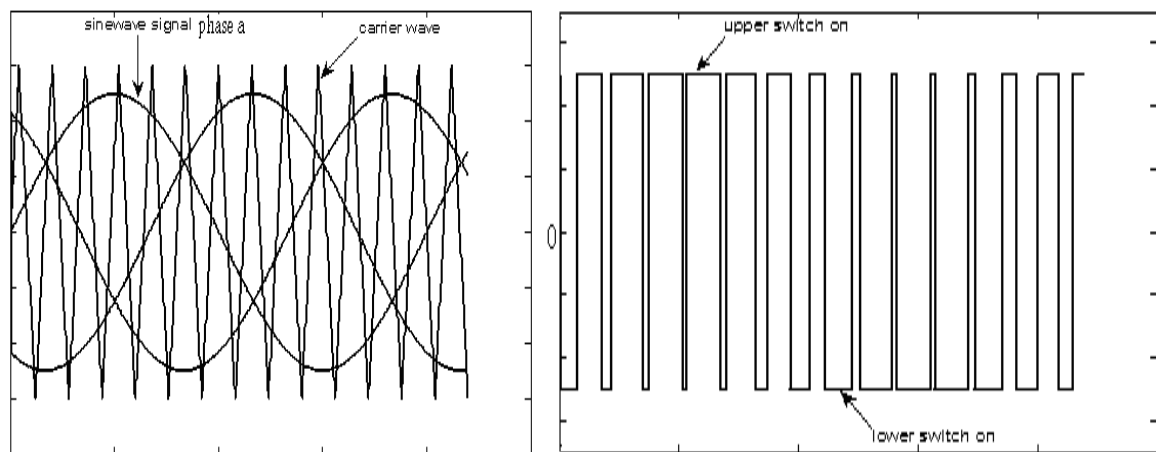
2.7 Pulse Width Modulation Technique

The most efficient method of controlling output voltage is to incorporate Pulse Width Modulation (PWM) control within inverters. In this method, a fixed DC voltage is supplied to inverter and a controlled AC output voltage is obtained by adjusting on-off period of inverter devices. PWM variable speed drives are increasingly applied in many new industrial applications that require superior performance. Recently, developments in power electronics and semiconductor technology have lead

improvements in power electronic systems. Hence, different circuit configurations namely PWM inverters have become popular and considerable interest by researcher are given on them. A number of PWM schemes are used to obtain variable voltage and frequency supply. When a PWM signal is applied to the gate of a power transistor, it causes the turn on and turns off intervals of the transistor to change from one PWM period to another PWM period according to the same modulating signal. The frequency of a PWM signal must be much higher than that of the modulating signal, the fundamental frequency, such that the energy delivered to the motor and its load depends mostly on the modulating signal. In this section, three of the most popular continuous methods for induction motor drives are discussed [13].

2.7.1 Sinusoidal PWM

The most popular PWM approach is the sinusoidal PWM. In this method a triangular (carrier) wave is compared to a sinusoidal wave of the desired fundamental frequency and the relative levels of the two signals are used to determine the pulse widths and control the switching of devices in each phase leg of the inverter. Therefore, the pulse width is a sinusoidal function of the angular position of the reference signal. The basic principle of three phases sinusoidal PWM is shown in Figure 2.10.



(a) Sine wave and carrier signals

(b) States of switches of phase a

Figure 2.10: Principle of three phase sinusoidal PWM

The sinusoidal PWM is easy to implement using analog integrators and comparators for the generation of the carrier and switching states. However, due to the variation of the sine wave reference values during a PWM period, the relation between reference values and the carrier wave is not fixed. This results in existence of harmonics in the output voltage causing undesired low-frequency torque and speed pulsations. The switching frequency is not constant and very narrow pulses may occur depending on the intersection between the carrier wave and the sine reference [14].

2.7.2 Space vector modulation

Space vector modulation is a PWM control algorithm for multi-phase AC generation, in which the reference signal is sampled regularly; after each sample, non-zero active switching vectors adjacent to the reference vector and one or more of the zero switching vectors are selected for the appropriate fraction of the sampling period in order to synthesize the reference signal as the average of the used vectors. The topology of a three-leg voltage source inverter is because of the constraint that the input lines must never be shorted and the output current must always be continuous a voltage source inverter can assume only eight distinct topologies. Six out of these eight topologies produce a nonzero output voltage and are known as non-zero switching states and the remaining two topologies produce zero output voltage and are known as zero switching states. As shown in this figure2.11, the voltages applied to machine is defined as V_{an}, b_n, c_n and the V_{aN}, bN, cN denote the pole voltages produced in the inverter stage in this research [15].

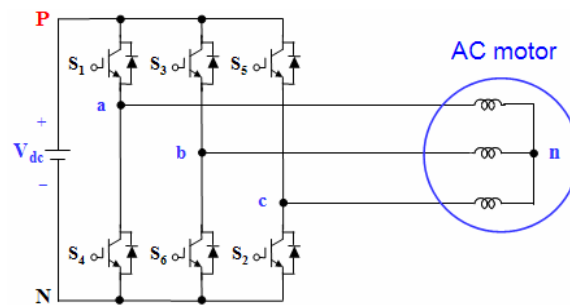


Figure 2.11: Three phase inverter fed induction motor

The available eight different switching states of the three phase inverter are depicted in the Figure 2.12. Note that all the machine terminals are connected to each other electrically and no effective voltages are applied to machine when the zero vectors presented by V_0 and V_7 are selected.

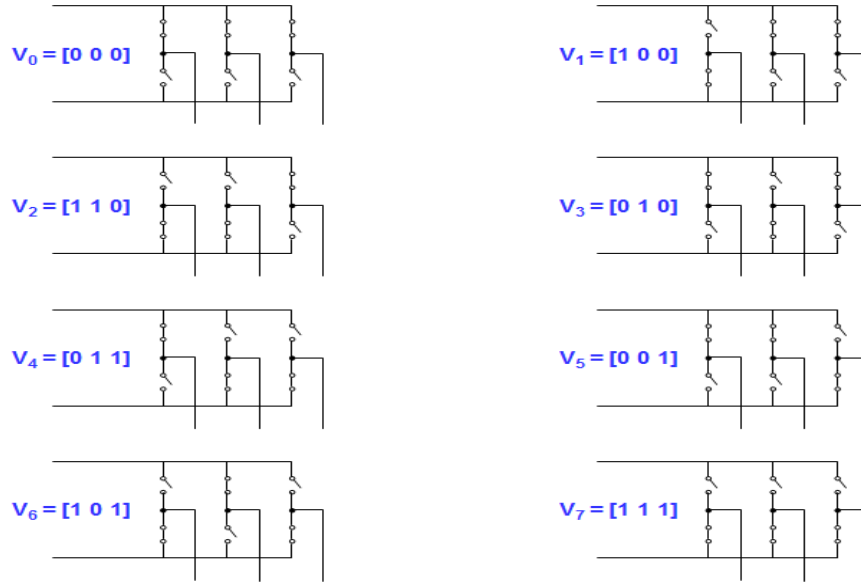


Figure 2.12: The eight inverter voltage vectors (V_0 to V_7)

Therefore, the six voltage vectors can be selected to apply an effective voltage to the machine and these vectors can be located on the vector space represented with the stator fixed d-q reference frame as shown in the figure 2.13.

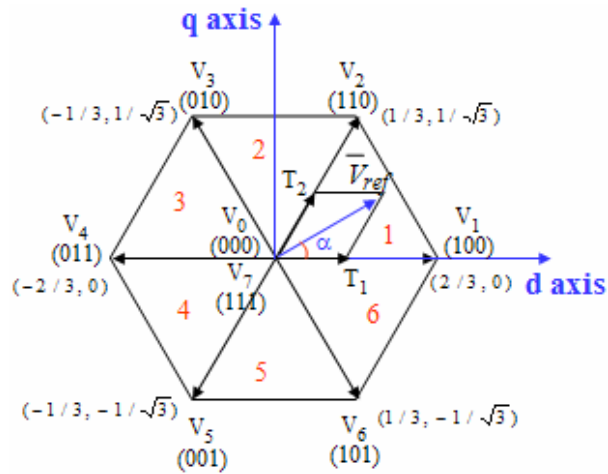


Figure 2.13: Space vector diagrams of the effective vectors

There are so many techniques which are used for controlling of induction motor drives. Space Vector Pulse Width Modulation (SVPWM) technique improves the quality of the current and reduces the torque ripple in induction motor drive efficiently while maintaining the other performance characteristics of the system [15].

2.7.3 Hysteresis band PWM

The Hysteresis Band PWM (HBPWM) is basically an instantaneous feedback current control method of PWM where the actual current continually tracks the command current within a specified hysteresis band. Figure 2.14 explains the operation principle of HBPWM for a half bridge inverter.

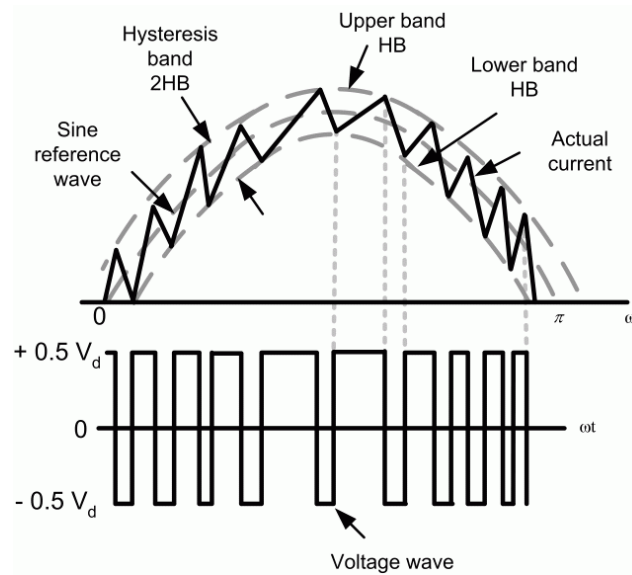


Figure 2.14: Principle of hysteresis-band current control

The control circuit generates the sine reference current wave of desired magnitude and frequency, and it is compared with the actual phase current wave. As the current exceeds a prescribed hysteresis band, the upper switch in the half-bridge is turned off and the lower switch is turned on. As a result the output voltage transitions from $+0.5V_d$ to $-0.5V_d$, and the current starts to decay. As the current crosses the lower band limit, the lower switch is turned off and the upper switch is turned on. The actual current wave is thus forced to track the sine reference wave within the hysteresis band by back- and-forth switching of the upper and lower switches. The inverter then

essentially becomes a current source with peak to peak current ripple, which is controlled within the hysteresis band irrespective of V_d fluctuation. The peak-to-peak current ripple and the switching frequency are related to the width of the hysteresis band. The HBPWM inverter control method is shown in the Figure 2.15 the inputs to the HBPWM controller are three phase current errors and the outputs are the switching patterns to the PWM inverter. Where k is the normalization factor and is used for the purpose of scaling the current error input to the HBPWM controller. The Pulse Separation PS circuit is used for the separation of pulses to the IGBTs in the upper and lower leg of the inverter [16].

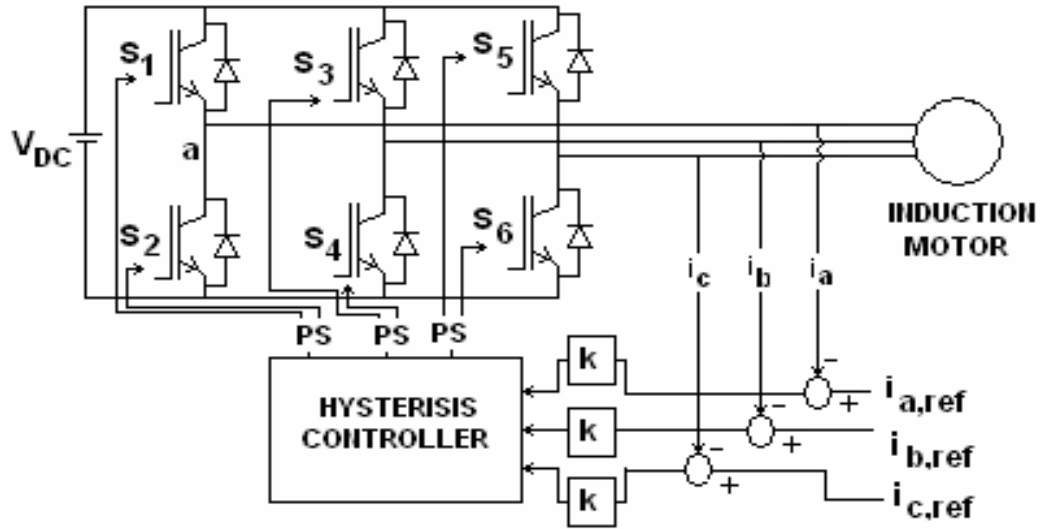


Figure 2.15: Conventional HBPWM inverter control method

Hysteresis-band current control is very popular because it is simple to implement, has fast transient response, direct limiting of device peak current and practical insensitivity to machine parameters because of the elimination of any additional current controllers. However, PWM frequency is not fixed which results in non-optimal harmonic ripple in machine current. The current error is not strictly limited and may leave the hysteresis band. There is no interaction between the three phases. These drawbacks limit the application of this approach into special applications.

2.8 Induction Motor Control Strategies

In motor drive systems, it is usually desired to control torque and rotational speed. In more demanding applications such as machine tools, servo mechanisms and robotic arms precise position control might be required as well.

