Comparative Analysis of PID and Fuzzy Logic Controller for Induction Motor Speed Control

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School of Electrical and Computer Engineering

Control Engineering Stream

Date: October 2019

A thesis submitted to Addis Ababa University Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in electrical and computer engineering (control engineering)

Advisor:

Dereje Shiferaw (Ph.D.)

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Approval by the board of examiners

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Chairman	Signature	Date
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Advisor	Signature	Date
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Examiner (external)	Signature	Date

Declaration

I, herewith declare that this thesis (Comparative Analysis of PID and Fuzzy Logic Control for Induction Motor Speed Control) is a presentation of my original research work. Wherever contributions are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgment of the collaborative research and discussion.

The work was done under the guidance of Dereje Shiferaw (Ph.D.), at Addis Ababa university institute of Technology (AAiT), Addis Ababa.

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Candidate Name signature

In my capacity as supervisor of this candidate's thesis, I certify that the above statements are true to the best of my knowledge.

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Guide's name signature

Date: October 2019

Addis Ababa Ethiopia

Acknowledgment

I would like to express my deepest gratitude to my advisor Dereje Shiferaw (Ph.D.)for his valuable guidance, support, advice, and encouragement during the preparation of this thesis. Whose help and guidance made possible the fulfillment of this thesis work.

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Last not least my special thanks forwarded to my beloved parent particularly my father Ato Hussen Muhiye and my mother W/r Alemnesh Ali for their moral support throughout the study.

Abstract

Induction motor (IM) is the most rigid, and relatively less expensive machine but much difficult to control. The advent of field-oriented control (FOC) makes IM useful in variable speed drive applications. The concept of FOC is to separate the torque and flux producing current and then control the torque and flux separately. The advent of different control theory makes difficulty in the choice of an appropriate controller.

In this thesis, a comparative analysis of fuzzy and PID control for IM speed control has been done. To solve this problem first an indirect field-oriented control (IFOC) method motor control is designed. In this design, the direct current i_{ds} is kept constant for a fast response. In addition, the motor is modeled using rotor flux and stator current as a state variable. This model is very important due to the presence of measurable quantity (stator current), and to mathematically quantify the alignment of rotor flux on the d-axis.

Both PID and fuzzy control of IM has been verified using simulation on MATLAB/SIMULINK. The performance of both PID and FLC is analyzed in terms of reference tracking, load variation, parameter variation, low-speed tracking, and speed reversal. The PID controller results 0.3s settling time with 10% overshoot and the fuzzy controller 0.2s settling time with 0% overshoot.

Keywords: Fuzzy control, FOC control, space vector modulation, PID control, and reference frame

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Abbreviation and acronyms

i_{as}, i_{bs}, i_{cs}	The three-phase stator current components
i_{ar}, i_{br}, i_{cr}	The three-phase stator current components
V_{as}, V_{ds}, V_{cs}	The three-phase rotor current components
V_{ar}, V_{br}, V_{cr}	The three-phase rotor voltage components
i_s	Stator current
i_{qs}, i_{ds}	Direct and quadrature component of stator current
i_{qm}, i_{dm}	Direct and quadrature component of magnetizing current
$i_{\alpha s}, i_{\beta s}$	Time-variant stator current in fixed two coordinate reference frame
V_{ds}, V_{qs}	Direct and quadrature component of stator current
V_{dr}, V_{qr}	Direct and quadrature components of rotor voltage
$\lambda_{ds}, \lambda_{qs}$	Direct and quadrature components of stator flux
$\lambda_{qm}, \lambda_{dm}$	Direct and quadrature components of air gap flux
λ_r	Rotor flux magnitude aligned with the d axis of synchronously rotating reference frame
θ_{field}	Rotor flux position
Ls, L_r, Lm	Per phase stator, rotor, and mutual inductance for symmetrical IM
R_s, R_r	stator and rotor phase resistance for symmetrical IM
T_e	Electromagnetic torque
T_L	Load torque
J	Moment of inertia of the motor
P	Number of poles
ρ	Time derivative operator
ω_m	Motor mechanical speed
ω_r	Electrical speed
ω	Speed of arbitrarily rotating reference frame
ω_s	Synchronous speed
F	Friction coefficient
T_d	Dry force

T_0, T_1, T_2	Space vector pulse width modulator switching duration
AC	Alternating Current
DC	Direct current
FLC	Fuzzy logic control
FOC	Field-oriented control
RFO	Rotor flux oriented
IM	Induction machine
MMF	Magnetomotive force
SPWM	Sine wave pulse width modulation
SVPWM	Space vector pulse width modulation

CHAPTER ONE

Introduction

1.1 General overview

Induction motor (IM) is an electromagnetic device, which converts electrical energy to mechanical energy. It has stator and rotor mounted on bearings and separated by an air gap as shown in figure (1.1). Both the stator and rotor windings of IM carry alternating current (AC). The AC current is applied to the stator winding, and the rotor gets AC current through induction. A three-phase IM is designed to operate from a three-phase AC source. For variable speed drives, the source is normally an inverter that uses power switches to produce approximately sinusoidal voltages and currents of controllable magnitude, frequency, and phase [1].

IM is of two types squirrel cage and wound rotor. In squirrel cage type IM, the rotor winding is inaccessible. Squirrel cage IM is so common in the industry that in many plants almost no other type of machine can be found. IM employs a simple but clever scheme of electromechanical energy conversion. In IM, no moving contacts, commutator, and brushes as DC motor or slip rings, and brushes as in synchronous machines are needed. This arrangement of IM greatly increases the reliability of IM and eliminates the danger of sparking, permitting squirrel cage IM to be safely used in harsh environments, even in an explosive atmosphere. An additional degree of ruggedness is provided by the lack of wiring in the rotor, whose winding consists of an uninsulated metal bar forming “squirrel cage” that gives the name to the motor. Such a robust rotor can run at high speed and withstand heavy electrical and mechanical overload [2].

Previously, IM was operated uncontrolled, running at constant speed near to rated speed, even an application where efficient control over their speed could be a very advantageous [2]. In this case, to decrease the speed other mechanisms such as gear and belt were used this mechanism causes power loss. In inverter fed IM control, the power electronics switch approximates a typical voltage level by timely switching “on” and “off” the supply voltage. There are a variety of applications in which speed control increasingly used (example: process industry, heating ventilating and air conditioning, and transportation system (elevator, conveyor, hoist and electric vehicle)). However, control of IM is not a simple issue due to its multivariable, and nonlinear nature. In addition, some of the parameters are time-variant, for example, the mutual inductance between the stator and rotor, and some of the state variables like stator flux, rotor current (for squirrel cage rotor) are not accessible for measurement [1], [3] .

In the past, DC motors were used extensively in areas where variable speed operation is required since the field and armature current could control their flux and torque easily. Now a day the shift from DC motor to IM is continued because of the development of power electronics converters, high computing microprocessors, and DSP, as well as the development of AC motor control theory such as field-oriented control, and intelligent control. The development of an accurate system model is fundamental in the design, analysis, and control of IM. These models must incorporate the essential element of both the electromagnetic and mechanical systems both for steady-state and for transient operating conditions.

