CHAPTER-I
INTRODUCTION
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1.1 Historical Overview

The history of electrical motors goes back as far as 1820, when Hans Christian Oersted discovered the magnetic effect of an electric current. One year later, Michael Faraday discovered the electromagnetic rotation and built the first primitive D.C. motor. Faraday went on to discover electromagnetic induction in 1831, but it was not until 1883 that Tesla invented the A.C asynchronous motor. Currently, the main types of electric motors are still the same, DC, AC asynchronous and Synchronous, all based on Oersted. Faraday and Tesla's theories developed and discovered more than a hundred years ago.

Before the introduction of micro-controllers and high switching frequency semiconductor devices, variable speed actuators were dominated by DC motors. Today, using modem high switching frequency power converters controlled by micro-controllers, the frequency, phase and magnitude of the input to an AC motor can be changed and hence the motor’s speed and torque can be controlled. AC motors combined with their drives have replaced DC motors in industrial applications (e.g. Electrical Engines for Locomotives), due to their lower cost, better reliability, lower weight, and reduced maintenance requirement. Squirrel cage Induction motors are more widely used than all the rest of the electric motors put together as they have all the advantages of AC motors and they are easy to build.

The main advantage is that induction motors do not require an electrical connection between stationary and rotating parts of the motor. Therefore, they do not need any mechanical commutator (brushes), leading to the fact that they are maintenance free motors. Induction motors also have low weight and inertia, high efficiency and a high overload capability. Therefore, they are cheaper and more robust, and less prone to any failure at high speeds. Furthermore, the motor can work in explosive environments because no sparks are produced. Taking into account all the advantages outlined above, induction motors must be considered the
perfect electrical to mechanical energy converter. However, mechanical energy is more than often required at variable speeds, where the speed control system is not a trivial matter.

The only effective way of producing infinitely variable induction motor speed drive is to supply the induction motor with three phase voltages of variable frequency and variable amplitude. A variable frequency is required because the rotor speed depends on the speed of the rotating magnetic field provided by the stator. A variable voltage is required because the motor impedance reduces at low frequencies and consequently the current has to be limited by means of reducing the supply voltages. Before the days of power electronics, a limited speed control of induction motor was achieved by switching the three-stator windings from delta connection to star connection, allowing the voltage at the motor windings to be reduced. Induction motors are also available with more than three stator windings to allow a change of the number of pole pairs. However, a motor with several windings is more expensive because more than three connections to the motor are needed and only certain discrete speeds are available.

Another alternative method of speed control can be realized by means of a wound rotor induction motor, where the rotor winding ends are brought out to slip rings. However, this method obviously removes most of the advantages of induction motors and it also introduces additional losses. By connecting resistors or reactance in series with the stator windings of the induction motors, poor performance is achieved.

With the enormous advances made in semiconductor technology during the last 20 years, the required conditions for developing a proper induction motor drive are present. These conditions can be divided mainly in two groups:

- The decreasing cost and improved performance in power electronic switching devices.
- The possibility of implementing complex algorithms in the new microprocessors.

However, one precondition had to be made, which was the development of suitable methods to control the speed of induction motors, because in contrast to its mechanical simplicity their complexity regarding their mathematical structure (multivariable and non-linear) is not a trivial matter.

The function of an electric drives system is the controlled conversion of electrical energy to a mechanical form, and vice versa, via a magnetic field. Electric drives is a multi-disciplinary field of study, requiring proper integration of knowledge of electrical machines, actuators, power
Electronic converters, sensors and instrumentation, control hardware and software, and communication links (Figure 1.1).

Fig 1.1 Electric Drive System

Industrial loads require operation at wide range of speeds. Such loads are generally termed as variable speed drives. These drives demand precise adjustment of speed in a step-less manner over the complete speed range required. The loads may be constant torque or a function of speed. These loads are driven by hydraulic, pneumatic or electric motors. An industrial drive has some special features when driven by electric motors. The available machines for variable speed applications are classified and shown in Figure 1.2.