There are many different ways to drive an induction motor. In the past simple control techniques had been applied such as pole changing, variable rotor resistance and variable supply voltage. Now, there are a number of significant control techniques available of induction motors, the most popular control methods are:

2.8.1 Scalar control

The scalar control is based on changing any one parameter like frequency, slip or pole. The speed can be changed by increasing or decreasing in frequency but this result in change of impedance. This in turn is the reason for change in current drawn by the motor. Reduction in supply frequency increase the air gap flux which result in saturation of the core. To avoid these problems, it is necessary to vary the frequency and the voltage at the same time. The scalar control technique gives constant flux in the stator as:

$$V_{rms}=4.44 N f \Psi \zeta \quad (2.6)$$

The torque-speed equation of induction motors reveals the voltage-torque-frequency relation, given by:

$$T_{ag}=\frac{3}{2\omega_m} I_r^2 \frac{R_r}{s} \quad (2.7)$$

From Equation (2.8) it reveals that frequency and torque is inversely proportional, while voltage is directly proportional to torque.

$$T \approx \frac{V^2}{2\pi f} \approx \frac{V}{f} \quad (2.8)$$

Where

V_{rms} =induced voltage in the stator.

f = frequency of the supplied voltage.

N =number of turns.

ψ =flux linkage in stator.

ζ =constant of coil.

In scalar (V/f) control of IM drive, both torque and flux are functions of stator voltage (V) and its frequency (f).Figure 2.16 shows frequency-voltage-torque curve.

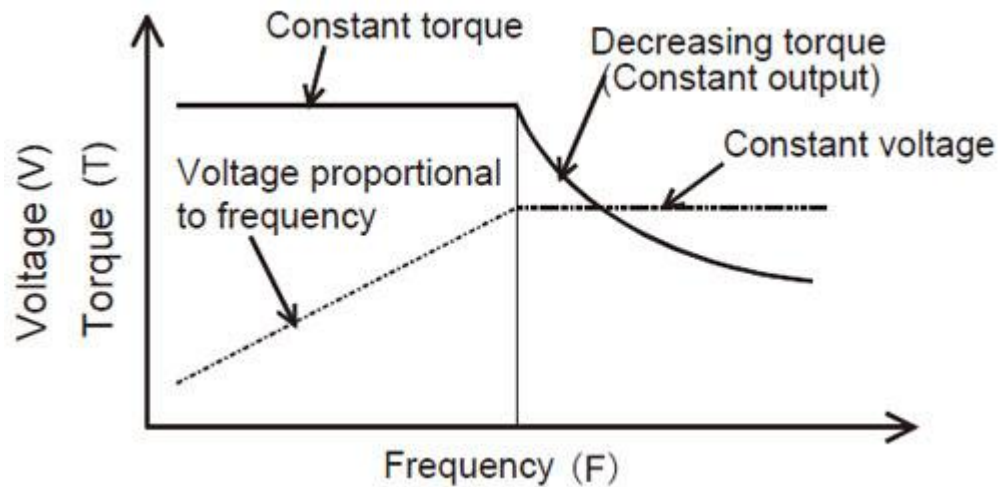


Figure 2.16: Frequency-voltage-torque curve

Thus, there is a coupling effect between flux and torque i.e. if torque is to be increased then we need to increase the stator frequency (slip) and when we change the stator frequency the corresponding stator voltage needs to be changed so as to maintain constant flux by making (V/f) ratio constant. During transient-state it is not possible to maintain the Victorian relationship between the flux- and torque producing components of the stator current and therefore degrades the drive performance. Scalar control presents strong dependency on the machine parameters, which variations cannot be compensated due to the lack of the signals feedback. If it is not handled properly, this will lead to poor performance of the drive. In scalar control, the torque developed is load dependent, as it is not controlled directly. Also, the transient response of such a control is not fast due to the predefined switching pattern of the

inverter. Because of this, motors under scalar control must be oversized in order to deliver the required torque during load transients. In addition, scalar techniques result in an inefficient system, power factor degradation in the utility's network and noisy operation is resulted. The main types of scalar control are [17]:

I. Open loop V/f speed control

Due to simplicity, low cost and immune from feedback system, open loop V/f control system is widely used in industry where precision is not great concern. Figure 2.17 shows the diagram of open loop V/f control technique.

Frequencies are defined from required speed and rough assumption is made that motor follow its synchronous speed. Required voltage is determined from V/f curve given by motor manufacturer.

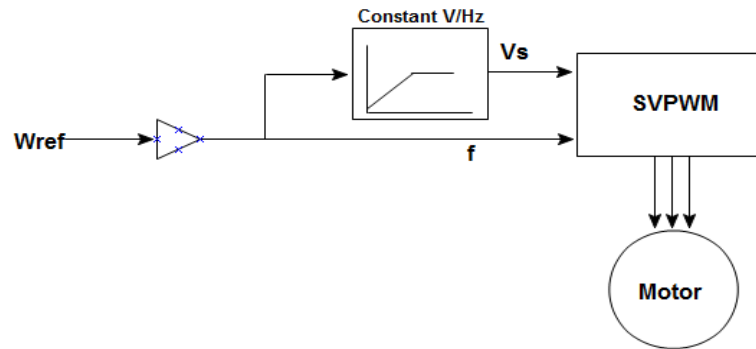


Figure 2.17: diagram of open loop V/f control

II. Close loop speed control

Major disadvantage in open loop control is that this technique doesn't control the torque so desired torque accessible only at nominal operating point. Torque control is provided by close loop and it gives more precious speed control. Figure 2.18 shows the diagram of close loop V/f control technique As shown in block diagram of close loop control speed is sensed by tachometer and it's compared with reference speed which gives error signal. Error signal is fed to PID controller which tries to reduce error to zero and according to PID output frequency and voltage is define for SVPWM inverter.

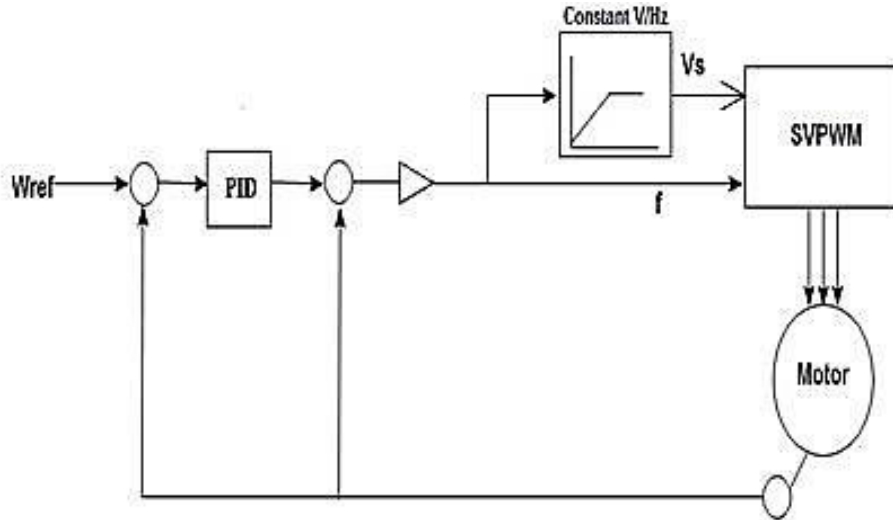


Figure 2.18: Diagram of close loop V/f control

It is clear that the V/Hz control does not take into account any dynamic characteristic of the induction machine, and therefore its transient performance is rather low. Closed-loop V/Hz control attempts to improve this situation by measuring or estimating rotational speed and control slip or even torque. However, the simplicity and economy of an open-loop approach remains the most important factor in scalar control drives, as the performance improvements in closed-loop are no match for more advanced control systems and quite often do not justify the added complexity and cost.

2.8.2 Vector control

The drawback of scalar control of IM drive can be overcome by using Vector Control (VC) or Field Oriented Control (FOC). In FOC of Induction Motor (IM) drive, the complex and coupled structure of induction machine is transformed into a rotating reference-frame in which the machine can be considered just as a decoupled separately-excited DC machine. Just like in a separately-excited dc motor the armature and field currents are decoupled and therefore can be controlled independently (which allows it to maintain constant flux below the base speed). Similarly in ac machines, we split the stator current, into two decoupled orthogonal currents namely, the direct-axis current (i_{ds}) and quadrature-axis current (i_{qs}) as shown in Figure 2.19[18].

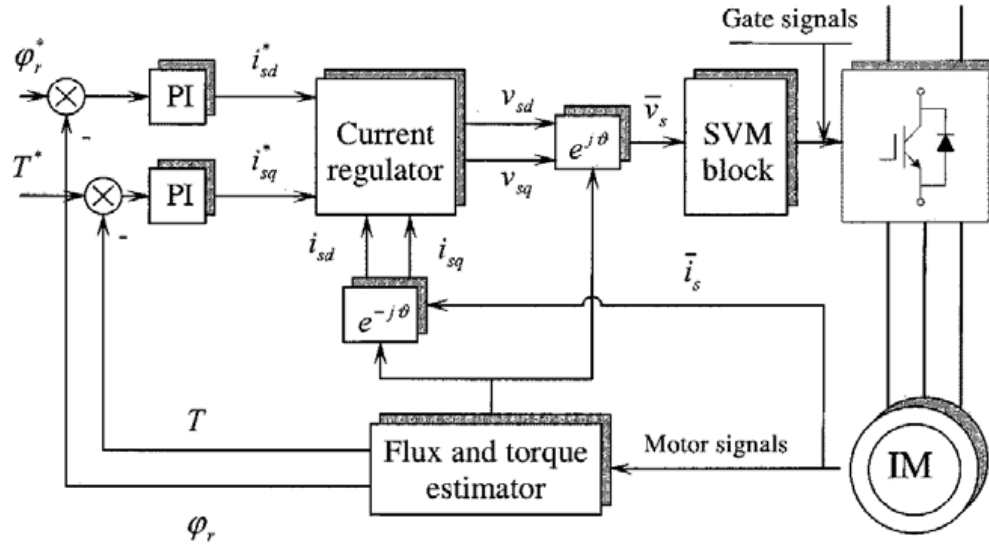


Figure 2.19: Basic Field-oriented control of induction motor drive

Development of vector control analysis has enabled us to get as good dynamic performance from an IM as a DC motor. The torque and the flux components can be controlled independently using vector control just like in a DC motor. In order to analyse vector control, a dynamic model of the IM is developed. This is done by converting the 3- ϕ quantities into 2-axes. There are two types of vector control:

I. Direct field oriented control

The Direct Field Oriented Control (DFOC) method depends on the generation of unit vector signals from the stator or air-gap flux signals. The air-gap signals can be measured directly or estimated from the stator voltage and current signals. The stator flux components can be directly computed from stator quantities. In these systems, rotor speed is not required for obtaining rotor field angle information [28]. In direct field oriented control strategy rotor flux vector is either measured by using a flux sensor mounted in air gap or mathematically by using the voltage equations starting from the electrical machine parameters. Figure 2.20 shows the direct field oriented control scheme [18].

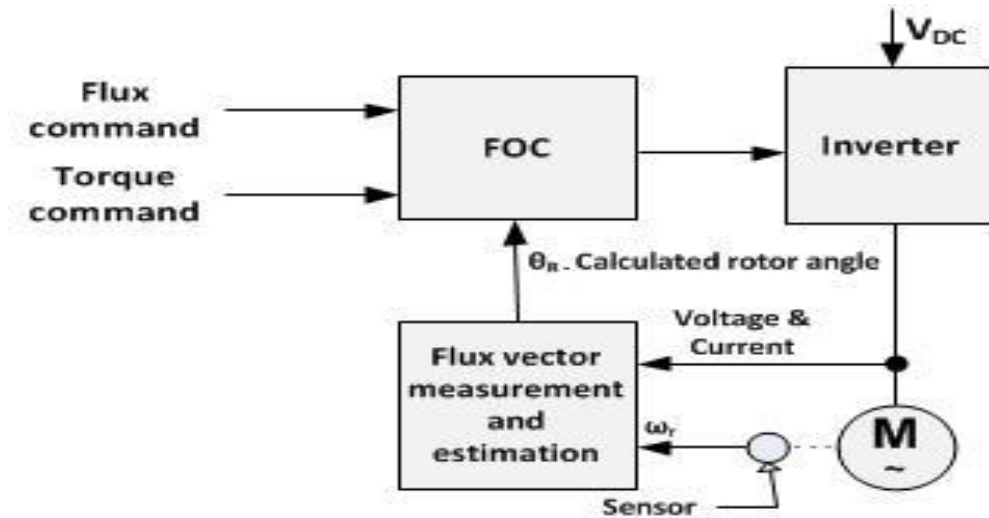


Figure 2.20: Direct field oriented control scheme

II. Indirect field oriented control

In the Indirect Field Oriented Control (IFOC) method, the rotor field angle and thus the unit vectors are indirectly obtained by summation of the rotor speed and slip frequency [28]. In indirect vector control strategy rotor flux vector is estimated by using the field oriented equations (current model) requiring a rotor speed measurement. IFOC is more popular than DFOC due to implementation simplicity and become the industrial standard .Figure 2.21 shows the IFOC scheme.

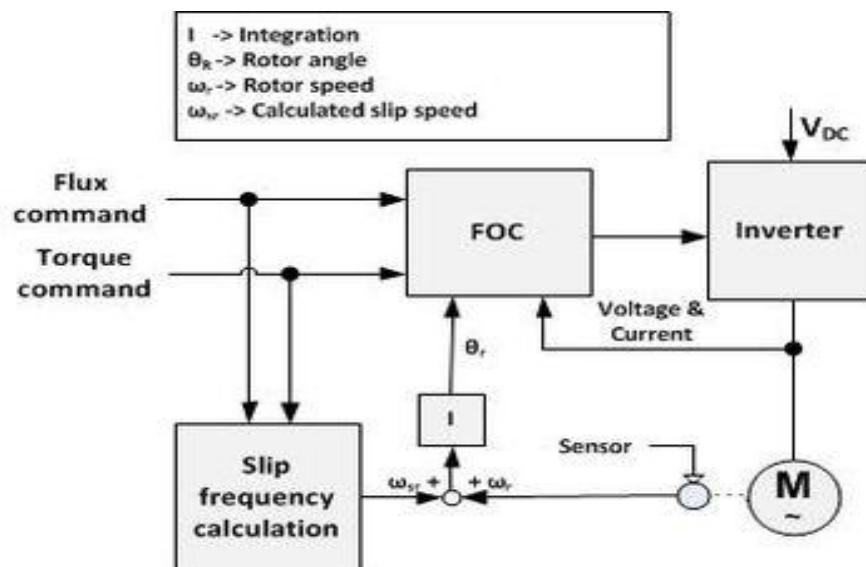


Figure 2.21: Indirect field oriented control scheme

2.8.3 Sliding mode control

Variable Structure Control (VSC) with sliding mode, or Sliding Mode Control (SMC), is one of the effective nonlinear robust control approaches since it provides system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode. The first step of SMC design is to select a sliding surface that models the desired closed-loop performance in state variable space. Then the control should be designed such that system state trajectories are forced toward the sliding surface and stay on it. The system state trajectory in the period of time before reaching the sliding surface is called the reaching phase.