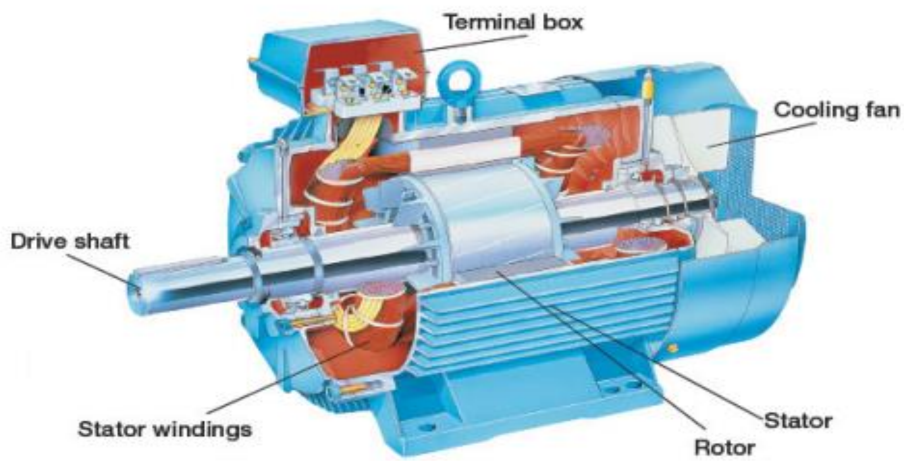


Figure 1. 1 The sectional view of IM

An electric drive consists of various components: driven mechanical system (load), electric machine, electric power converter, controller, etc. interconnected as shown in figure (1.2) below. Industrial loads require operations at any one of a wide range of speeds. Such loads generally termed as variable speed drives. These drives demand precise adjustment of speed in a step-less manner over the complete speed range required.

With thyristor power converters providing a variable voltage, and variable frequency supply the speed control of IM has become simple, making them viable competitors to DC motor. Variable speed drives in the industry employ IM as their drive motors mainly because they enjoy various specific advantages, such as overload capacity, smooth speed control over a wide range, the capability of operating in all the four quadrants of the speed-torque plane, etc. Variable frequency drives are controlled by a pulse width modulator (PWM) switching techniques. Various types of PWM techniques are there. Space vector pulse width SVPWM is used in this thesis.

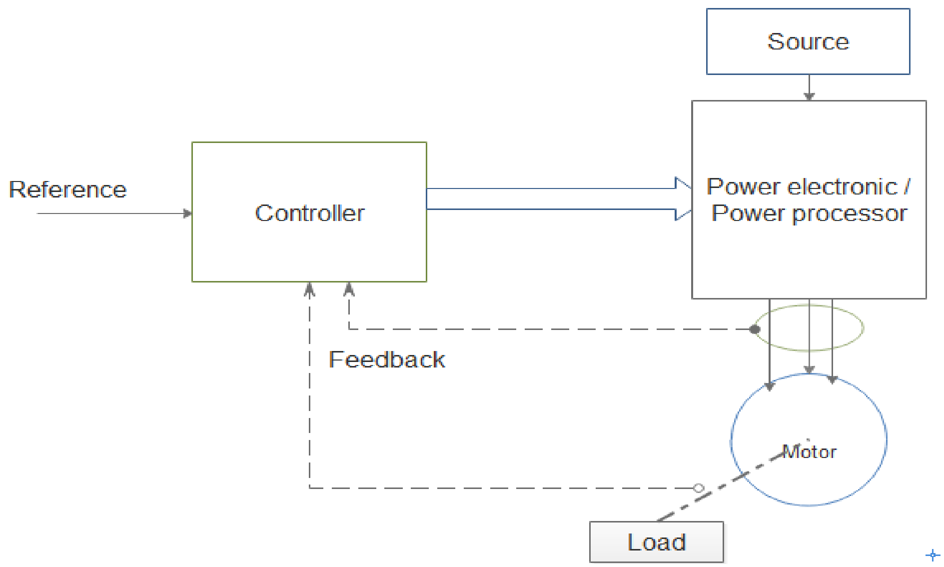


Figure 1. 2 Electric drive general block diagram

In this thesis, the design of the fuzzy and PID controller for IM using simulation and comparing them has been done. The IM model is used to determine the PID controller parameters. The fuzzy control, it is based on the idea of fuzzy set theory introduced by Prof. Lotfi Zadeh in 1965, is an intelligent control has a smooth control behavior. In fuzzy control design, the mathematical model is used to approve the controller using mathematical simulation in order to avoid potential errors, to tune the fuzzy controller, i.e. to tune the universe of discourse, type of membership function, and rule base. In addition, the model was used in developing expert knowledge about the system to develop a fuzzy rule base.

1.2 Statement of the problem

An induction motor has many interesting futures (high power to mass ratio, relatively low cost, reliable, and maintenance-free) however, it is much difficult to control so it is an important control problem. Now a day selecting a suitable controller for a given application is a much difficult problem due to the advent of many different control theories. Many works on fuzzy control have focused only on its advantages so it needs a critical investigation on its possible disadvantages and limitations. People working in fuzzy control says no mathematical model is needed to design a fuzzy controller. Moreover, the most important advantage of FLC is considered to be no need for the mathematical model in the design of FLC. This eliminates the challenges control engineers encounter to bring accurate mathematical models. However, without the mathematical model and simulation analysis, the controller cannot be implemented directly into the hardware. In addition, it is not possible to form expert knowledge that is important to form a rule base for such a complex system without the system model.

The PID controller, on the other hand, has a well-defined design procedure. The effect of PID controller parameters on transient response is known. The PID controller parameters depend on the system model. PID controller parameters can be determined from the linearized system model but systems in nature are nonlinear so the PID controller is good in the linear operating region. Even though FLC can control a system better than PID but the designer may not able to design the FLC that controls a system with maximum possible.

To know, is it possible to design a fuzzy controller that can control better than PID and vice versa? is a problem. Because even if fuzzy control is an excellent intelligent control scheme in the presence of uncertainty due to vagueness and lack of information it is difficult to even impossible to design if there is no expert knowledge or if the controlled system is too complex to derive the decision rule. Therefore, this paper proposed to undergo Comparative Analysis of PID and FLC for IM speed control.

1.3 The objective of the study

1.3.1 General objective

The main objective of this investigation is to undergo a comparative analysis of PID and fuzzy logic controllers for IM speed control and to give a precise conclusion.

1.3.2 Specific objectives

- Mathematical modeling of IM in the rotating reference frame
- Develop a fuzzy inference mechanism and fuzzy RULE base
- Design both fuzzy and PID controllers for IM
- Compare the result obtained for PID and Fuzzy controllers using mat lab simulation

1.4 Methodology

The general block diagram of PID and FLC of the IM speed control algorithm to be used in this thesis is shown in figure (1.3). In this thesis work, IFOC is used. Flux position for vector transformation is determined indirectly from rotor speed measurement and slip speed. The rotor flux and/or direct stator current is kept constant for fast response time. The data to analyze the system is collected through a literature survey and simulation. In this system, the SVPWM determines the switching sequence for the inverter based on the flux and torque controller outputs.