Fig 1.2 Classifications of Electric Motor
The primitive electric drive system uses a fixed-speed drive supplied from the grid, while mostly employing the DC motor. Adjustable speed drive systems offer more flexible control and increased drive efficiency when compared to the fixed speed drive. DC motors inherently offer decoupled flux and torque control, with fast dynamic response and simple control mechanism. However, the operating voltage of the DC machines is limited by the mechanical commutator’s withstand voltage. In addition, the maintenance requirement is high due to its brush and commutator arrangement.

DC motors are discriminated against ac machine because of their brushes and commutators, low overload capability, lower voltage operation (<650V dc), low speed (<6,000 rpm), low power density, and low efficiency. Introduction of inverters and pulse width modulation in 1964 opened the door for mainstream motor drives i.e. Induction and Wound Rotor Synchronous motor.

The Adjustable Speed Drives (ADS) are generally used in industry. In most drives AC motors are applied. Because of their robustness, cheapness, high speed operation and less maintenance requirements, the induction motors (IM) are the most common type of electromechanical drive in industrial, commercial and residential applications. To reach the best efficiency of induction motor drive (IMD), many new techniques of control have been developed in the last few years. The control of AC machines can be broadly classified into ‘scalar’ and ‘vector’ controls (Figure 1.3). Scalar controls are easy to implement and offer a relatively steady-state response, even though the dynamics are sluggish. To obtain high precision and good dynamics, as well as a steady-steady response, ‘vector’ control approaches are to be employed with closed-loop feedback control.

![Diagram](image.png)

Fig 1.3 Classification of Motor control scheme
Vector Control aims to control the rotor flux and torque of the motor by estimating the speed and voltage. This estimation can be either directly done through measurements or indirectly through calculations. A simpler alternative to the vector control is the direct torque control (DTC). While DTC and VC have different concept of operation, they both provide an effective control of the flux and torque.

The direct torque control (DTC) is the main interest of this work and it will be described in the following sections. However, a brief introduction about IM design and characteristics, IM model and its observability and controllability need to be labeled first for better understanding.

Historically, several general controllers have been developed:

1.1.1 Scalar controllers:

Despite the fact that "Voltage-Frequency" (V/f) is the simplest controller, it is the most widespread, being in the majority of the industrial applications. It is known as a scalar control and acts by imposing a constant relation between voltage and frequency. The structure is very simple and it is normally used without speed feedback. However, this controller doesn’t achieve a good accuracy in both speed and torque responses, mainly due to the fact that the stator flux and the torque are not directly controlled. Even though, as long as the parameters are identified, the accuracy in the speed can be 2% (except in a very low speed), and the dynamic response can be approximately around 50ms.

1.1.2 Vector Controllers:

In these types of controllers, there are control loops for controlling the torque and the flux, the most widespread controllers of this type are the ones that use vector transform such as either Park or Ku; its accuracy can reach values such as 0.5% regarding the speed and 2% regarding the torque, even when at stand still. The main disadvantages are the huge computational capability required and the compulsory good identification of the motor parameters.

1.1.3 Field Acceleration method:

This method is based on maintaining the amplitude and the phase of the stator current constant, while avoiding electromagnetic transients. Therefore, the equations used can be simplified saving the vector transformation, which occurs in vector controllers. This technique has achieved
some computational reduction, thus overcoming the main problem with vector controllers and allowing this method to become an important alternative to vector controllers.

Fig. 1.4 shows a block diagram of an AC motor drive system. A single-phase or three-phase AC power supply and an AC/DC converter provide a DC input to an inverter. A micro-controller decides the switching states for the inverter to control the motor’s torque or speed. A sensing unit feeds back terminal values such as motor speed, voltage and current to the micro-controller as needed for the closed-loop control of the motor. Controllers used in AC motor drives are generally referred to as vector or field-oriented controllers mentioned above.

![Block diagram for AC motor drive system](image)

The field-oriented control methods are complex and sensitive to inaccuracy in the motor’s parameter values. Therefore, in this field, a considerable research effort is devoted. The aim is to find even simpler methods of speed control for induction machines. One method, which is popular at the moment, is Direct Torque Control (DTC). This method has emerged over the last decade to become one possible alternative to the well-known Vector Control of Induction Machines. Its main characteristic is the good performance, obtaining results as good as the classical vector control but with several advantages based on its simpler structure and control diagram.