Once the system trajectory reaches the sliding surface, it stays on it and slides along it to the origin. The system trajectory sliding along the sliding surface to the origin is the sliding mode. The insensitivity of the control system to the uncertainties exists in the sliding mode, but not during the reaching phase. Thus the system dynamics in the reaching phase is still influenced by uncertainties. The idea of sliding mode is shown in figure 2.22[19].

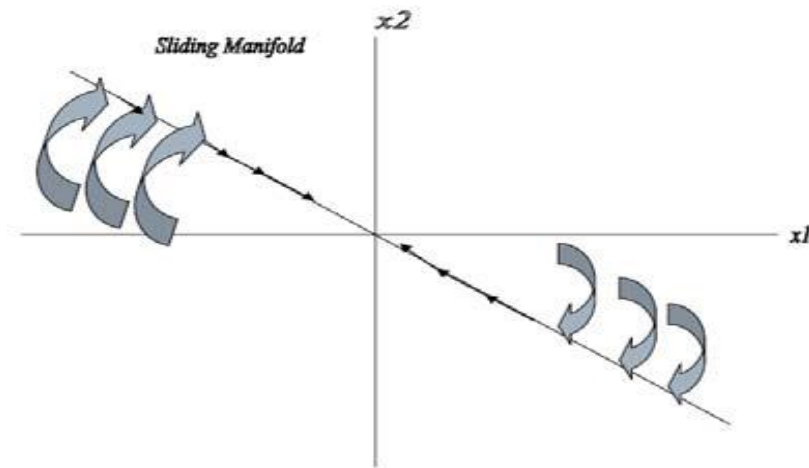


Figure 2.22: Idea of sliding mode

SMC techniques are applicable to any minimum phase systems with relative degree less than the system order. The control algorithm is based on the model of the motor in a frame rotating with stator current vector, which is rarely used in the field oriented control.

2.8.4 Direct torque control

DTC is a technique used in variable frequency drive for controlling the torque and finally the speed of three phase AC motor drive. It includes calculation of an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor. DTC has a simple control scheme and also very less computational requirement, such as current control, rotor position measurement, PWM control and co-ordinate transformation is not required. The main feature of DTC is simple control scheme, good dynamic behavior, decoupled control of torque and flux, absence of mechanical transducers, reduced parameter sensitivity, high performance and efficiency. By DTC principle, an independent management of torque and flux can be attained by the use of suitable voltage vectors in such a manner that the error between the estimated torque and flux with its reference values will remain within the limits of hysteresis comparators. The desired voltage vectors are chosen for compensating the errors based on the torque and flux hysteresis comparator output and the locus of stator flux vector from the basic equation governing induction motor operation stator flux. The basic DTC scheme is shown in Figure 2.23.

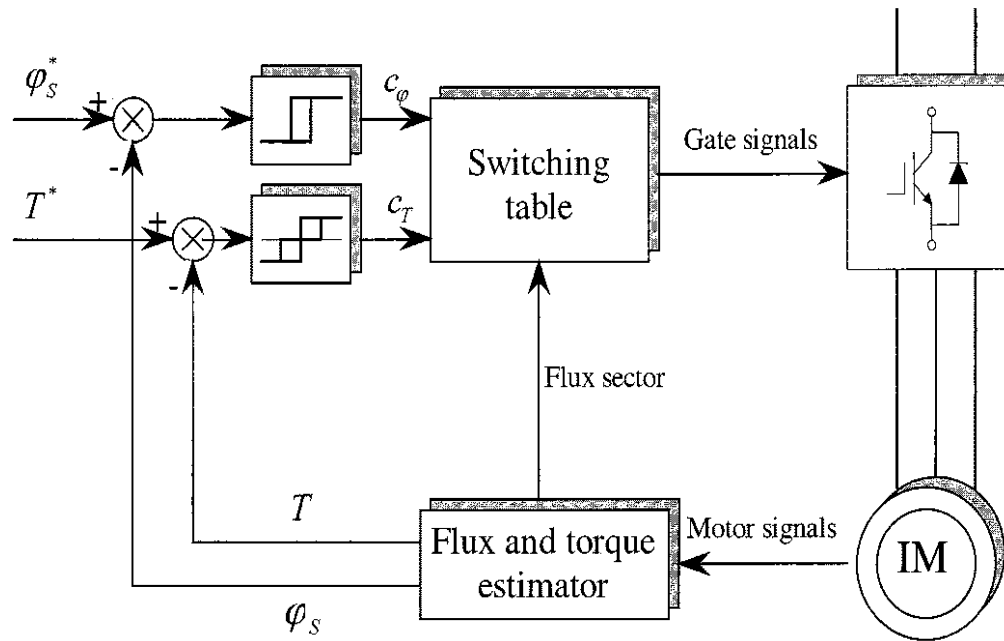


Figure 2.23: Basic DTC scheme

On the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within prefixed band limits. Unlike FOC, DTC does not require current regulators, coordinate transformations or a PWM modulator (as a consequence timers are not required). In spite of its simplicity, DTC allows for good torque control in both steady-state and transient operating conditions [20].

2.9 Motor Load Types

In order to make a correct selection of a VSD unit for an application, the load type and the demand of the driven system needs to be established. The load demand is achieved by changing the speed of the motor driving the system. Motor torque /Speed characteristic are very important, because the motor provides the torque that the load requires and not the VSD. VSD (Inverter) only provides speed change and the current to drive the motor. So the sizing of the motor to provide power and torque and rated speed is critical. Then based on the selected motor and load type a VSD can be selected. VFD applications can be divided into the following individual motor load types.

2.9.1 Constant torque loads

Figure 2.24 shows the constant torque load curve.

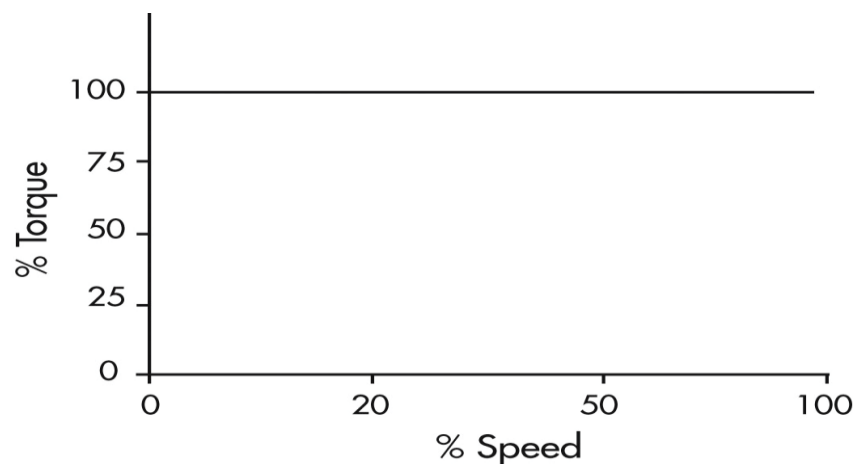


Figure 2.24: Constant torque load curve

A constant torque load is characterized as one in which the torque is constant regardless of speed. As a result the horsepower requirement is directly proportional to the operating speed of the application and varied directly with speed. Since torque is not a function of speed, it remains constant while the horsepower and speed vary proportionately. Typical examples of constant torque applications include: Conveyors, Extruders, Mixers Positive displacement pumps and compressors. Some of the advantages VFDs offer in constant torque applications include precise speed control and starting and stopping with controlled acceleration/deceleration.

2.9.2 Constant horsepower loads

Figure 2.25 shows the constant horsepower load curve

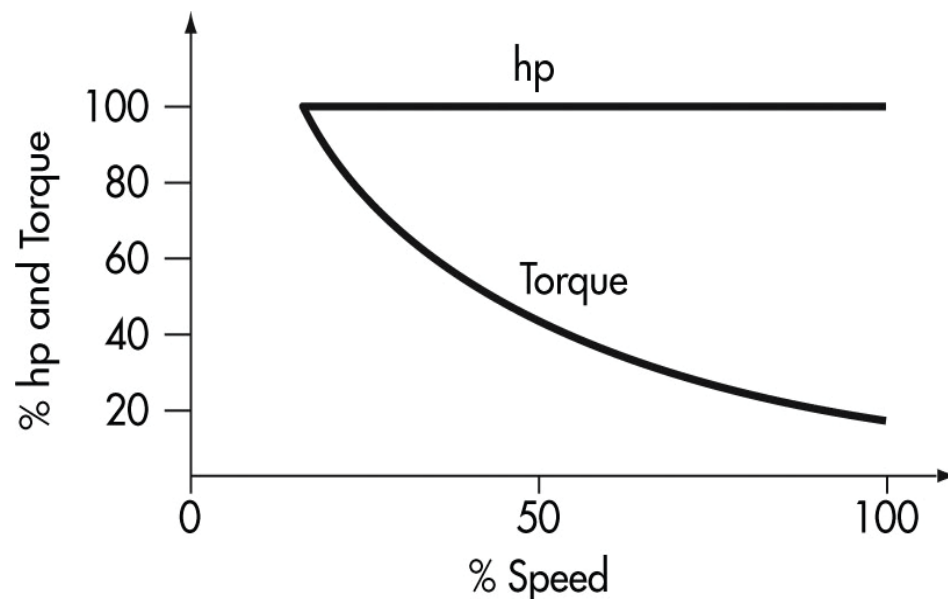


Figure 2.25: Constant horsepower load curve

In these applications the torque requirement varies inversely with speed. As the torque increases the speed must decrease to have a constant horsepower load. Examples of this type of load would be a lathe or drilling and milling machines where heavy cuts are made at low speed and light cuts are made at high speed. These applications do not offer energy savings at reduced speeds [21].

2.9.3 Variable torque loads

The variable torque load curve is shown in figure 2.26.

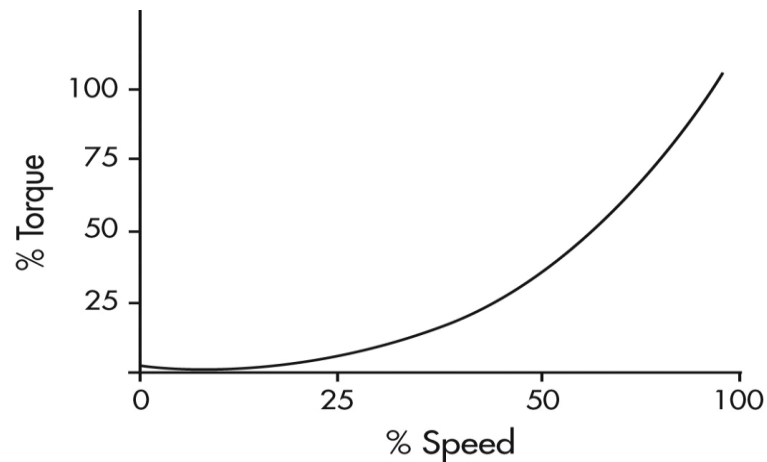


Figure 2.26: Variable torque load curve

Examples include centrifugal pumps, blowers and fans. The use of a VFD with a variable torque load may return significant energy savings. In these applications:

- Torque varies directly with speed squared.
- Power varies directly with speed cubed. This means that at half speed, the horsepower required is approximately one eighth of rated maximum.

Throttling a system by using a valve or damper is an inefficient method of control because the throttling device dissipates energy which has been imparted to the fluid. A variable frequency drive simply reduces the total energy into the system when it is not needed. In addition to the major energy saving potential, a drive also offers the benefits of increased process control often impacting on product quality and reducing scrap [21].

2.10 Ac Drive Operation

There are four possible modes of operation which is depicted in Fig. 2.27. When the controlled motor is operated in the first and third quadrants which are forward motoring and reverse motoring modes; the supplied voltage is greater than the back emf. When the motor operated in second and fourth quadrant which are forward

braking and reverse braking modes, the value of back emf generated by the motor should be greater than the supplied voltage.

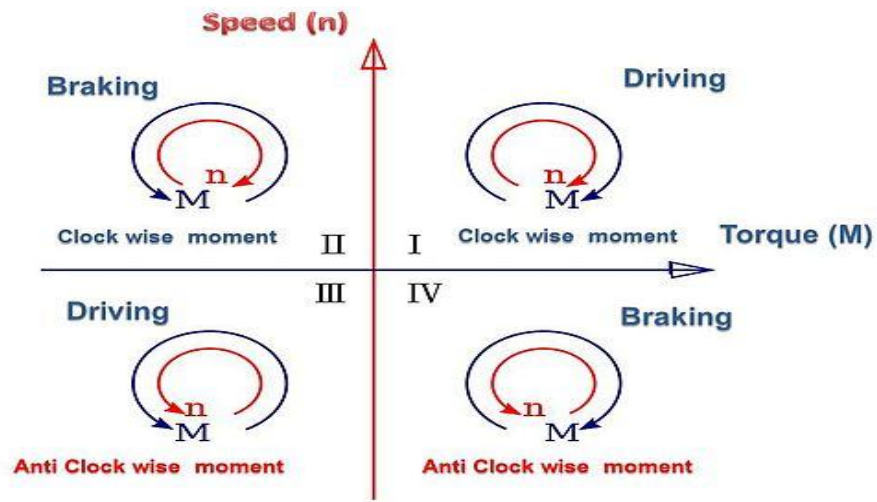


Figure 2.27: Electric motor speed-torque charts

The direction of current flow is reversed. The controlled motor is initially made to rotate in clockwise direction, but when the speed reversal command is obtained, the control goes into the clockwise regeneration mode, which brings the rotor to the standstill position. Instead of waiting for the absolute standstill position, continuous energizing of the main phase is attempted. This rapidly slows down the rotor to a standstill position. Therefore, there is the necessity for determining the instant when the rotor of the machine is ideally positioned for reversal [22].