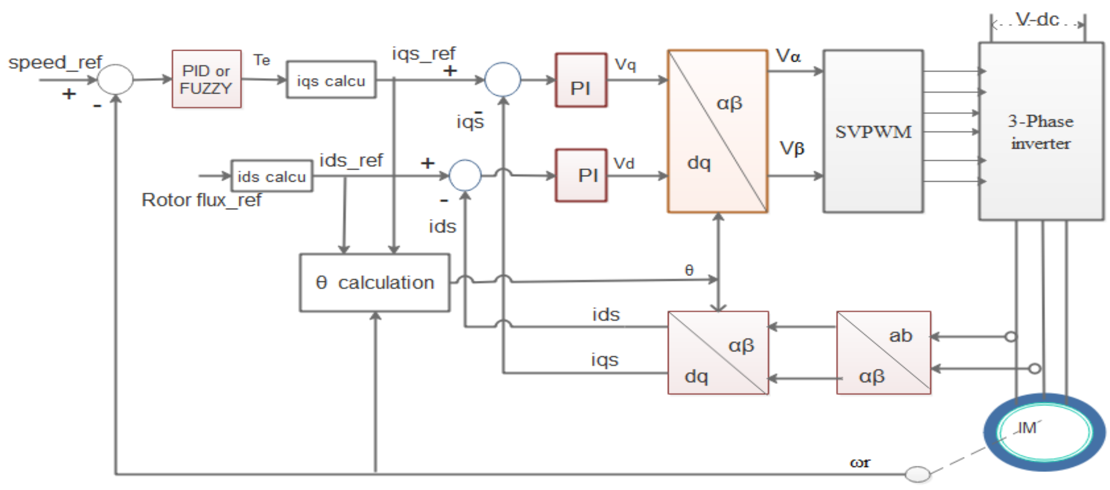


Figure 1. 3 Block diagram of indirect field oriented control of IM

1.5 Thesis organization

This thesis organized into five chapters:

Chapter 1 describes the general background of the IM drive. In this chapter, the general background of IM speed control, Problem statement, objectives, and methods to solve the problem are presented.

Chapter 2 describes the literature review about the problem. Under this chapter, related works were done before and many concepts to solve the problem are presented. This chapter includes Inverter, FLC, SVPWM, reference frame theory, and vector control strategies.

Chapter 3 describes the general methods to solve the problem. Mathematical modeling of squirrel cage IM and the design of both FLC and PID controllers are presented in this chapter.

Chapter 4 describes the simulation results and discussion on the result obtained. This chapter includes results and discussions with load and at no load, for parameter variation, and low-speed response for both PID and FLC controllers.

Chapter 5 describes the conclusion drawn on the designed system and giving directions for future work are presented.

CHAPTER TWO

Literature Review

2.1 Related works

Three-phase IM is the workhorse of industrial and residential motor applications due to its simple construction and durability. These properties of IM attract the researcher's attention and different control methods are proposed to use IM in variable speed drive applications. Implementation of the IM control strategy can be classified as scalar control and vector control [4]. A simple method of IM control is to vary the supply stator voltage at supply frequency. This method of speed control has poor dynamic and static performance. This method also has a high slip power loss. An efficient method of speed control for IM is to change the stator frequency since the speed is close to synchronous speed the operating slip is small, and slip power loss in the rotor circuit is small. However, this method of speed control requires a frequency converter, which is expensive. Slip current control, v/f control [5] , and vector control uses frequency converter. In v/f control, both voltage and frequency varied kept their ratio constant [6]. Both v/f control and slip current control fail to provide satisfactory transient performance [7]. These control strategies called scalar control in which only the magnitude and frequency of stator current and voltage are controlled. Fast and precise torque response for a high-performance AC IM drive is achieved by the use of a vector or FOC method [8]. The concept of FOC is based on the decomposing of stator current into torque and flux producing component [9]. Therefore, it provides separate control of flux and torque. In vector control, all the magnitude, frequency, and phase are controlled.

There are different field orientations. The most common field orientations are stator-flux field orientation, air-gap flux field orientation, and rotor-flux field orientation [4], [10] . Rotor flux field-oriented control is the first field-oriented control; this is achieved by aligning the rotor flux on the d-axis of the rotating reference frame. Field-oriented control can be classified into two: Direct method of field-oriented control, it is the first FOC, utilizes direct sensing of the air gap flux vector by using different measurement techniques like air gap hall sensors, sensing coils, or other measurement techniques. Since this method uses feedback control and direct sensing of the regulated variable, it is essentially insensitive to variation. However, this method is very problematic because it needs additional wiring it adds cost and complexity to the drive [11]. It may be difficult to mount the sensing device in the air gap. The other type of field-oriented control is indirect field-oriented control, which avoids the requirements of flux sensing devices by using known motor parameters to compute the appropriate motor slip frequency to obtain the desired flux position. This method is very popular because this method is simpler to implement than direct field-oriented control. Sensorless control, in which the speed and/or position sensors are missing, was proposed in reference [12], [13]. In sensorless control, the speed and flux vector is online estimated from the voltage and current measurement. This future decreases the drive cost. Sensorless speed control is also important when there is a difficulty for additional wiring due to temperature, corrosive contact, etc. Indirect field-oriented control of IM without the need of the current sensor also has been proposed in reference [14]. In this control strategy, no current sensors are needed and also it eliminates the two current feedback loops and their associated controllers result in overall design simplicity and cost reduction for vector controllers. However, as there are no voltage and current feedback, the performance of the drive might deteriorate due to parameter deviation/mismatch and disturbance. In IM FOC, many controllers were proposed (fuzzy control, neural network, Genetic Algorithm, Adaptive control, SMC, neuro-fuzzy, and many others). In this thesis, the IFOC method is proposed because of its excellent behavior.

2.2 Reference frame theory

There are possibly three commonly used reference frames that are used to transform a three-phase (abc) variable to two-dimensional variables [11].

1. Reference frame fixed on the rotor (R. H. Park)
2. Reference frame rotating in synchronous speed (G. Kron)
3. Stationary reference frame (H.C. Stanley)

Previously these reference frames are treated and analyzed separately but now a general reference frame that contains all reference frames in one is introduced which is called an arbitrary reference frame. All reference frames can be extracted from the arbitrary reference frame by assigning the appropriate speed of reference frame, that is, $\omega = 0$ for the stationary reference frame, $\omega = \omega_s$ for synchronously rotating reference frame and, $\omega = \omega_r$ for the rotor fixed reference frame.

2.3 Vector transformation

A change of variables that transform three-phase stationery (abc) variables into two-dimensional (dq) variables may be expressed as in equation (2.1) below [1], [11], [15], [16].

$$f_{qdos} = K_s f_{abcs} \tag{2.1}$$

Where $[f_{abcs}]^T = [f_{as} \quad f_{bs} \quad f_{cs}]$, and

$$[f_{qdos}]^T = [f_{qs} \quad f_{ds} \quad f_{os}]$$

In the above equation, f represents voltage, current, flux, or electric charge.

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

K_s = a vector transformation matrix preserving amplitude.