### 1.2 Currently Available Devices and Methods

There are a number of devices utilizing a range of control methods available on today’s market. These devices range from the simplest of controllers consisting of manually adjusted
transformers (variacs) to more sophisticated devices such as variable frequency drives, flux vector drives and direct torque control drives.

Each of these methods has advantages and disadvantages, run at different efficiencies and aim to provide specific types of control. This section describes the currently available ‘off the shelf’ and the trade-offs involved with these devices.

1.2.1 DC Motors:

DC motors are the one of the oldest methods of converting electrical power into mechanical rotations. DC motors rely on a commutative system to ensure that the flux is perpendicular to the rotor to achieve optimal performance. In a DC motor speed and torque control is easily achieved and has low initial cost. A flow chart illustrating the control loop used to control a DC motor can be seen in Fig 1.5

![Fig 1.5 Block diagram for DC motor drive system](image)

1.2.2 Variac Control:

Variac (variable autotransformer) control is one of the oldest forms of AC motor control. Variacs cause a drop in voltage and hence torque, the resulting drop in torque causes the speed to decreases. This method of control does not provide for accurate control and may cause the motor to overheat and burn out which is obviously undesirable and was once of the limiting factors when implementing AC motor systems into industrial applications until recent times.

The overall workings of a variac are shown below in Figure 1.6. By altering the windings on the secondary the voltage can be transformers.
1.2.3 Variable Frequency Drives:

Variable frequency drives were once formed by using a DC motor to drive an AC generator; this was due to the relative ease of speed control for DC machines. Newer VFDs rely on semiconductor technology to switch the supply and thus modify the frequency of the voltage being delivered to the motor, and with the constant increases in semiconductor performance and characteristics such as speed, cost, switching time and power flow capabilities such systems are becoming cheaper and easier to implement.

Unlike other devices, VFDs do not require feedback to operate, instead relying on the adjustable motor parameters of voltage and frequency. As a result of this, torque is not monitored or controlled and the magnetic fields are not correctly oriented so as to provide optimum operating conditions.

VFDs rely on Pulse Width Modulation (PWM) to gain the desired effects, however up to 30% of PWM ‘switches’/changes are considered unnecessary and add to the noise and harmonics of the system and introduces large amount of torque ripples. Due to the large amounts of harmonics expensive filtering circuits need to be implemented to counteract the negative impacts causes by the switching. Figure 1.7 shows the control loop for frequency control of an induction motor.
1.2.4 Flux Vector Drives:

Flux vector drives aim to mimic the magnetic operating conditions inside a DC machine; they do this by taking feedback from speed and position sensors (to determine the position of the rotor) and using electronic systems, as opposed to mechanical, the magnetic field within the motor can be oriented in such a way to control the torque and speed.

Flux vector drives allow for characteristics close to that of the DC machine. The main advantages are that they require decreased maintenance and provide greater efficiency, improved torque response, speed control and full torque even at zero speed.

Despite these benefits, there are drawbacks to implanting flux vector drives; these include the requirement for feedback and feedback sensors and the added system complexity due to these said sensors which also increases cost. Furthermore, the flux vector drive does not have direct control over the torque; this is indirectly achieved via speed control which gives less precise control. The control loop in Figure 1.8 shows the basic method to control an induction motor using the flux vector method.
1.2.5 Direct Torque Control Drives:

Direct torque control drives operate using some of the same principles as FVDs, but uses motor theory to calculate the torque; what this means is the operating conditions of the motor can be determined without the use of encoders, speed sensors or shaft angle sensors.

To be able to meet the goal of ‘sensor-less’ operation, DTC requires a fast processor capable of performing calculations and in conjunction the selection of the correct switching states once every 25 microseconds. DTC has numerous advantages over FVD including no feedback sensors, response times that are up to 10 times greater, accurate torque outputs at low frequencies and 1%-2% torque repeatability. Direct torque control also avoids over current tripping.