2.10.1 Braking/regeneration

When the rotor of an induction motor turns slower than the speed set by the applied frequency, the motor is transforming electrical energy into mechanical energy at the motor shaft. This process is referred to as motoring. When the rotor turns faster than the synchronous speed set by a drive output, the motor is transforming mechanical energy from the motor shaft into electrical energy. It may be a ramp to stop, a reduction in commanded speed or an overhauling load that causes the shaft speed to be

greater than the synchronous speed. In any case this; condition is referred to as regeneration. Essentially, mechanical energy is converted to electrical energy [22].

2.10.2 Harmonics

Harmonics are produced by VFD's because the current is not drawn from the source in a sinusoidal form, but in pulses. These pulses occur when the AC source is at a higher voltage than the DC bus of the drive, during which time the rectifier bridge diodes are forward biased and conduct. Harmonic currents flow from the load toward the utility, seeking a low impedance path to ground, and causing a voltage drop through the distribution system according to Ohm's law. Harmonic voltages combine with the fundamental source voltage producing voltage distortion throughout the power system. Other equipment is affected by the harmonic-laden system voltage and may inject even more harmonic currents into the system. Additionally, harmonic distortion can result in low power factor. Most variable frequency motor drives will have a negligible effect on displacement power factor because the current lag associated with a diode bridge is relatively small. Conversely, if significant harmonic currents are present and the utility measures true power factor, or the ratio of real power divided by the total apparent power comprised of real, reactive, and harmonic power, power factor will be lower than displacement power factor [23].

The AC line choke design provides some smoothing on the DC bus and reduces the amount of ripple current that must be tolerated by the main capacitors. This has an effect of extending the life of these components. The choke provides a limiting function to the magnitude of the DC bus current during normal operation. These results in an improved overall power factor of the VFD and reduced harmonic currents flowing in the power distribution network.

2.11 Summary

This chapter illustrates briefly the three phase induction motor speed/torque relationship, the centrifugal dredge pump and general types of motor drives. The theory of operation of centrifugal pump and effects of speed variations on its

performance curve is illustrated. A detail description about an AC drives control the speed of three phase induction motor is given which include the following items:

- Construction and principles of operation.
- Inverter topologies of Ac drive including CSI, VSI.
- PWM techniques.
- Control strategies of AC drive scalar and vector.
- Motor load types of AC drive characteristics.
- Operation of AC drives including harmonics effects.

CHAPTER THREE

MATHEMATICAL MODEL OF THREE PHASE INDUCTION MOTOR

3.1 Introduction

The voltage and torque equations that describe the dynamic behavior of an induction motor are time-varying. It is successfully used to solve such differential equations and it may involve some complexity. A change of variables can be used to reduce the complexity of these equations by eliminating all time-varying inductances, due to electric circuits in relative motion, from the voltage equations of the machine. By this approach, a three phase winding can be reduced to a set of two phase windings (q-d) with their magnetic axes formed in quadrature. In other words, the stator and rotor variables (voltages, currents and flux linkages) of an induction machine are transferred to a reference frame, which may rotate at any angular velocity or remain stationary. Such a frame of reference is commonly known in the generalized machines analysis as arbitrary reference frame [24].

Various models have been developed, and the d-q or two-axis model for the study of transient behavior has been well tested and proven to be reliable and accurate. It has been shown that the speed of rotation of the d-q axes can be arbitrary although there are three preferred speeds or reference frames as follows:

- (a) The stationary reference frame when the d- q axes do not rotate.
- (b) The synchronously rotating reference frame when the d-q axes rotate at synchronous speed.
- (c) The rotor reference frame when the d-q axes rotate at rotor speed.

The stationary and synchronously rotating reference frames are most frequently used, the particular reference frame should be chosen in relation to the problem being investigated and the type of computer (analog or digital) that is used [25].

3.2 Induction Motor Model

The dynamic model of the induction motor is derived by using a two-phase motor in direct and quadrature axes. It is desirable because of the conceptual simplicity obtained with two sets of windings, one on the stator and the other in the rotor. The equivalence between the three phase and two phase machine models is derived from simple observation, and this approach is suitable for extending it to model a three phase machine by means of a two phase machine. The concept of power invariance is introduced; the power must be equal in the three-phase machine and its equivalent two-phase model. The required transformation in voltages, currents, or flux linkages is derived in a generalized way. To study the dynamic performance of the machine model, a motor model has been developed in a stationary reference frame [26].

3.2.1 Park's transformation

The Park's transformation is a three-phase to two-phase transformation for synchronous machine analysis. It is used to transform the stator variables of a synchronous machine onto a dq reference frame that is fixed to the rotor. The +ve q-axis is aligned with the magnetic axis of the field winding and the +ve d-axis is defined as leading the +ve q-axis by $\pi/2$. The result of this transformation is that all time-varying inductances in the voltage equations of an induction machine due to electric circuits in relative motion can be eliminated. It is easier to look on dynamic of IM using two-phase model. This can be constructed from the three phase model using Park's transformation as shown in figure.3.1 [27].

Current equations can be transforming to dq0 axes as :

$$\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - 120) & \cos(\theta + 120) \\ \sin \theta & \sin(\theta - 120) & \sin(\theta + 120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad \} \quad (3.1)$$

Under balanced conditions, i_0 is zero, and therefore it produces no flux at all.

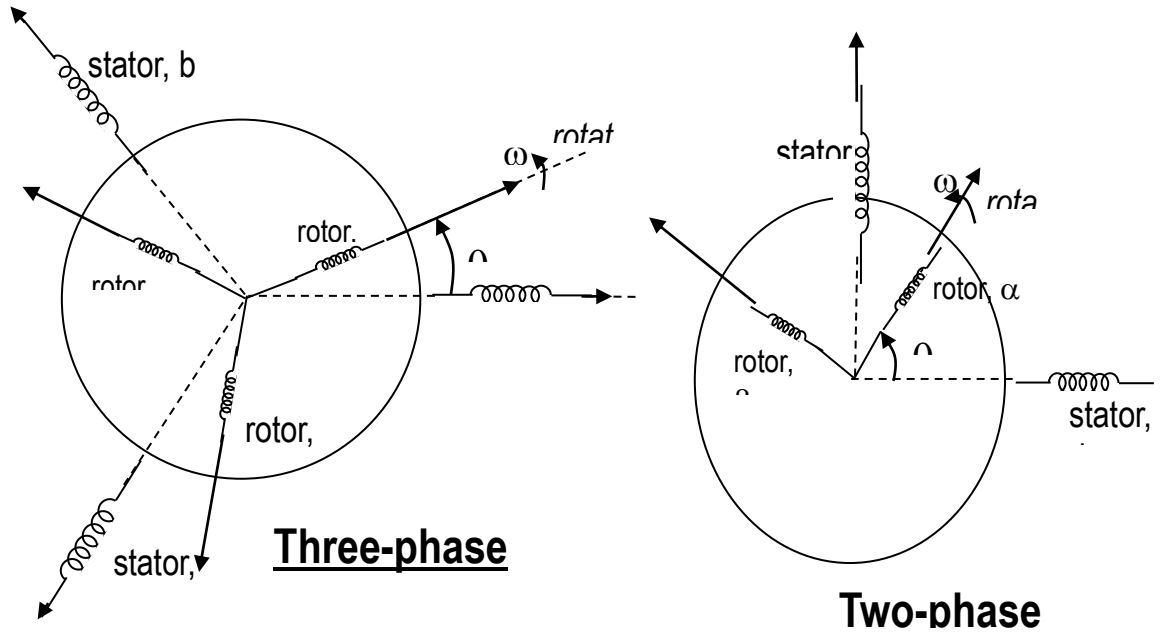


Figure 3.1: Three phase to two phase transformation scheme

3.2.2 Stationary reference frame model equations

For power system studies, induction machine loads, and the other types of power system components, are usually simulated on the system's synchronously rotating reference frame. But for the transient studies of variable-speed drives, it is easy to simulate an induction machine and its converter on a stationary reference frame. The equation of the machine in the stationary reference frame can simply be obtained by setting the speed of the arbitrary reference frame, ω_c , to zero and $\frac{d}{dt} \theta = 0$. Generally, the following assumptions are made while implementing the induction motor models [28]:

- Negligible spatial MMF harmonics.
- The effects of the stator slots may be neglected.
- There is no fringing of the magnetic circuit.
- The magnetic field intensity is constant quantity and directed radials across the air-gap. Hysteresis and eddy current effects are negligible.
- No magnetic saturation.

Assuming that the three phases voltages are balanced and sinusoidal given by:

$$\begin{aligned}
V_{as} &= V_m \cos(\omega_s t) \\
V_{bs} &= V_m \cos(\omega_s t - 2\pi/3) \\
V_{cs} &= V_m \cos(\omega_s t + 2\pi/3)
\end{aligned}
\quad \} \quad (3.2)$$

3.2.3 Voltage equations in d, q axes

The induction motor voltage equations can be given as:

$$\begin{aligned}
V_{ds} &= R_s \cdot I_{ds} + \frac{d}{dt}(\lambda_{ds}) \\
V_{Dr=0} &= R_r \cdot I_{dr} - \omega_r \cdot \lambda_{qr} + \frac{d}{dt}(\lambda_{dr}) \\
V_{qs} &= R_s \cdot I_{qs} + \frac{d}{dt}(\lambda_{qs}) \\
V_{Qr=0} &= R_r \cdot I_{qr} + \omega_r \cdot \lambda_{dr} + \frac{d}{dt}(\lambda_{qr})
\end{aligned}
\quad \} \quad (3.3)$$

3.2.4 Flux equations

The flux equation can be written as follows:

$$\begin{aligned}
\lambda_{ds} &= L_s \cdot I_{ds} + L_m \cdot I_{dr} \\
\lambda_{qr} &= L_r \cdot I_{qr} + L_m \cdot I_{qs} \\
\lambda_{qs} &= L_s \cdot I_{qs} + L_m \cdot I_{qr} \\
\lambda_{dr} &= L_r \cdot I_{dr} + L_m \cdot I_{ds}
\end{aligned}
\quad \} \quad (3.4)$$

Substituting flux equations in voltage equations yields:

$$\begin{bmatrix} v_{ds} \\ 0 \\ v_{qs} \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_r & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{dr} \\ i_{qs} \\ i_{qr} \end{bmatrix} + \begin{bmatrix} L_s & L_m & 0 & 0 \\ L_m & L_r & 0 & 0 \\ 0 & 0 & L_s & L_m \\ 0 & 0 & L_m & L_r \end{bmatrix} P \begin{bmatrix} i_{ds} \\ i_{dr} \\ i_{qs} \\ i_{qr} \end{bmatrix} + \omega_r \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -L_m & -L_r \\ 0 & 0 & 0 & 0 \\ L_m & L_r & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{dr} \\ i_{qs} \\ i_{qr} \end{bmatrix} \quad (3.5)$$

$$[V] = [R] [I] + [L] P [I] + \omega_r [G] [I]$$

3.2.5 Current equations

Equation (3.5) can be rearranged to find the current equations as follows:

$$\begin{bmatrix} i_{ds} \\ i_{dr} \\ i_{qs} \\ i_{qr} \end{bmatrix} = \begin{bmatrix} L_s & L_m & 0 & 0 \\ L_m & L_r & 0 & 0 \\ 0 & 0 & L_s & L_m \\ 0 & 0 & L_m & L_r \end{bmatrix}^{-1} \begin{bmatrix} v_{ds} \\ 0 \\ v_{qs} \\ 0 \end{bmatrix} - \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_r & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{dr} \\ i_{qs} \\ i_{qr} \end{bmatrix} - \omega_r \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -L_m & -L_r \\ 0 & 0 & 0 & 0 \\ L_m & L_r & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{dr} \\ i_{qs} \\ i_{qr} \end{bmatrix} \quad (3.6)$$

$$P [I] = [L]^{-1} ([V] - [R] [I] - \omega_r [G] [I])$$

3.2.6 Electromagnetic torque

The electromagnetic torque is developed by the interaction of air gap flux and rotor mmf which can be expressed in general form as:

$$T_e = [I]^T [G] [I] \quad (3.7)$$

So electromagnetic torque equation is [39]:

$$T_e = \frac{3}{2} \frac{P}{2} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (3.8)$$

The mechanical rotor speed, ω_r , is given by

$$\frac{d}{dt}(\omega_r) = \frac{P}{2} \cdot \frac{1}{J} \cdot (T_e - B \omega_r - T_\ell) \quad (3.9)$$

Where:

$$[V] = [v_{ds} \ 0 \ v_{qs} \ 0]^T$$

$$[I] = [i_{ds} \ i_{dr} \ i_{qs} \ i_{qr}]^T$$

$$[R] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_r & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix}, [L] = \begin{bmatrix} L_s & L_m & 0 & 0 \\ L_m & L_r & 0 & 0 \\ 0 & 0 & L_s & L_m \\ 0 & 0 & L_m & L_r \end{bmatrix}, [F] = \begin{bmatrix} 0 & 0 & L_s & L_m \\ 0 & 0 & 0 & 0 \\ -L_s & -L_m & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, [G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -L_m & -L_r \\ 0 & 0 & 0 & 0 \\ L_m & L_r & 0 & 0 \end{bmatrix}$$