To avoid the difficulty in MATLAB implementation, reference frame transformation can be simply employed in two steps; that is

1. abc –to-αβ it is called Clark transformation
2. αβ-to-dq which is called Park transformation

The relationship between reference frames is shown in figure (2.1).

abc-to-αβ (Clark Transformation)

The Clark transformation changes the three-phase stator quantity (in this particular case stator current) to time-varying stationary two-dimensional αβ signal.

The Clark transform mathematically given by

$$[i_{\alpha\beta os}] = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}[i_{abcs}]f_{qdos} = K_s f_{abcs} \qquad (2.2)$$

Equation 2.2 can be written in expanded form as below in equation 2.3a and equation 2.3b

$$i_{\alpha s} = \frac{2}{3}i_{as} - \frac{1}{3}i_{bs} - \frac{1}{3}i_{cs} \qquad (2.3a)$$

$$i_{\beta s} = \frac{\sqrt{3}}{3}i_{bs} - \frac{\sqrt{3}}{3}i_{cs} \qquad (2.3b)$$

Using the fact, $(i_{as} + i_{bs} + i_{cs} = 0)$ we get the following equation

$$i_{\alpha s} = i_{as} \qquad (2.4a)$$

$$i_{\beta s} = \frac{1}{\sqrt{3}}i_{as} + \frac{2}{\sqrt{3}}i_{bs} \qquad (2.4b)$$

This equation indicates only the two-phase stator current needs to be measured.

αβ-to-dq (Park transformation)

The park transformation transforms the time-varying two-dimensional signal to rotating a two-dimensional time-invariant signal. Resolving αβ to dq reference frame, we will get the following equation.

$$i_{qs} = i_{\alpha s}\sin(\theta_{field}) + i_{\beta s}\cos(\theta_{field}) \qquad (2.5a)$$

$$i_{ds} = i_{\alpha s}\cos(\theta_{field}) + i_{\beta s}\sin(\theta_{field}) \qquad (2.5b)$$

Inverse Park transform (dq-to-αβ)

For the system to be designed an SVPWM is used. An SVPWM uses a space vector concept to calculate the duty cycle of the six switching devices in the inverter. Therefore, SVPWM to be used the rotating time-invariant V_{dq} needs to transform into a fixed time-varying voltage, $V_{\alpha\beta}$.

$$V_{\alpha s} = V_{ds}\cos(\theta_{field}) - V_{qs}\sin(\theta_{field}) \quad (2.6a)$$

$$V_{\beta s} = V_{ds}\sin(\theta_{field}) + V_{qs}\cos\theta_{field} \quad (2.6b)$$

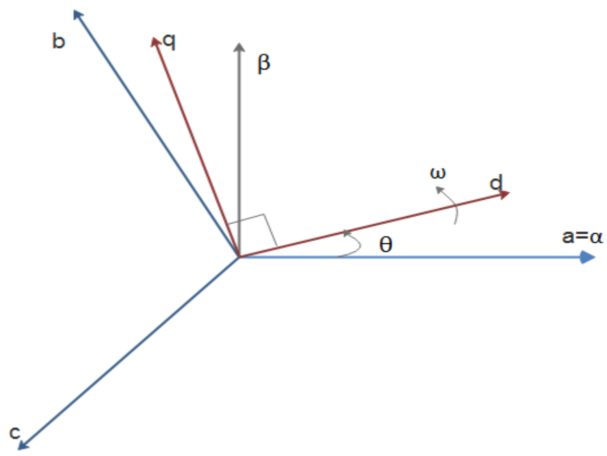


Figure 2. 1 Relationship between different reference frames

2.4 Vector control

From the point of view of the controlled signals, induction machine controllers classified into two classes [17].

1) Scalar control: here the magnitude, and frequency of voltage and/or current are controlled
    - Open-loop v/f constant control
    - Slip frequency control
2) Vector control: here the magnitude, frequency, and phase of voltage and /or current are controlled
    - Field oriented control
    - Direct torque

The electrical DC drive systems are still used in a wide range of applications although they are less reliable than the AC drives. Because of simple and precise command and control structure. The AC drives, some times more expensive but far more reliable, require complex modern control techniques. The IM is a relatively cheap and rugged machine because its construction is realized without slip rings or commutators. These advantages have determined an important development of the electrical drives, with IM as the actuator element, for all related aspects: starting, braking, and speed reversal, speed change, etc.

Recent years have seen the evolution of a new control strategy for AC motors, called "vector control", which has made a fundamental change in the problem of IM drives in regards to dynamic performance. Vector control makes it possible to control an IM in a manner similar to the control of a separately excited DC motor and achieve the same quality of dynamic performance of DC motor.

The technique called vector control can be used to vary the speed of an IM over a wide range. In vector control scheme a complex current is synthesized from two-quadrant components, one of which is responsible for the flux level, and another controls the torque production in the motor. In vector control of AC machine phase, magnitude, and frequency of the stator current are all controlled.

Essentially, the control problem is reformulated to resemble the control of a DC motor. Vector control offers a number of benefits including speed control over a wide range, precise speed regulation, fast dynamic response, and operation above base speed. IM runs below the synchronous speed given by $N_S = \frac{120f}{P}$ for variable frequency drive, this synchronous speed can be made large by decreasing the frequency so the motor still runs below the new synchronous speed but above base speed on the nameplate.

Field-oriented control for IM drive can broadly be classified into two types, Indirect field-oriented control (IFOC) and Direct field-oriented control (DFOC). In the DFOC strategy, the rotor flux vector is either measured by means of flux sensor mounted in the air gap or estimated by using the voltage equations starting from the IM parameters. However, in the case of IFOC rotor flux vector is estimated using (current models) requiring rotor speed/position measurement. Between the two schemes, IFOC is more commonly used because in the closed-loop mode it can easily operate throughout the speed ranges from zero speed to high-speed field weakening. The basic difference is on the rotor flux position determination strategy.

2.5 Field-oriented control fundamental

Vector control is the most popular control technique of ac IMs. In special reference frames, the expression for the electromagnetic torque of the smooth air gap machine is similar to the expression for the torque of the separately excites DC machine. In the case of IM vector control, the control is usually performed in the reference frame whose direct axis attached to the rotor flux space vector. That is why the implementation of vector control requires information about the space angle (position) of the rotor flux. In vector control, the stator currents of the IM are separated into flux and torque-producing components by utilizing transformation to the d-q coordinate system, whose direct axis d is aligned with the rotor flux space vector. This means the q axis component of the rotor flux space vector is always zero.

2.5.1 Vector control strategies for IM

Vector control consists of controlling stator currents represented by a vector. The aim of vector control is usually to decouple the stator current i_s into its flux producing and torque producing component (i_{ds} and i_{qs}) respectively. In order to obtain a decoupled control of the flux and electromagnetic torque, a special reference frame fixed to different space vector variable have to be selected. Different vector control strategies are there [4].