Despite the advantages of DTC, there are still some disadvantages including high torque and flux ripple which fuzzy logic implementation hopes to decrease. Figure 1.9 shows the simplicity of the DTC system control loop. It can be seen that it requires no feedback components.

![Fig 1.9 Control Loop for DTC system](image)

1.3 Current Developments in Research

Due to the non-linear and multivariable structures of AC motors, they generally require complex control systems to achieve fast and reliable speed and torque control.

The advantage of AC motors often outweighs these complications and for such reasons, research has been done to implement simple yet effective methods of torque and speed control. For this to be achieved control of frequency, voltage, and current must be accomplished.

Latest high speed microcontrollers and switching power converters provide the required computational power and speed to match the control capabilities of DC motors.
Until now induction motor control has been employed in high performance industrial applications using Field Oriented Control (FOC) or Vector Control. This provides high speed torque response and has been a reliable alternative to DC motors however this method is susceptible to flux variations which can affect accuracy and performance.

The latest method of AC motor control is the DTC method. Introduced in the 1980’s this method provides a cheap and effective way of controlling the torque of an induction motor by directly controlling an inverter. It does not require feedback methods to return information about the motor such as the rotor speed or position. This decreases cost and increases reliability.

DTC relies on selecting stator voltage vectors depending on the differences between the torque and flux linkage to set reference points. This method directly controls an inverter and thus can be characterized by its simple implementation and high speed dynamic response. However it does come with its disadvantages such as high torque ripple due to Bang- Bang operation and slow transient response to step changes in torque during the start-up phase.

In this thesis we present the idea of implementing DTC with Fuzzy Logic. Fuzzy logic is a relatively new yet powerful logical reasoning tool. It is described as precise logic for imprecision and approximate reasoning.

Fuzzy systems have been implemented in a large number of industrial applications in recent years from items such as washing machines and cookers to the operation of cranes. Without fuzzy logic in such devices standard logic may simply breakdown or produces unacceptable inaccuracies.

Fuzzy logic was first proposed in 1965 by Lofti & Zadeh and due to the large computational power needed to obtain accurate results. It has only become prominent in recent years. Traditional logic works on simply true or false i.e. 0 or 1, whereas fuzzy logic variables may have truth ranges between 0 and 1 i.e. partial truth.

### 1.4 Features of Direct Torque Control

DTC main features are as follows:

i. Direct control of flux and torque.

ii. Indirect control of stator currents and voltages.
iii. Approximately sinusoidal stator fluxes and stator currents.
iv. High dynamic performance even at stand still.

The main advantages of DTC are:

i. Absence of co-ordinate transforms.
ii. Absence of voltage modulator block, as well as other controllers such as PID for
iii. Motor flux and torque.
iv. Minimal torque response time, even better than the vector controllers.

However, some disadvantages are also present such as:

i. Possible problems during starting.
ii. Requirement of torque and flux estimators, implying the consequent parameters
identification.

iii. Inherent torque and stator flux ripple.

### 1.5 Fuzzy Logic Controller

To overcome the complexities of conventional controllers, fuzzy control has been implemented in many motor control applications. In the last three decades, fuzzy control has gained much popularity owing to its knowledge based algorithm, better non-linearity handling features and independence of plant modeling. The Fuzzy Logic Controller (FLC) owes its popularity to linguistic control. Here, an exact mathematical model for the system to be controlled is not required. Hence, Fuzzy logic basically tries to replicate the human thought process in its control algorithm. The FLC has thereby proven to be very beneficial in the industries as it has the proficiency to provide complex non-linear control to even the uncertain nonlinear systems. In addition to the aforementioned attributes, a fuzzy logic controller also makes good performance in terms of stability, precision, reliability and rapidity achievable.

Advantages of Fuzzy Logic Controller are listed below:

i. It is simple to design.
ii. It provides a hint of human intelligence to the controller.
iii. It is cost effective.
iv. No mathematical modeling of the system is required.

v. Linguistic variables are used instead of numerical ones.
vi. Non-linearity of the system can be handled easily.

vii. System response is fast.

viii. Reliability of the system is increased.

ix. High degree of precision is achieved.