3.3 Direct Torque Control

Figure 3.2 shows the block diagram of conventional direct torque controlled induction motor drive. There are two hysteresis control loops, one for the control of torque and other for the control of stator flux. The flux controller controls the machine operating flux to maintain the magnitude of the operating flux at the rated value till the rated speed. Torque control loop maintains the torque close to the torque demand. Based on the outputs of these controllers and the instantaneous position of stator flux vector, a proper voltage space vector is selected. Based on the outputs of hysteresis controllers and position of the stator flux vector, the optimum switching table will be constructed. This gives the optimum selection of the switching voltage space vectors for all the possible stator flux linkage space vector positions [29]

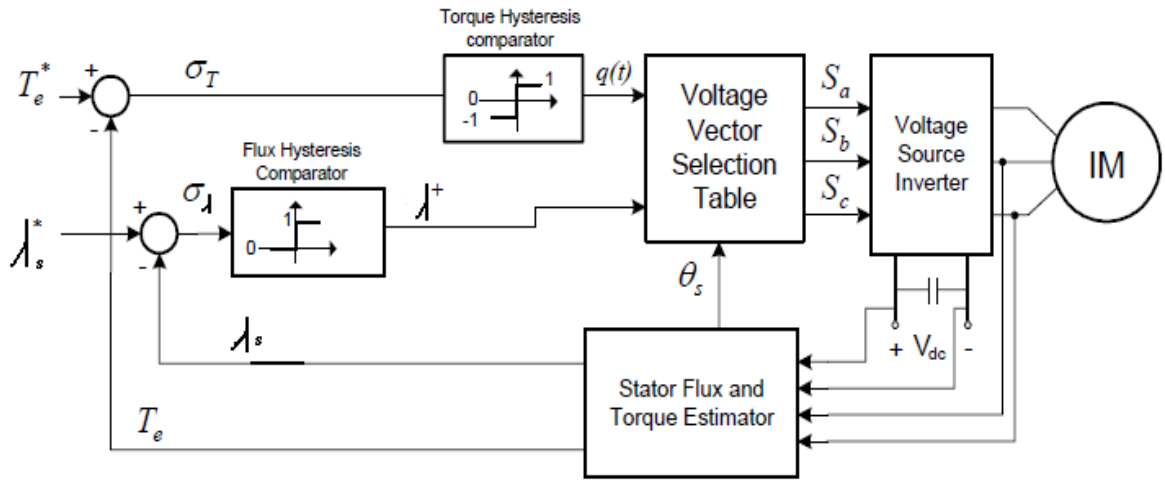


Figure 3.2: conventional DTC scheme

At each sampling time the voltage vector selection block chooses the inverter switching state (S_a, S_b, S_c) which reduces the flux and torque errors. Hence the inverter fed induction machine develops torque, which is carried out by a hysteresis controller that selects one of the six non-zero and two zero inverter voltage vectors as shown in Figure 3.3, and this selection is made in order to maintain the torque and flux error inside the hysteresis band in which the error is indicated.

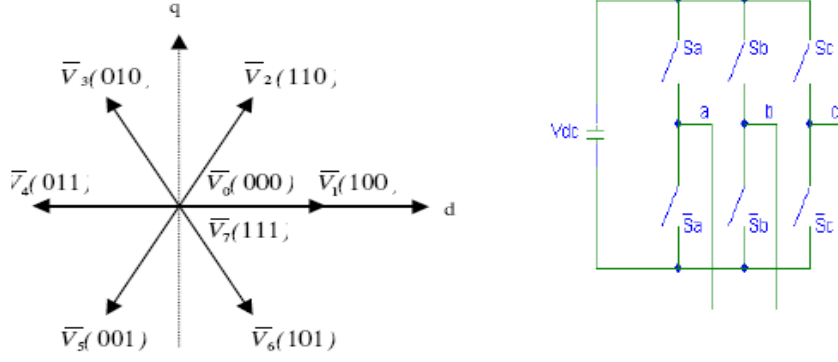


Figure 3.3: Inverter output voltage vectors and voltage source inverter

The upper switching states can be defined as the equation given below.

$$\left. \begin{aligned} V_{as} &= \frac{2S_a - S_b - S_c}{3} V_{dc} \\ V_{bs} &= \frac{S_a + 2S_b - S_c}{3} V_{dc} \\ V_{cs} &= \frac{-S_a - S_b + S_c}{3} V_{dc} \end{aligned} \right\} \quad (3.10)$$

Hence, the space vector is

$$V_{ss} = \frac{2}{3} V_{dc} (S_a + S_b e^{j2\pi/3} + S_c e^{j4\pi/3}) \quad (3.11)$$

This simple approach allows a quick torque response to be achieved; however, the steady-state performance is characterized by undesired ripple in current, flux and torque. This is largely due to the absence of information about torque and rotor speed values in the voltage vector selection algorithm.

3.3.1 Switching table

The voltage vector selection table is given in table (1). The voltage vector that is most suitable for the obtained flux and torque errors in all the sectors is given.

Table 3.1: Switching table of inverter voltage vectors

ΔT_e	$\Delta \lambda_s $	Sector					
		I	II	III	IV	V	VI
1	1	V_2	V_3	V_4	V_5	V_6	V_1
0	1	V_7	V_0	V_7	V_0	V_7	V_0
-1	1	V_6	V_1	V_2	V_3	V_4	V_5
1	0	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_0	V_7	V_0	V_7	V_0	V_7
-1	0	V_5	V_6	V_1	V_2	V_3	V_4

In conventional DTC systems, the torque error and flux error are used to generate directly next switching condition of the VSI. However, the new method is that use two errors to produce stator reference voltage vectors, then they are modulated by means of the SVPWM technology. At last, a constant switching frequency signal is exported to the VSI.

3.3.2 DTC of IM using space vector modulation

Common disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up. Several techniques have been developed to improve the torque performance. One of them is to reduce the ripples is based on SVM technique. SVM was first presented by a group of German researched in the second half of the 1980s. Since then, a lot of work has been done on the theory and implementation of SVM techniques. SVM techniques have several advantages that are offering better DC bus utilization, lower torque ripple, lower Total Harmonic Distortion (THD) in the AC motor current, lower switching losses, and easier to implement in the digital systems. At each cycle period, a preview technique is used to obtain the voltage space vector required to exactly compensate the flux and torque errors. The torque ripple for this SVM DTC is significantly improved and switching frequency is maintained constant [30]. The SVM DTC scheme is shown in figure 3.4.

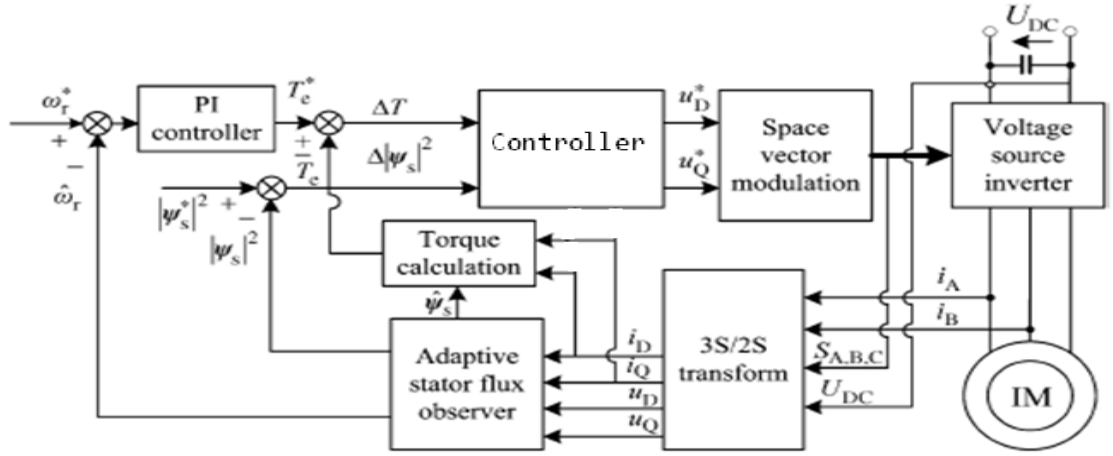


Figure 3.4: DTC-SVM

As shown in this scheme the stator voltage and current parameters are used for calculation or estimation of actual flux and torque. Estimated flux and torque are compared with reference flux & torque values. The torque error is obtained by PI control. With a view to have a self-regulated speed, the speed of induction is sensed and controlled by employing a suitable closed loop control. The speed of IM is sensed at a regular interval and is compared with its reference counterpart ω_r^* . The error signal is processed in a PI controller. Error obtained after comparison is given to the flux and torque controller. Suitable vector is selected from the lookup table as per the values of flux error, torque error and flux sector number. The vector selected is given to the inverter and the converter output is applied to the motor [31].

3.3.3 Stator flux control

By selecting the appropriate inverter output voltage V_i , the stator flux λ_s rotates at the frequency ω_s inside a specified band. The IM stator voltage equation is given by:

$$V_s = R_s \cdot I_s + \frac{d}{dt}(\lambda_s) \quad (3.13)$$

If the stator ohmic drops are neglected, the stator voltage impresses directly the stator flux in accordance with the equation as follow:

$$V_s = \frac{d}{dt}(\lambda_s) \quad (3.14)$$

Therefore the variation of the stator flux space vector due to the application of the stator voltage vector V_s during a time interval of dt can be approximated as

$$\Delta \lambda_s = V_s \cdot \Delta t \quad (3.15)$$

3.3.4 Torque control

The electromagnetic torque of induction machine is as cross product of the stator and rotor flux vector or stator current and flux as given by equation (3.16) is a sinusoidal function of γ and the angle between λ_s and λ_r are shown in figure.3.5.

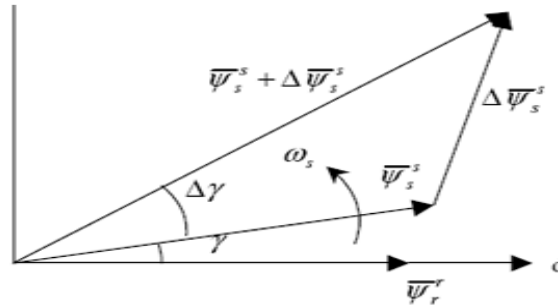


Figure 3.5: Stator and rotor flux space vector

$$T_e = \frac{3}{2} \frac{P}{2} i_s^* j \lambda_s \quad (3.16)$$

The magnitude of electromagnetic torque is written as

$$T_e = \frac{3P}{4} \frac{L_m}{L_r L_s'} \lambda_s \lambda_r \sin \gamma \quad (3.17)$$

Where: $L_s' = L_s L_r - L_m^2$

Hence by selecting appropriate inverter voltage vectors V_i to obtain strong rotation speed of ω_s a good dynamic performance can be achieved. The actual stator flux can be estimated from the equivalent circuit of the motor as follows [32]:

$$\lambda_{ds} = \int (V_{ds} - R_s i_{ds}) dt \quad (3.18)$$

$$\lambda_{qs} = \int (V_{qs} - R_s i_{qs}) dt \quad (3.19)$$

$$\lambda_s = \sqrt{(\lambda_{ds})^2 + (\lambda_{qs})^2} \leq \tan^{-1} \frac{\lambda_{qs}}{\lambda_{ds}} \quad (3.20)$$

The torque equations can be written with corresponding variables as

$$T_e = \frac{3P}{4} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (3.21)$$

3.4 Summary

In this chapter detail dynamic model of IM is discussed in stationary reference frame. In order to understand and design vector controlled drives the dynamic model of the machine to be controlled must be known which could be a good approximation of the real plant. To formulate the model two axes theory and space pharos notations have been used. It has been proved that space pharos notation is compact and easier to work with. It also deals with the detailed modeling of induction motor and drives equivalent two phase mathematical model which can be easily implemented in matlab/Simulink.

The second section gives the detail description of the conventional DTC scheme and Space vector DTC. The DTC scheme has many advantages over other vector control which has been discussed in previous chapter but also has some drawbacks like generation of flux and torque ripple and variable switching frequency. The flux and torque ripple is due to the hysteresis controller which can however be reduced by reducing the sampling period. The variable switching frequency is due to sector change of the stator flux vector.

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSION

4.1 Introduction

Regarding to the widespread use of three phase induction motor in industrial processes under variable loads such as centrifugal pumps, there is an obviously important need for a real model of pumping process in order to enhance of efficiency. Conventionally, mechanical methods are used for speed control like gear box and throttling valves which are getting obsolete. Now a day's digital approach is used because of its higher reliability and energy conservation. This chapter describes the development and simulation of a speed controller for a three phase squirrel cage induction motor driving heavy duty dredge pump using MATLAB/ SIMULINK. In this work the (DTC) strategy is used, which is known to produce quick and robust response in speed controllers. The AC4 SIMULINK block set is selected from SimPowerSystem library and is used to develop our controller. Internal parameters of the system are controlled to obtain the required output. The AC4 block set integrates all the required subsystems including rectifier, inverter, dredge pump speed and direct torque controller. The system is simulated and the torque and speed outputs of the controller are obtained. Figure 4.1 shows the block diagram model of DTC drive.