1. **Stator flux field orientation (SFO):** The stator flux oriented control or fixed on stator flux control is obtained by considering a non-commonly used rotating reference frame the one whose d-axis coincides with the stator flux, λ_s. For this vector control strategy a state-space model of IM formed by stator flux and stator current $x = [\lambda_{qs} \quad \lambda_{ds} \quad i_{qs} \quad i_{ds}]^T$ as a state variable is appropriate.
2. **Rotor flux field orientation (RFO):** The rotor flux oriented control also called field-oriented control is obtained by considering a non-commonly used rotating reference frame the one whose d-axis coincides with the rotor flux, λ_r. For this case IM model with rotor flux and stator current $x = [\lambda_{qr} \quad \lambda_{dr} \quad i_{qs} \quad i_{ds}]^T$ as a state variable is appropriate.
3. **Air gap flux field orientation (AFO):** The air gap flux oriented control also called field-oriented or fixed on air gap flux control is obtained by considering a non-commonly used rotating reference frame the one whose d-axis coincides with the air-gap flux, λ_m. For this

method IM model with air gap flux and stator current $x = [\lambda_{qm} \quad \lambda_{dm} \quad i_{qs} \quad i_{ds}]^T$ as a state variable is appropriate.

4. **Stator current orientation (SCO):** The stator current oriented control or fixed on stator current control is obtained by considering a non-commonly used rotating reference frame the one whose d-axis coincides with the stator current, i_s. For this type of vector control of IM, the model with stator flux and stator current $x = [\lambda_{qs} \quad \lambda_{ds} \quad i_{qs} \quad i_{ds}]^T$ as state a variable is suitable.
5. **Rotor current orientation (RCO):** The rotor current oriented control or fixed on rotor current control is obtained by considering a non-commonly used rotating reference frame the one whose d-axis coincides with the rotor current, i_r. For this method, the model with rotor current and stator flux $x = [\lambda_{qs} \quad \lambda_{ds} \quad i_{qr} \quad i_{dr}]^T$ as a state variable is appropriate.

   For wound type rotor since rotor currents are available for measurement rotor current as a state variable can be used instead of stator current state variables for all vector control strategies.

2.6 Fuzzy logic controller

2.6.1 Fuzzy control overview

Fuzzy logic control is an intelligent control based on the principle of the fuzzy set theory. The fuzzy controller provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to best control a system. The block diagram of a general fuzzy control system is given below in figure (2.2) [18], [19].

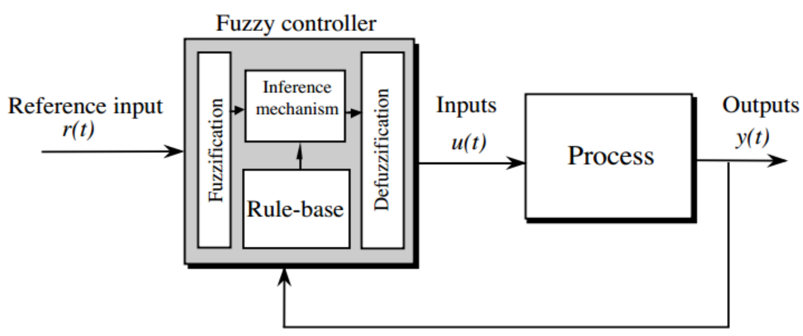


Figure 2. 2 Fuzzy logic control system general architecture

The fuzzy logic controller has four main components [20].

1) The “rule-based” holds the knowledge, in the form of a set of rules, of how best to control the system.
2) The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant or control output should be.
3) The fuzzification inference simply modifies the inputs so that the inference engine can interpret them and compare it with the rule base. It converts the crisp set into a fuzzy set.
4) The defuzzification inference converts the conclusion reached by the inference mechanism into crisp value inputs to the plant. It converts the fuzzy set to a crisp set.

Fuzzy control can be viewed as an artificial decision-maker that operates in a closed-loop system in real-time. It gathers plant output data y(t), compares it with the reference input r(t), and then decides what the plant input or controller output u(t) should be to ensure that the performance objectives will be met [18]. To design the fuzzy controller, the control engineer should have information on how the artificial decision-maker should act in the closed-loop system. Sometimes this information can come from a human decision-maker who performs the control task, while at other times the control engineer can come to understand the plant dynamics and write down a set of rules about how to control the system without outside help. These rules say, “IF the plant output and reference input are behaving in a certain manner, THEN the plant input should be some value.” If a whole set of such a rule base is loaded into the rule base, and an inference strategy is chosen, then the system is ready to be tested to see if the closed-loop specification is met.

2.7 PID control

PID controller is today probably the most widespread type of controller in the industry. The PID controller has the advantage that the physical effect of each of its three gain terms is clearly visualized in the features of the transient response: that is the effect of the three gains k_p, k_i, and k_d is known. That is k_p is responsible for overshoot, k_i is responsible for the speed of response and steady-state error, and k_d is responsible for the damping effect.

PID control is widely used in systems that employ output feedback control. In such systems, the controlled output is measured and fed back to a summing point where it is subtracted from the reference input. The difference between the reference and feedback corresponds to the control loop error (or servo error) and forms the input to the PID controller.

The PID controller output is the parallel sum of three paths error, error integral, and error derivative multiplied by their corresponding gains. The user adjusts the relative weights of each path to optimize transient response performance.

The control output for a PID control algorithm is given by equation (2.7)

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau + k_d \frac{de(t)}{dt} \tag{2.7}$$

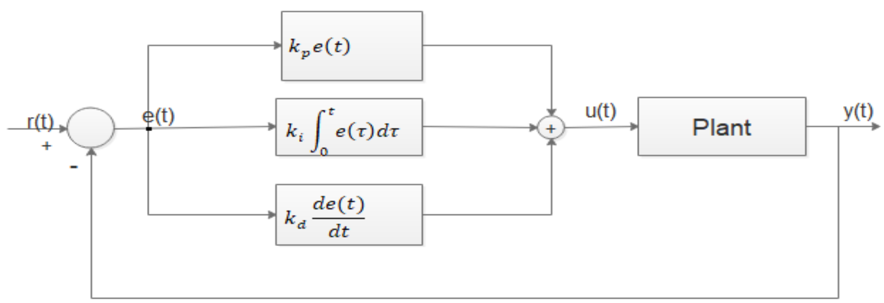


Figure 2. 3 PID control structure

2.8 Inverters for ac drives (DC-AC)

Inverters are circuits that convert dc power to an ac power at a desired output voltage and frequency. More precisely, the inverter transfers electric power from a dc source to an ac load. Inverters can be classified into two major classes; voltage source inverter (VSI) and current source inverter (CSI). VSI is one in which the dc source has small or negligible impedance. In other words, a VSI has a stiff dc voltage source as its input terminal. On the other hand, a CSI is fed with adjustable current from a dc source of high impedance i.e. from a stiff dc current source. In VSIs using thyristors, some type of forced commutation is usually required. In case VSIs are made up of using GTOs, power transistors, power MOSFETs, or IGBTs, self-commutation with base or gate drive signals is employed for their controlled turn-on and turn-off.

2.9 Space vector modulation (SVPWM)

The vast majority of variable speed IM drives are voltage source inverters. These variable speed drives are controlled using pulse width modulation techniques. The circuit model of a typical three-phase voltage source PWM inverter is shown in figure (2.4). There are different types of PWM, sine wave pulse width modulation (SPWM), and SVPWM is among the most widely used pulse width modulation techniques [21].