These advantages allow fuzzy controllers can be used in systems where description of the process and identification of the process parameters with precision is highly difficult. Hence, it provides a fuzzy characteristic to the control mechanism.

1.6 Statement of the Problem

A simplified variation of field orientation known as direct torque control (DTC) was developed by Takahashi and Depenbrock. Fig. 1.5 shows a DTC of an induction motor. In direct torque controlled induction motor drives, it is possible to control directly the stator flux linkage and the electromagnetic torque by the selection of an optimum inverter switching state. The selection of the switching state is made to restrict the flux and the torque errors within their respective hysteresis bands and to obtain the fastest torque response and highest efficiency at every instant. DTC is simpler than field-oriented control and less dependent on the motor model, since the stator resistance value is the only machine parameter used to estimate the stator flux.

One of the disadvantages of DTC is the high torque ripple. Under constant load in steady state, an active switching state causes the torque to continue to increase past its reference value until the end of the switching period. Then, a zero voltage vector is applied for the next switching period causing the torque to continue to decrease below its reference value until the end of the switching period. That results in high torque ripple as shown in Fig. 1.11 (a). A possible solution to reduce the torque ripple is to use a high switching frequency; however, that requires expensive processors and switching devices. A less expensive solution is to use duty ratio control. In DTC with duty ratio control, the selected voltage vector is applied for a part of the switching period rather than the complete switching period as in conventional DTC.
Fig 1.10 Direct torque control scheme

Fig 1.11 Effect of duty ratio control on torque ripple
By applying a nonzero voltage vector for only a portion of the switching period, and the zero voltage vectors for the remainder of the period, the effective switching frequency is doubled. Therefore, over any single switching period, the torque variations above and below the average value are smaller, as shown in Fig. 1.11 (b). Further, because the duty ratio is controlled, the average stator voltage is adjusted directly. There is no need to make coarse corrections by the use of multiple switching periods with a nonzero voltage vector or a whole switching period with a zero voltage vector. The average phase voltage is adjusted more smoothly, and the overall torque ripple is reduced. The use of a duty ratio fuzzy controller is proposed by Vas Mir & Elbuluk.

The theme of this thesis is to verify by simulation that a DTC with a duty ratio fuzzy controller reduces the torque ripple compared to conventional DTC.

1.7 Objective of Work

The objective of the work is:

i. To analyze the various techniques of speed control of AC motors and their advantages/disadvantages.

ii. To analyze various DTC schemes and their advantages/disadvantages.

iii. To develop mathematical model for IM.

iv. To analyze the impact of Stator resistance and stator flux to Direct Torque Control for the motor model.

v. To develop a duty ratio based torque controller using the fuzzy logic approach.

vi. To compare the simulation results of the proposed model with existing conventional DTC model.
1.8 Overview of the Thesis

Chapter I:
This chapter provides the brief introduction about the subject of the thesis. It also highlights the problems associated with the existing models of DTC and how the proposed approach provides better results.

Chapter II:
This chapter provides the brief about the literature being surveyed during the course work. It also analyzed the work carried out by different experts in the field of DTC, Fuzzy, Duty ratio, MATLAB, Torques ripple minimization techniques, Estimation techniques etc., to acquire knowledge for the proposed approach on torque ripple minimization in DTC of IM.

Chapter III:
This chapter provides a review of the induction motor modeling, field-oriented control methods and their limitations. A SIMULINK model is being developed for the induction machine model and simulated for three phasors to two phase transformation of induction machine model. This chapter also covers the fundamentals of the DTC of induction motors. Methods to deal with DTC limitations on flux estimation accuracy are discussed in detail. The chapter details the theory and introduction of fuzzy logic controller used in the proposed duty ratio controller to minimize the torque ripple in DTC. It also details the design of duty ratio fuzzy controller.

Chapter IV:
This chapter develops the fuzzy logic controller, determines the duty ratio according to torque error, flux error, and flux position. SIMULINK/MATLAB is being used to simulate the proposed DTC with duty ratio fuzzy control and then, comparison has been made of the simulation results of proposed model with the conventional DTC.

Chapter V:
This chapter provides the summary, conclusions and direction for future work.