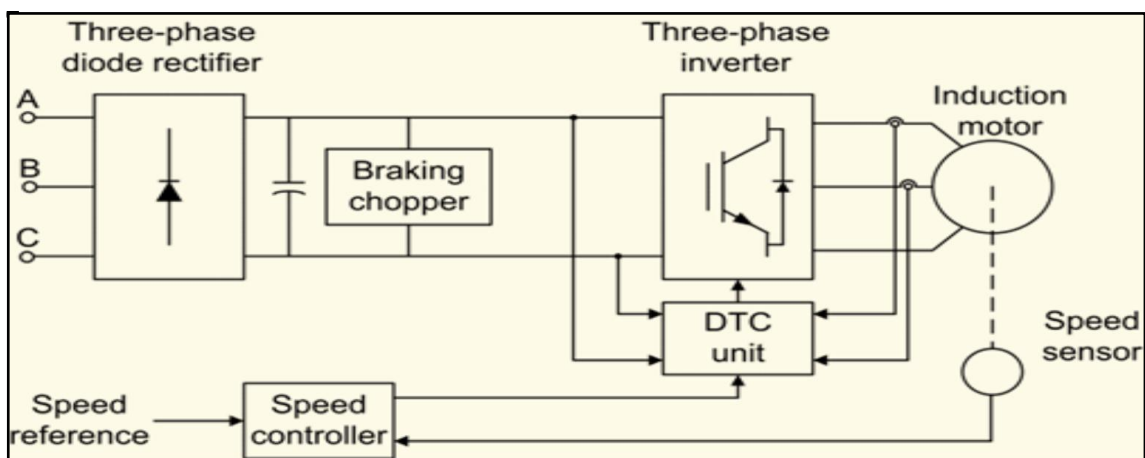


Figure 4.1: block diagram module of DTC drive

The induction motor parameters used in this thesis are given in Table 4.1.

Table 4.1 Parameter Values of IM used in Simulation

Parameter	Value
Motor Power	160 KW
Motor voltage	400 V
Motor Frequency	50 Hz
Motor Speed	1487 rpm
Motor Current	271.7 A
Motor Nominal Torque	1018 Nm
Stator Resistance, R_s	0.01379 Ω
Rotor Resistance, R_r	0.00778 Ω
Stator Leakage Inductance, L_s	0.000152H
Rotor Leakage Inductance, L_r	0.000152H
Mutual Inductance, L_m	0.0076 H
Inertia, J	11 kgm ²
Flux Density, B_m	0.8bwb
Number of Poles, P	4
Frictions	0.05658N-M-S

4.2 Model Description

The model is developed using the AC4 block of SimPowerSystems library of MATLAB as shown in figure 4. 2. A three phase power is supplied to the controller along with speed reference values. The induction motor is fed by an inverter which is built using universal bridge block. The speed control loop uses a proportional-integral controller to produce the flux and torque references for the DTC block. The DTC block computes the motor torque and flux estimates and compares them to their respective reference. The comparators' outputs are then used by an optimal switching table which generates the inverter switching pulses. The output of the block displays

motor current, speed, and torque signals [33]. Figure 4.3 illustrates its connections with a 200 hp three phase induction motor (detailed parameters specified in table.3) using (DTC) technique.

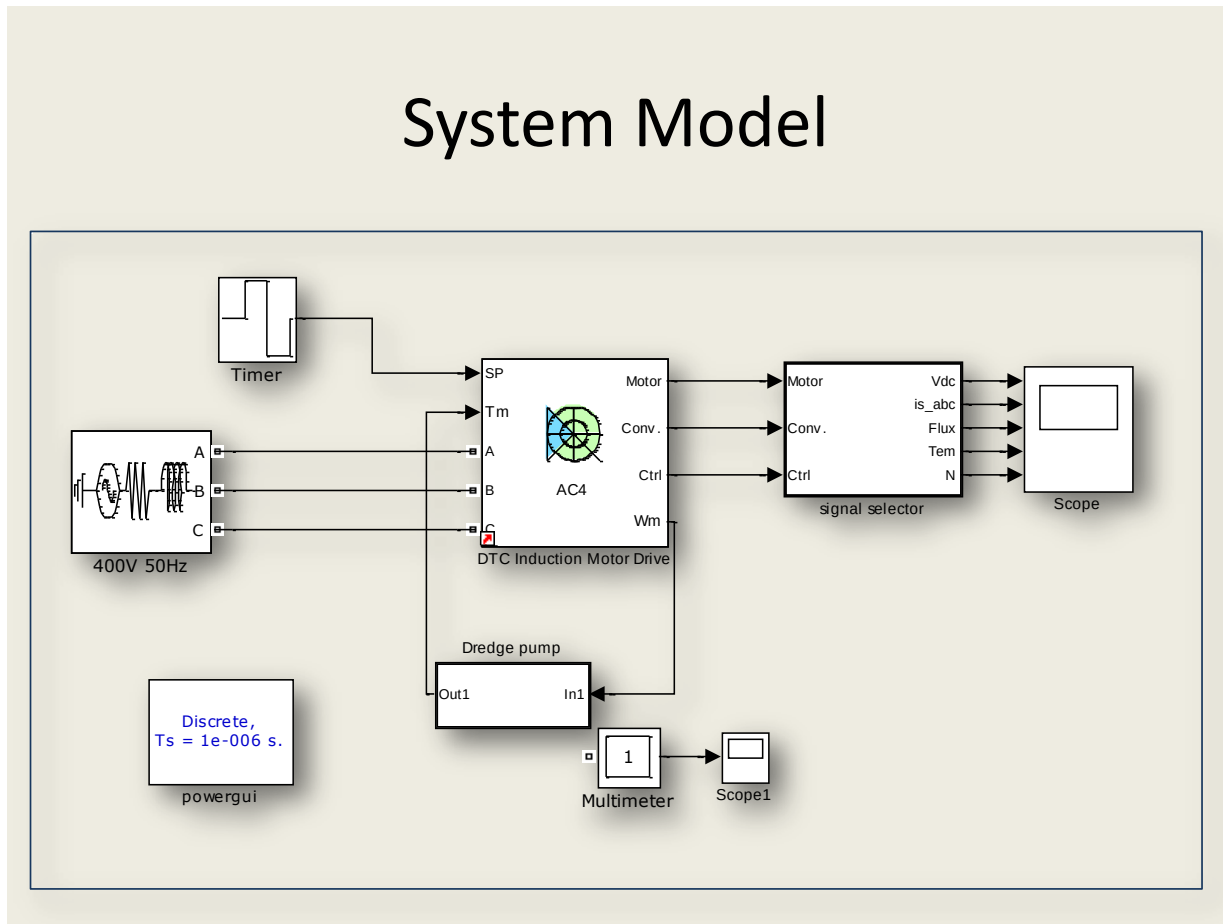


Figure 4.2: DTC model

The system and AC4 models consist of different types of subsystem.

They are:

- Signal Selector subsystem
- Dredge pump subsystem
- Motor Speed Controller Model
- Induction Motor mode

AC4 model

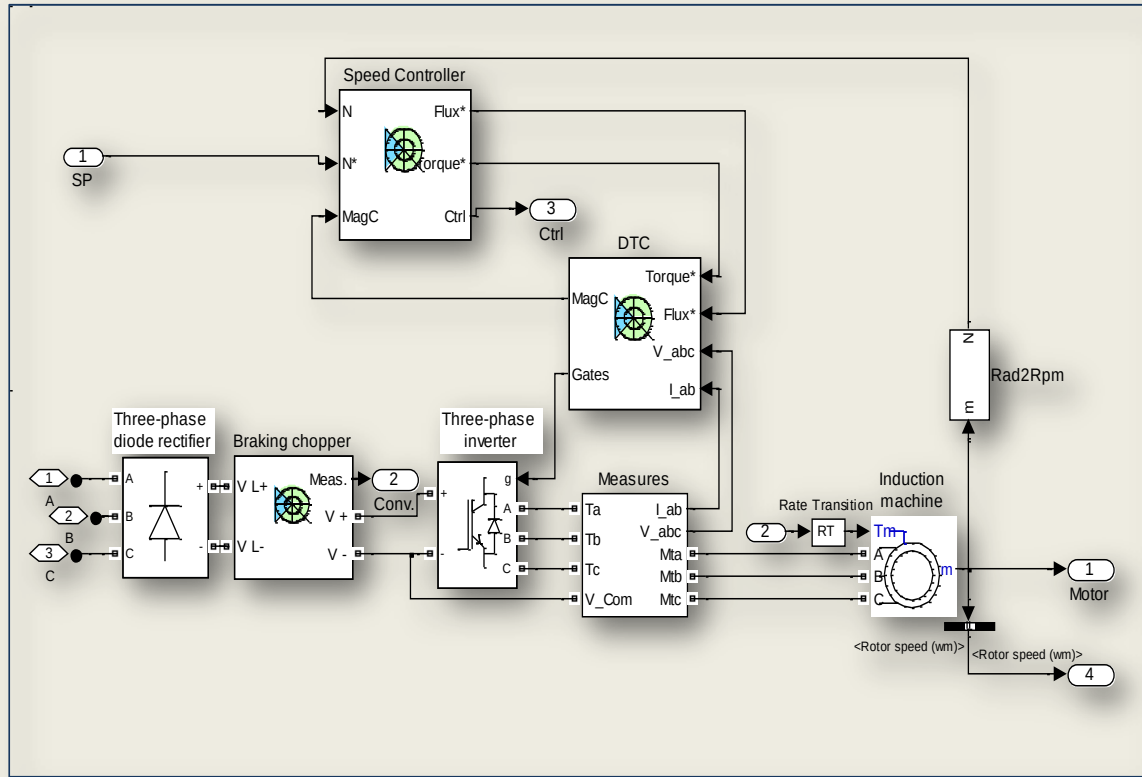


Figure 4.3: Subsystems of DTC induction motor drive (AC4)

All the subsystems perform different functions according to their modeling which is based upon the equations used. With the help of these subsystems the voltages and currents are calculated and then torque and flux for a particular motor operation is estimated with the help of this scheme. Then comparison of torque and flux with their reference values is done and according to their difference the next procedure is followed. The voltages and currents are calculated according to the motor parameters given and these parameters are selected according to the reference frame. In this DTC scheme the stationary reference frame model is used. The main subsystems are:

4.2.1 Signal selector subsystem

Figure 4.4 shows the main components of signal selector subsystem.

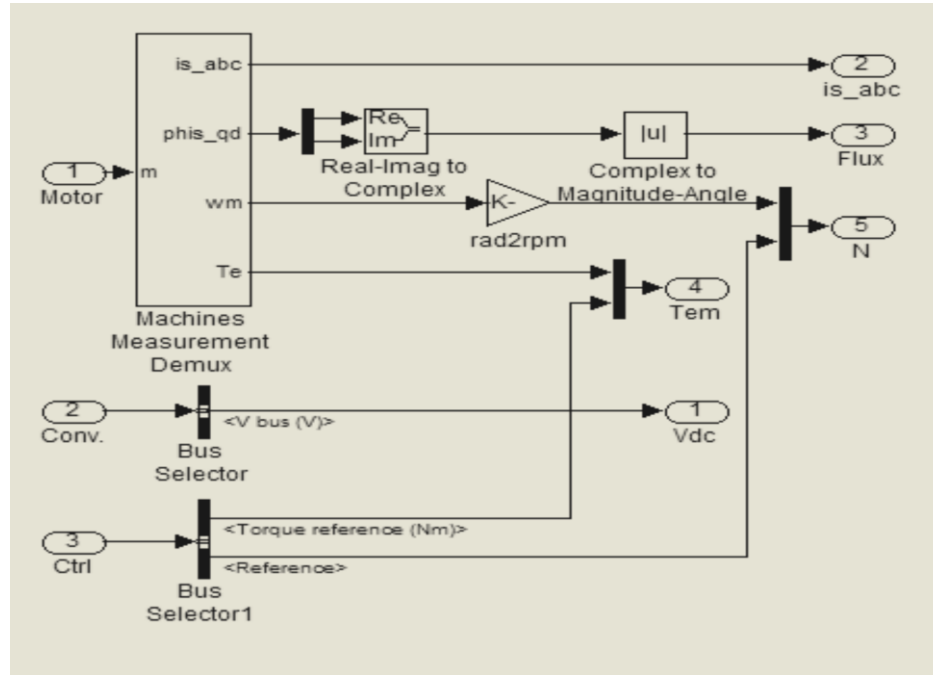


Figure 4.4: signal Selector Subsystem

The rad/rpm block contains the constant $30/\pi$ to convert the rotor speed from rad/s to rpm. A real-image to Complex block and a complex to magnitude-angle block compute the magnitude of the flux vector.

4.2.2 Dredge pump subsystem

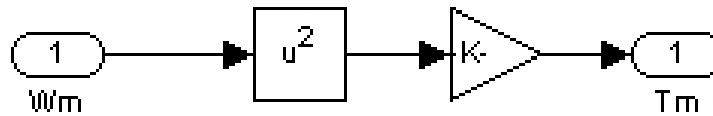


Figure 4.5: Dredge pump subsystem

The T_m input of the AC4 block represents the load torque applied to the shaft of the induction motor. In this case, the load torque is opposed by a dredge pump. This type of torque is typically a quadratic function of the speed as follows:

$$T_m = K \cdot (\omega_m)^2 = K' \cdot (N_m)^2 \quad (4.1)$$

Where ω_m is the speed in rad/s , N_m is the speed in rpm, K and k' are constants. The constant K must be imposed so that at nominal speed, the motor develops nominal torque.

4.2.3 Speed Controller

The speed controller is based on PI regulator. PI controller is an algorithm that can be implemented without resorting to any heavy control theory. The aim of such an algorithm is to determine the plant input (in our case the stator volt-age frequency) that will make the measured output (in our case the speed of the rotor) reach the reference (the speed the user wishes to have). PI stands for Proportional and Integral, two terms which describe two distinct elements of the controller [34].figure 4.6 shows the main details of the speed controller.