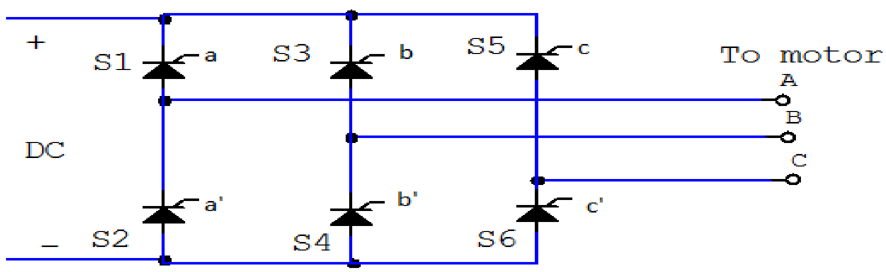


Figure 2. 4 Three-phase voltage source PWM inverter

In sine wave PWM, two signals are used to generate the PWM signal: one of which is a reference sinusoidal wave V_{ref} and another of which is a triangular carrier wave V_{car}. To generate the SPWM, a comparator is used to compare the instant values of V_{ref} and V_{car} signals. When the V_{ref} is greater than V_{car} , the output of the PWM signal is high ("on"), and when the V_{ref} is less than V_{car} , the output of the PWM signal is low ("off").

SVPWM is a special switching sequence of the upper three power transistors of a three-phase power inverter. SVPWM method treats the modulating signals as a single unit called the reference voltage. In SVPWM it is possible to generate the switching signal directly using the space vector of the reference voltage. It is known that the three switching arms in the converter have eight base states as shown in figure (2.5).

There are two possible vectors zero vector and active vector. Six vectors of them have non-zero magnitudes, while the other two are zero-length vectors. Referring to figure (2.5), suppose a reference voltage V_{ref} is to be applied to the IM. If V_{ref} is not identical to one of the base vectors, it must be approximated using these eight vectors. The objective of the SVPWM technique is to approximate the reference vector Vref using the eight switching patterns.

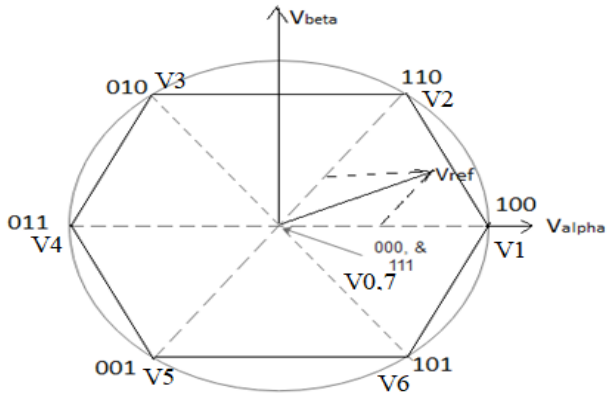


Figure 2. 5 Rotating reference voltage Vref within a hexagon

The ON and OFF states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistor are determined. The output phase voltage, the line-to-line voltage in terms of DC-link V_{dc} for the eight possible switch combinations is given in table (2.1).

Voltage vectors	Switching state			Phase voltage			Line to line voltage		
	A	B	C	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V0	0	0	0	0	0	0	0	0	0
V1	1	0	0	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	V_{dc}	0	$-V_{dc}$
V2	1	1	0	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	0	V_{dc}	$-V_{dc}$
V3	0	1	0	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-V_{dc}$	V_{dc}	0
V4	0	1	1	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-V_{dc}$	0	V_{dc}
V5	0	0	1	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	0	$-V_{dc}$	V_{dc}
V6	1	0	1	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	V_{dc}	$-V_{dc}$	0
V7	1	1	1	0	0	0	0	0	0

Table 2. 1 SVPWM output voltage waveform

Switching time

The calculation of the switching time for the base vector is described in figure (2.6) below. In figure (2.6), V1 and V2 are two adjacent base vectors and V_{ref} is an arbitrary reference voltage required to be approximated using the two adjacent base voltages by adjusting the switching time of the switching device. Using vector principle

$$T_0 = (1 - (r_1 + r_2))$$

$$T_1 = r_1 T$$

$$T_2 = r_2 T$$

Where

$$r_1 = \sqrt{3}\,\frac{V_{ref}}{V_{DC}}\sin(60 - \theta)$$

$$r_2 = \sqrt{3}\,\frac{V_{ref}}{V_{DC}}\sin(\theta)$$

Where: T is the PWM period, if T is too small the PWM signal more approximate the original signal.

T_0 Duration of zero vectors

T_1 , and T_2 are the duration of V1 and V2 respectively

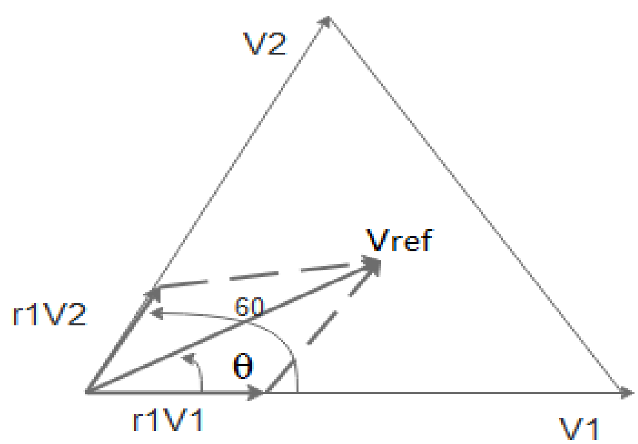


Figure 2. 6 SVPWM switching time

The main advantages of SVPWM generated gate pulse are the following.

1) Wide linear modulation range
2) Less switching loss
3) Less total harmonic distortion in the spectrum of the switching waveform
4) Relatively easy implementation
5) Gives the theoretical maximum voltage gain of 0.866

SVPWM consists of two main parts

1) Selection of the switching vectors and
2) Computation of the vector time interval

SVPWM can be implemented using the following three steps [22], [23]

1) Determine V_d, V_q, V_{ref} and angle α
2) Determine time duration T_1, T_2, and T_0
3) Determine the switching time of each transistor (S1 to S6)

CHAPTER THREE

Field Oriented Control Design

3.1 Introduction

The vector control algorithm is based on two fundamental ideas [1], [11], [16], [24]. The first fundamental idea is separating the flux and torque producing currents [9] . An IM can be modeled most simply (and controlled most simply) using two quadrature currents rather than the familiar three-phase currents actually applied to the motor. These two currents called direct (i_d) and quadrature (i_q) are responsible for producing flux and torque respectively in the motor. By definition, the i_q current is in phase with the stator flux, and i_d is at right angles. Of course, the actual voltages applied to the motor and the resulting currents are in the familiar three-phase system. The move between a stationary reference frame and a reference frame, which is rotating synchronous with the stator flux, becomes then the problem. This leads to the second fundamental idea behind vector control, which is a reference frame theory.