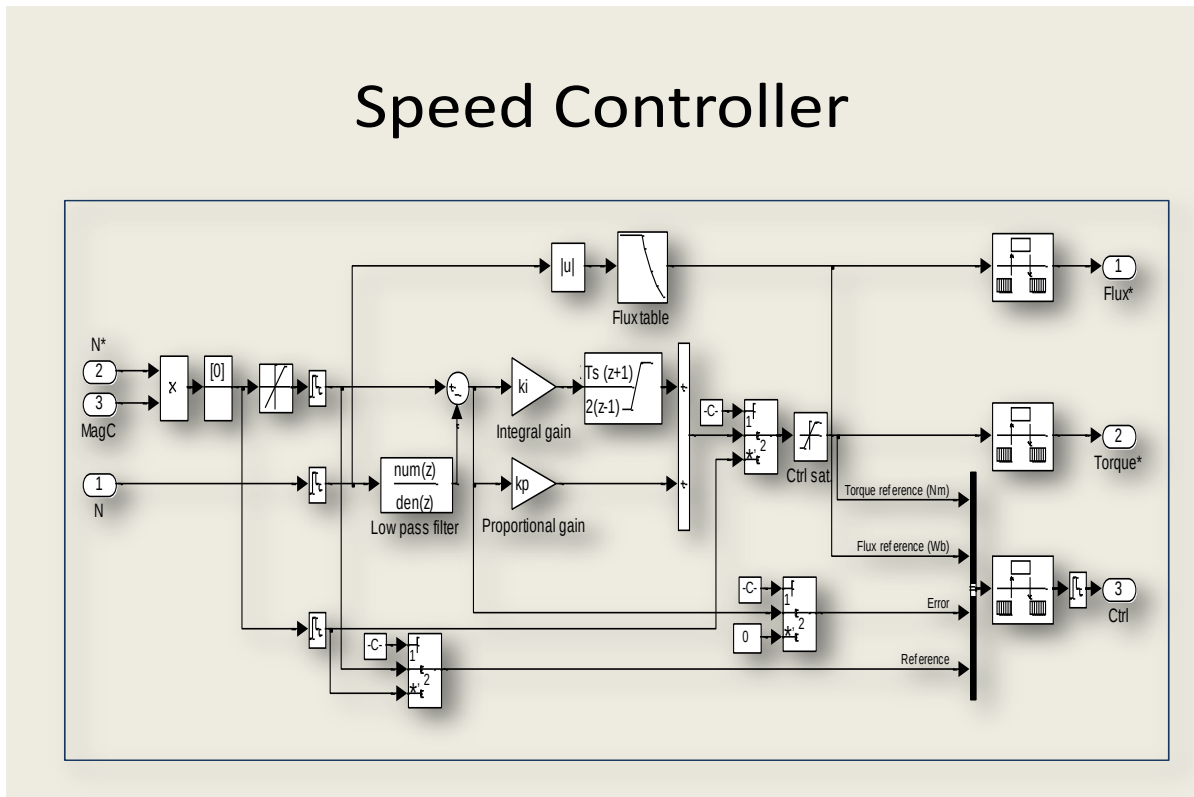


Figure 4.6: Speed controller

4.24 Direct torque control

The fundamental principle of DTC is that it uses inverter switching to directly control the motor flux and torque. DTC uses motor's torque and stator flux as primary control variables, obtained directly from the motor. DTC can provide accurate control at a very low speed. It eliminates the need to use a separate sensor for feedback. The complete scheme of the DTC subsystem is shown in figure 4.7.

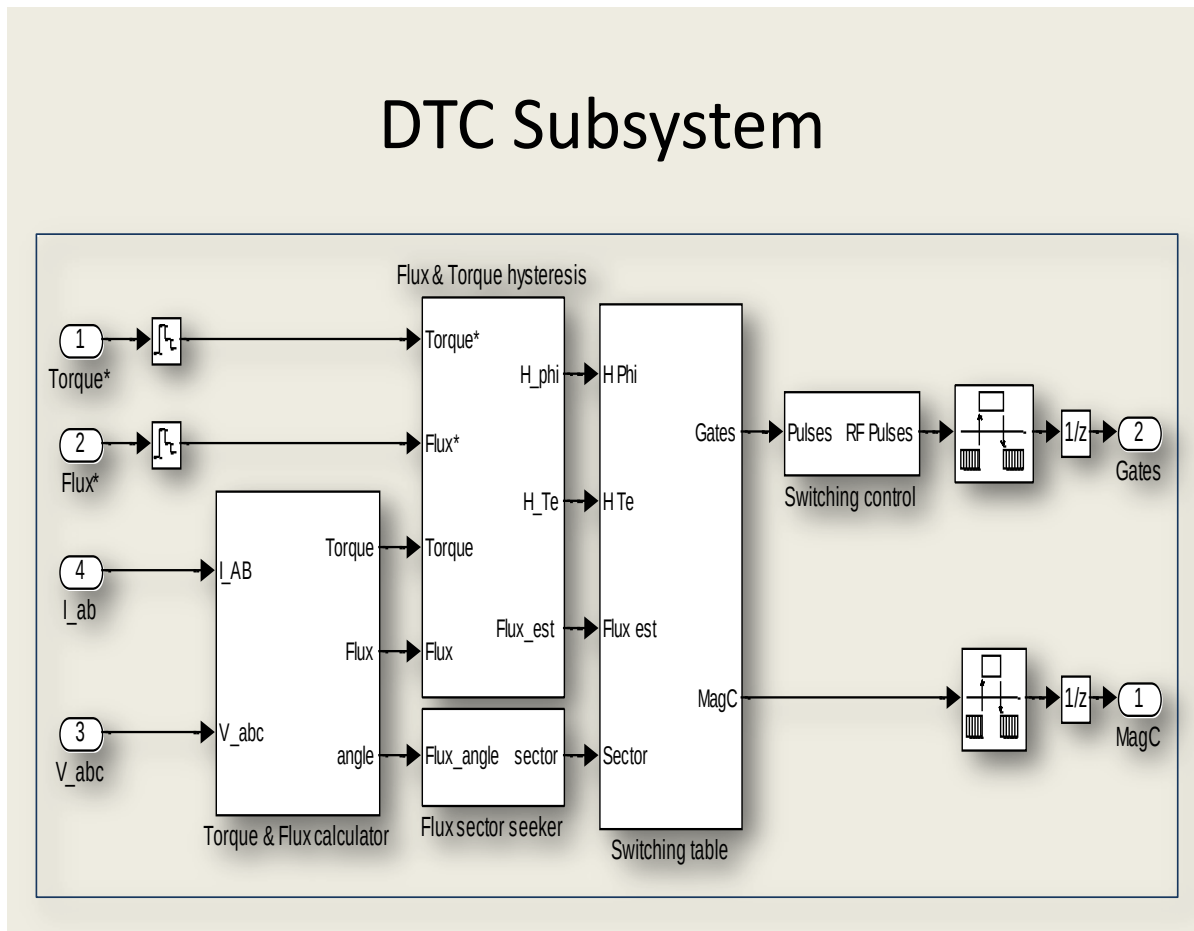


Figure 4.7: DTC subsystem

4.2.5 Braking Chopper

The braking chopper block contains DC bus capacitor and the dynamic braking chopper (consist of braking resistance series with chopper), which is used to absorb the energy produce by motor deceleration. Baking resistance is used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor. The dynamic baking is activated when the bus voltage reaches the upper limit

of hysteresis band. Figure 4.8 illustrates the braking chopper hysteresis logic. The dynamic braking is shutdown when the bus voltage reaches the lower limit of hysteresis band. The output of braking chopper is applied to three-phase inverter [34].

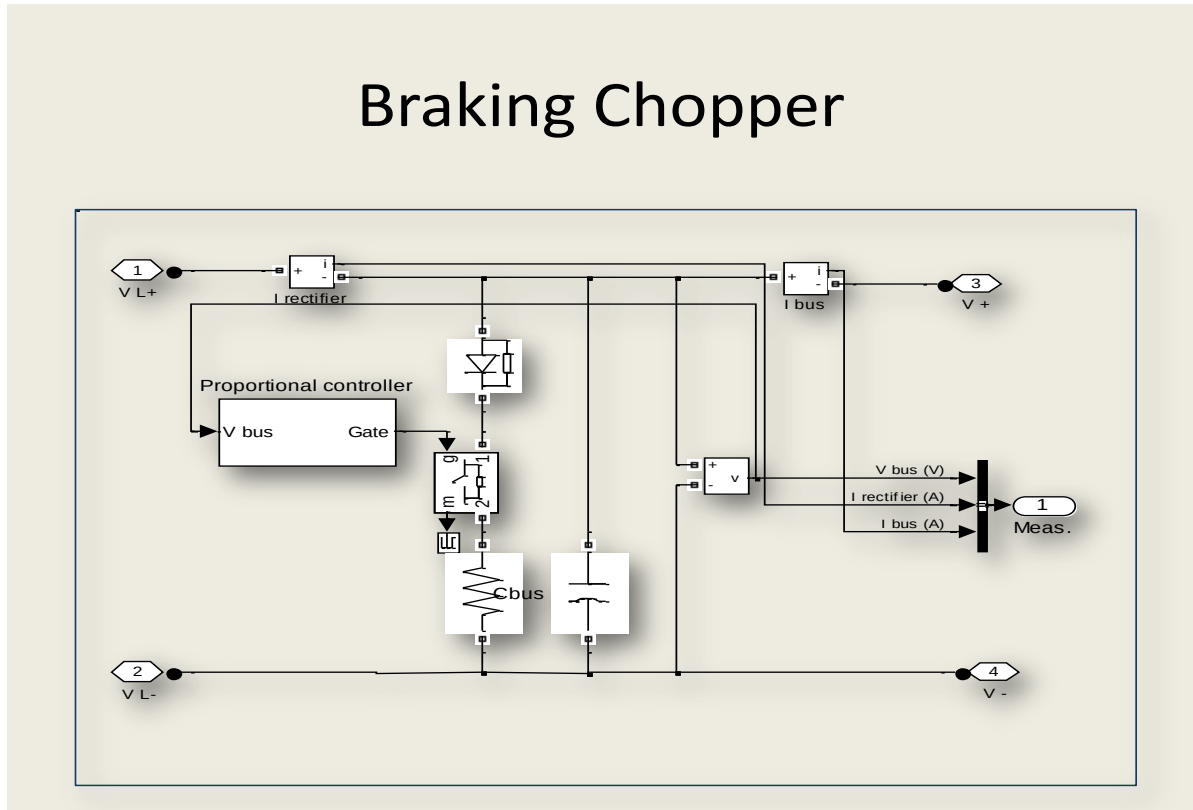


Figure 4.8: Braking Chopper subsystem

4.2.6 Three-Phase Inverter

It converts DC signal to AC signal and applied to three-phase induction motor. Here we are using Voltage Source Inverter which is used to regulate the speed of three-phase squirrel cage motors by changing the frequency and voltage and consist of input rectifier, DC link, output converter. They are available for low voltage range and medium voltage range .Figure 4.9 shows the circuit diagram of the voltage source inverter.

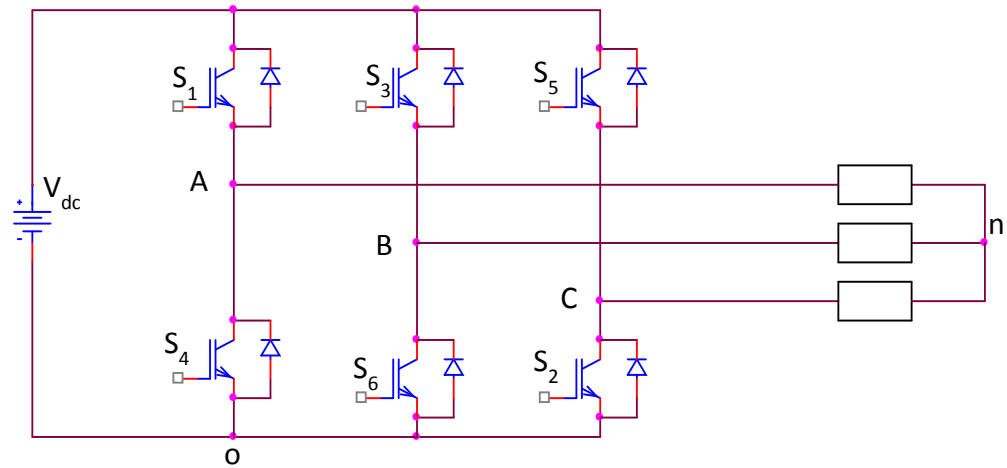


Figure 4.9: Voltage source inverter

4.2.7 Induction motor model

Figure 4.10 shows the main blocks of the induction motor model.

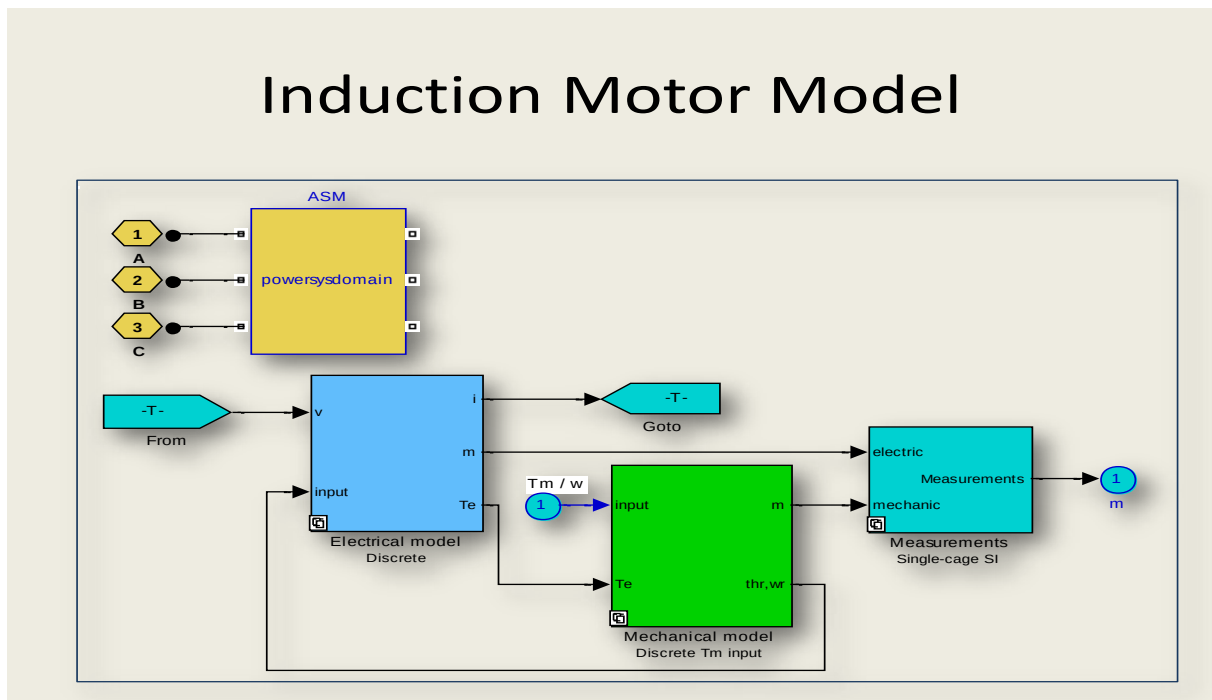


Figure 4.10: Induction Motor model

4.3 Simulation Results

The induction motor is fed by a voltage source inverter which is built using a Universal Bridge Block. The speed control loop uses a proportional-integral controller

to produce the flux and torque references for the DTC block. The DTC block computes the motor torque and flux estimates and compares them to their respective reference. The comparators outputs are then used by an optimal switching table which generates the inverter switching pulses. The result of simulation of the speed control with different reference speed and load torque is shown below:

4.3.1 Variable torque control mode

Figure 4.11 shows the behavior of induction motor under variable torque control mode. The torque command is first set at 400Nm, at 0.8 seconds the torque command is changed to 800 Nm, at 1.6 seconds the torque command is changed to 0 Nm, finally at 2.4 seconds the torque command is changed to 400Nm.

From 0 s to 0.8 s, the pump speed increases because of the 400 N.m acceleration torque produced by the induction motor. At $t = 0.8$ s, the electromagnetic torque jumps up to 800 N.m and the pump speed increases again because of the 800 N.m acceleration torque produced by the induction motor. At $t = 1.6$ s, the electromagnetic torque jumps down to 0 N.m and the speed decreases because of the load torque opposed by the dredge pump. At the same time the Dc bus voltage increases as a result of torque and speed reduction (braking). The braking chopper limits the DC bus voltage to 700 V. The electromagnetic torque jumps back to 400 N.m and the speed settle around 580 rpm and starts increasing due to acceleration torque produced by the induction motor.

The flux stays around 0.8 Wb throughout the simulation. The flux and torque oscillation amplitudes are slightly higher than 0.02 Wb and 10 N.m respectively as specified in the user interface. This is due to the combined effects of the 15 μ s DTC controller sampling time, the hysteresis control, and the switching frequency limitation. The observed ripple in both electromagnetic torque and flux is due to the use of hysteresis controllers. The torque controller simulation results were very good verifying, an excellent torque control response, either in steady-state or transient regime.

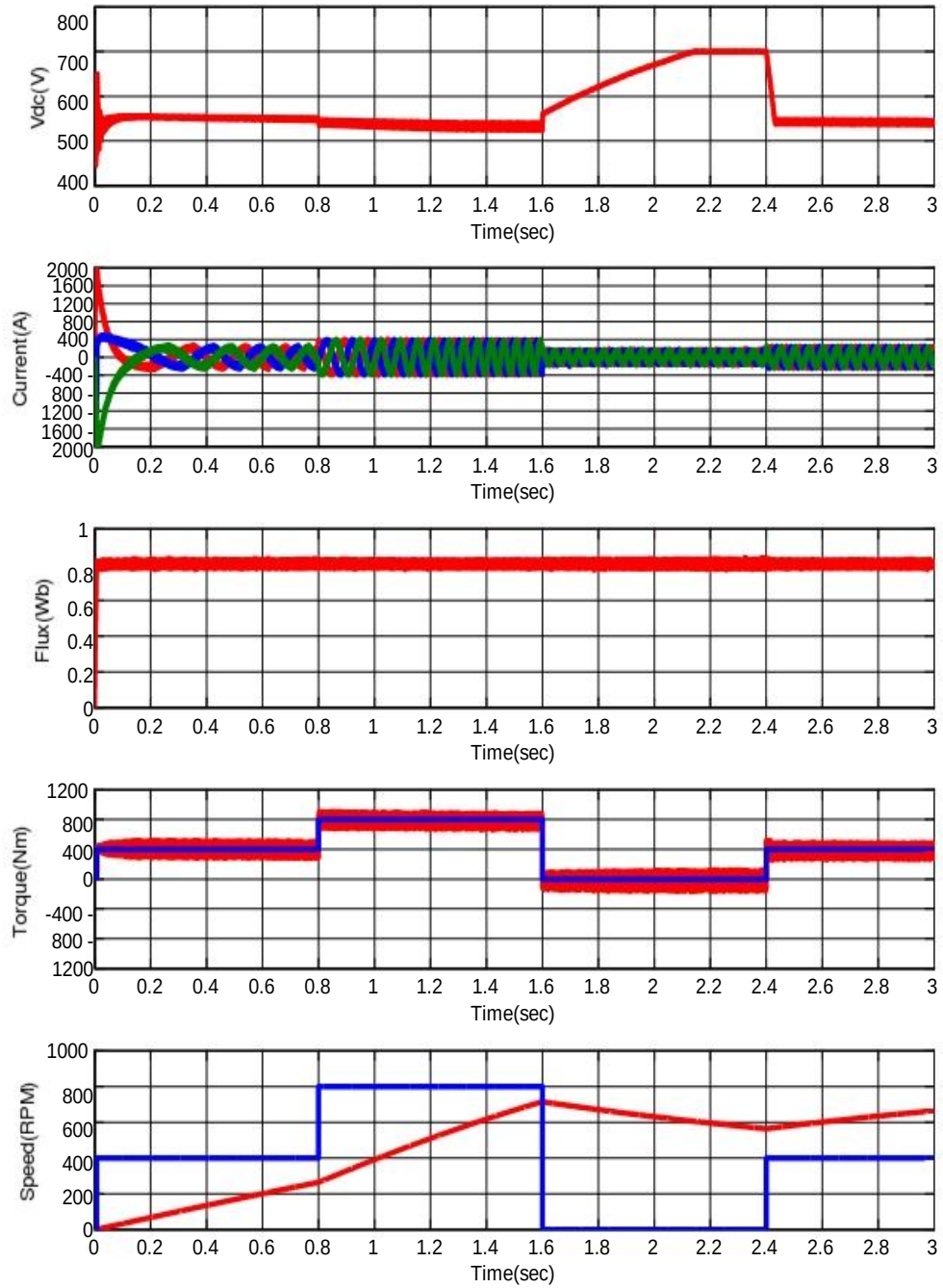


Figure 4.11: The induction motor behavior under variable torque command

4.3.2 Speed Control Mode

It is possible to implement a speed controller in closed loop using the DTC method .In the speed mode operation, the estimated speed is compared with the speed reference. The error is applied to speed controller, which supplies an electromagnetic torque reference. The actual torque is compared and then the required signals are applied to the inverter. The simulation results of the speed control with different reference speed are shown in figure 4.12.

At time $t = 0$ s, the speed set point is 400 rpm. Observe that the speed follows precisely the acceleration ramp. Ramping speed is specified here as 900 rpm/s. At time $t = 0.44$ s, speed is ramping to final set value. The speed of motor remains at 400rpm until at time $t = 0.8$ s, the controller attains the new set point of 800 rpm. Accelerating at the specified ramping speed that is 900rpm/s the motor attains the required speed of 800 rpm.

The speed of motor remains at 800rpm until at $t = 1.6$ s, the speed set point is changed to 0 rpm. The speed decreases down towards 0 rpm by following precisely the deceleration ramp even though the mechanical load is decrease abruptly, passing from 0 Nm to -1037 Nm, at $t = 1.7$ s. Before reaching 0 rpm, the speed set point is changed to 400 rpm and the speed follows the acceleration ramp to the final set value and remains there till the end of the simulation process.

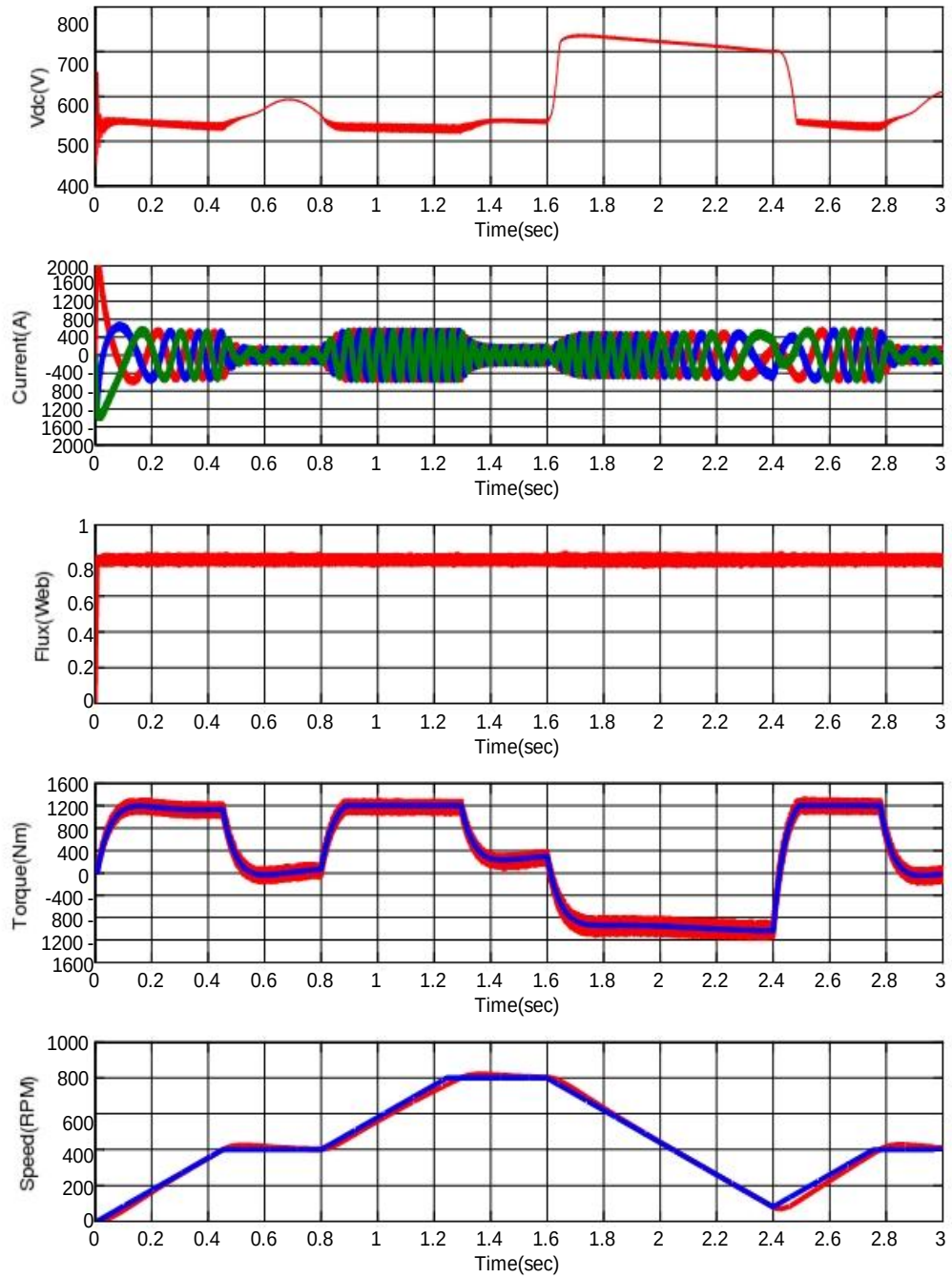


Figure 4.12: The induction motor behavior under variable speed command

4.4 Summary

In this chapter, MATLAB/SIMULINK is used for the development and simulation of the DTC controller designed for the dynamic behavior of the induction motor driving heavy duty dredge pump. It has been presented an implementation of the DTC control method associated with the three phase induction motor. Two control modes have been implemented, the electromagnetic torque mode and the speed control mode. As the name suggests, DTC controls the motor torque and flux directly. The DTC is simple and gives fast dynamic response. In spite of its simplicity, it gives additional steady state ripple in torque, flux and current. From the simulation results the same can be concluded.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Three phase induction motors are the most widely used motors for pump applications; hence, they are often called the workhorse of the motion industry. However, induction motors can only run at their rated speed when they are connected to the main power supply. This is the reason why speed control methods are needed to vary the rotor speed of an induction motor. In this thesis a mathematical model of three phase induction motor is derived into two equivalents D/Q model that can be easily implemented in MATLAB/SIMULINK.

Direct torque control method is one of the best control strategies which allow a torque control in steady state and transient operation of induction motor. The main aim of direct torque control strategies is to effectively control the torque and flux of induction motor. Direct torque control method made the motor more accurate and fast torque control, high dynamic speed response and simple to control. This method based on space vector modulation and it's considered as an alternative to field oriented control technique. Direct torque control methods are the first technology to control the 'real' motor control variable of torque and flux. And it has also more advantage such as it not required a feedback device and also not need external excitation. The proposed direct torque control strategy is used because of its higher reliability and quicker response. This strategy is used to control the speed of a three phase squirrel cage induction motor. MATLAB/SIMULINK is used for the development and simulation of the controller designed. The simulation results show that the model developed has the capability of controlling the speed according to the user defined reference values. This method, especially suitable for sophisticated industrial applications like centrifugal fans and pumps etc, can conserve energy as well as stabilize the torque.

5.2 Recommendations

DTC might be preferred for high dynamic applications, but, on the other hand, shows higher current and torque ripple. This last drawback can be partially compensated by the new DTC scheme Discrete Space Vector Modulation (DSVM). DTC can be implemented in real-time environment and results can be validated with obtained simulated result. The performance of the classical DTC can be improved by neural network based DTC schemes. SVPWM switching patterns can be analyzed and fed to VSI fed induction motor drive and proposed technique can be implemented in DSP processor.

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