The second fundamental idea is that of reference frames theory. The idea of a reference frame is to transform a quantity that is sinusoidal in one reference frame, to a constant value in a reference frame, which is rotating at the same frequency. Once a sinusoidal quantity is transformed to a constant value by careful choice of reference frame, it becomes possible to control that quantity simply.

3.2 IM mathematical modeling

A conventional control system design requires a precise mathematical model. The PID controller parameters will be determined from the mathematical model describing the plant dynamics. The space vector form of the voltage equations gives the AC IM model. The model is supposed to be ideally symmetrical IM with a linear magnetic circuit characteristic as mentioned in chapter one. The development of an accurate system model is fundamental in the design, analysis, and control of IM. These models must incorporate the essential element of both the electromagnetic and mechanical systems both for steady-state and for transient operating conditions. In IM modeling, usually, the following assumptions are made [1].

1. No magnetic saturation, i.e. inductance not affected by the current level
2. No saliency effect, i.e. inductance are not functions of the position
3. Negligible spatial MMF, i.e. stator and rotor windings are arranged to produce sinusoidal MMF distribution
4. There is no fringing of the magnetic circuit
5. Eddy current and hysteresis effects are negligible, and
6. Uniform air gap

In general, fourteen state-space models out of fifteen possible IM the models are used in the analysis and design of IM control [4], [25]. The state-space model with state variables of air-gap flux and magnetizing current ($x = [\lambda_{qm} \quad \lambda_{dm} \quad i_{qm} \quad i_{dm}]^T$) cannot be used in the analysis and design of IM control as these vectors have the same direction. It does not represent a valid state-space model. The control model of IM can be classified into three major classes.

1. **Flux linkage state-space variable models**: This category includes the following possible state vector variables $x = [\lambda_{qr} \quad \lambda_{dr} \quad \lambda_{qs} \quad \lambda_{ds}]^T$, $x = [\lambda_{qr} \quad \lambda_{dr} \quad \lambda_{qm} \quad \lambda_{dm}]^T$, and $x = [\lambda_{qs} \quad \lambda_{ds} \quad \lambda_{qm} \quad \lambda_{dm}]^T$.
2. **Current state-space variable models:** This category of state-space model has the following possible state-space variables $x = [i_{qr} \quad i_{dr} \quad i_{qs} \quad i_{ds}]^T$, $x = [i_{qr} \quad i_{dr} \quad i_{qm} \quad i_{dm}]^T$, and $x = [i_{qs} \quad i_{ds} \quad i_{qm} \quad i_{dm}]^T$.
3. **Mixed current-flux state-space variable models:** This type of state-space model has an acceptable computational burden than the other models. In addition, a mixed current flux model with stator current as a state variable is the best important model because of the presence of measurable stator current. This includes the following possible state-space variables $x = [\lambda_{qr} \quad \lambda_{dr} \quad i_{qs} \quad i_{ds}]^T$, $x = [\lambda_{qr} \quad \lambda_{dr} \quad i_{qm} \quad i_{dm}]^T$, $x = [i_{qs} \quad i_{ds} \quad \lambda_{qm} \quad \lambda_{dm}]^T$, $x = [i_{qr} \quad i_{dr} \quad \lambda_{qs} \quad \lambda_{ds}]^T$, $x = [i_{qr} \quad i_{dr} \quad \lambda_{qm} \quad \lambda_{dm}]^T$, $x = [\lambda_{qr} \quad \lambda_{dr} \quad i_{qs} \quad i_{ds}]^T$, $x = [\lambda_{qr} \quad \lambda_{dr} \quad \lambda_{qm} \quad \lambda_{dm}]^T$, and $x = [\lambda_{qs} \quad \lambda_{ds} \quad i_{qm} \quad i_{dm}]^T$.

The choice of the state space model is based on the mathematical computation burden of the model, type of vector control to be designed, and the availability of measurable output states. A state-space model with stator current as a state-space variable is the right one because it corresponds to a direct measurable quantity stator current. The voltage equation of IM in the arbitrary reference frame is given by the following differential equations [11], [26].

$$V_{qdos} = R_S i_{qdos} + \omega\lambda_{dqs} + \frac{d}{dt}\lambda_{qdos} \tag{3.1}$$

$$V_{qdor} = Rr i_{qdor} + (\omega - \omega_r)\lambda_{dqr} + \frac{d}{dt}\lambda_{qdor} \tag{3.2}$$

Where

$[f_{qdos}]^T = [f_{qs} \quad f_{ds} \quad f_{os}]$

$[f_{qdor}]^T = [f_{qr} \quad f_{dr} \quad f_{or}]$

The voltage equations above in expanded rewritten as

$$V_{qs} = R_s i_{qs} + \omega\lambda_{ds} + \rho\lambda_{qs} \tag{3.3a}$$

$$V_{ds} = R_s i_{ds} - \omega\lambda_{qs} + \rho\lambda ds \tag{3.3b}$$

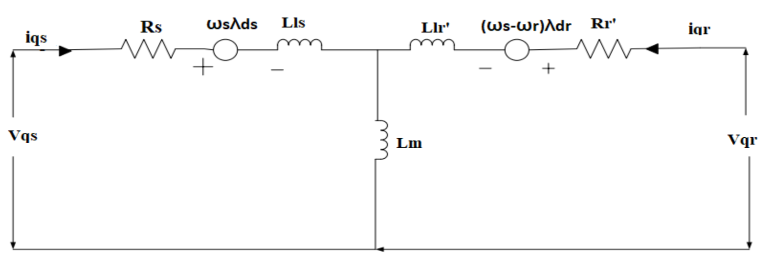
$$V_{os} = R_s i_{os} + \rho\lambda_{os} \tag{3.3c}$$

$$V_{qr} = R_r i_{qr} + (\omega - \omega_r)\lambda'_{dr} + \rho\lambda_{dr} \tag{3.3d}$$

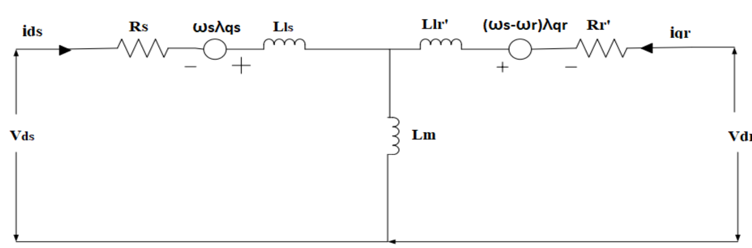
$$V_{dr} = R_r i_{dr} - (\omega - \omega_r)\lambda'_{qr} + \rho\lambda dr \tag{3.3e}$$

$$V_{or} = R_r i_{or} + \rho\lambda'_{or} \tag{3.3f}$$

From the above equations, the equivalent circuit representation of the model in the synchronous reference frame is shown in figure (3.1a and 3.1b).



a) q-axis circuit representation



b) d-axis circuit representation

Figure 3. 1 IM equivalent circuit in the synchronous reference frame

The voltage equation above is complete if the expression for the flux linkage is known. The flux equation is given by the following equations

$$\begin{bmatrix} \lambda_{qdos} \\ \lambda_{qdor} \end{bmatrix} = \begin{bmatrix} K_s L_s (K_s)^{-1} & K_s L'_{sr} (K_r)^{-1} \\ K_r (L_{sr})^T (K_s)^{-1} & K_r L'_r (K_r)^{-1} \end{bmatrix} \begin{bmatrix} i_{qdos} \\ i_{qdor} \end{bmatrix} \quad (3.4)$$

For this investigation considering symmetrical IM, the equation for the flux simplified as shown in equation (3.5) below.

$$\begin{bmatrix} \lambda_{qdos} \\ \lambda'_{qdor} \end{bmatrix} = \begin{bmatrix} \begin{pmatrix} L_{ls} + L_m & 0 & 0 \\ 0 & L_{ls} + L_m & 0 \\ 0 & 0 & L_{ls} \end{pmatrix} & \begin{pmatrix} L_m & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ \begin{pmatrix} L_m & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} L'_{lr} + L_m & 0 & 0 \\ 0 & L'_{lr} + L_m & 0 \\ 0 & 0 & L'_{lr} \end{pmatrix} \end{bmatrix} \begin{bmatrix} i_{qdos} \\ i'_{qdor} \end{bmatrix} \quad (3.5)$$

Then the flux equation in the expanded form will be as below

$$\lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i'_{qr}) \quad (3.6a)$$

$$\lambda_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i'_{dr}) \quad (3.6b)$$

$$\lambda_{os} = L_{ls} i_{os} \quad (3.6c)$$

$$\lambda'_{qr} = L'_{lr} i'_{qr} + L_m (i_{qs} + i'_{qr}) \quad (3.6d)$$

$$\lambda'_{dr} = L_{ls} i'_{dr} + L_m (i_{ds} + i'_{dr}) \quad (3.6e)$$

$$\lambda'_{or} = L'_{lr} i'_{or} \quad (3.6f)$$

Generally, to analyze balanced or symmetrical conditions of IM either stationary or synchronously rotating reference frame is used. The synchronous reference frame is better to use when the linearized model of IM needs in the analysis and design of the controller. Linearized machine equation, used to determine Eigenvalues and transfer function, is obtained from the voltage equation expressed in the synchronous reference frame [11]. Due to the above-mentioned reasons, here a synchronous reference frame is used for this thesis work. The synchronous reference frame model is obtained by simply letting the speed of the arbitrary reference frame equal to synchronous speed. The linearized mathematical model will be used in the design of the PID controller. For the fuzzy controller design, the model is used to develop expert knowledge about the system by carefully analyzing the model, to tune the fuzzy controller, and to check the performance using simulation before hardware implementation to avoid the potential errors.

IM model with mixed stator current and rotor flux as state variables are suitable for synchronously rotating frame let try to eliminate $\left(i_{dr}, i_{qr}, \lambda_{ds}, \text{and } \lambda_{qs}\right)$ and model the system using $\left(\lambda_{dr}, \lambda_{qr}, i_{ds}, \text{and } i_{qs}\right)$ as state variables. It contains the advantages of measurable output quantities (stator currents) and acceptable computational burden. The matrix equation and the electromagnetic torque relation are presented below. Moreover, this model is suitable for rotor flux oriented control because rotor flux orientation can be quantified analytically by this model.

For cage type, the rotor winding is shorted and for wound type, the rotor circuit terminals are open and accessible to add an external resistor to obtain the required torque-speed characteristics and after adding the required resister, it needs to be shorted. Therefore, both cage and wound rotor type IM rotor circuit is short-circuited at running. Therefore, equation (3.3d) and (3.3e) rewritten as follows.

$$0 = R_r i_{qr} + (\omega - \omega r)\lambda'_{dr} + \rho\lambda'_{qr} \quad (3.7a)$$

$$0 = R_r i_{dr} - (\omega - \omega r)\lambda'_{qr} + \rho\lambda'_{dr} \quad (3.7b)$$

Where: ρ = the time derivative operator

The flux equation (3.6a) – (3.6f) rewritten as

$$\lambda_{qs} = L_s i_{qs} + L_m i'_{qr} \quad (3.8a)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i'_{dr} \quad (3.8b)$$

$$\lambda'_{qr} = L'_r i'_{qr} + L_m i_{qs} \quad (3.8c)$$

$$\lambda'_{dr} = L'_r i'_{dr} + L_m i_{ds} \quad (3.8d)$$

Where $L_s = L_{ls} + L_m$ and $L'_r = L'_{ls} + L'm$

From 3.8c and 3.8d we have

$$i'_{qr} = \frac{1}{L'r}(\lambda'_{qr} - L_m i_{qs}) \tag{3.9a}$$

$$i'_{dr} = \frac{1}{L'_r}(\lambda'_{dr} - L_m i_{ds}) \tag{3.9b}$$

Substitute equation 3.9a and 3.9b into 3.7a and 3.7b we obtain the following differential equations.

$$\frac{d\lambda'_{qr}}{dt} = -\frac{R_r}{L_r}\lambda'_{qr} + \frac{L_m R_r}{L_r} i_{qs} - (\omega - \omega_r)\lambda'_{dr} \tag{3.10a}$$

$$\frac{d\lambda'_{dr}}{dt} = -\frac{R_r}{L_r}\lambda'_{dr} + \frac{L_m R_r}{L_r} i_{ds} - (\omega - \omega_r)\lambda'_{qr} \tag{3.10b}$$

Substitute equation 3.9a and 3.9b into 3.8a and 3.8b we obtain

$$\lambda_{qs} = L_s i_{qs} + L_m(\frac{1}{L'_r}(\lambda'_{qr} - L_m i_{qs})) \tag{3.11a}$$

$$\lambda_{ds} = L_s i_{ds} + L_m(\frac{1}{L'_r}(\lambda'_{dr} - L_m i_{ds})) \tag{3.11b}$$

Substitute equation 3.11a and 3.11b into equation 3.3a and 3.4b we get the following equations

$$\frac{di_{ds}}{dt} = -\gamma i_{ds} + \omega i_{qs} + \frac{\omega_r L_m}{L_m L_r \sigma}\lambda'_{qr} + \frac{L_m R_r}{L_s L_r^2 \sigma}\lambda'_{dr} + \frac{1}{L_s \sigma}V_{ds} \tag{3.12a}$$

$$\frac{di_{qs}}{dt} = -\gamma i_{qs} - \omega i_{ds} + \frac{\omega_r L_m}{L_m L_r \sigma}\lambda'_{dr} + \frac{L_m R_r}{L_s L_r^2 \sigma}\lambda'_{qr} + \frac{1}{L_s \sigma}V_{ds} \tag{3.12b}$$

The mechanical equation of an IM is given by equation (3.13)

$$\frac{Jd\omega_m}{dt} = T_e - T_l \tag{3.13}$$

With $T_e = \frac{3PL_m}{4L'_r}\left(\lambda'_{dr} i_{qs} - \lambda'_{qr} i_{ds}\right)$ [16] [27] [25]

Then

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(\frac{3PL_m}{4L'_r}\left(\lambda'_{dr} i_{qs} - \lambda'_{qr} i_{ds}\right) - (F\omega_m + T_L + T_d)\right) \tag{3.14}$$

Then the mathematical model that can represent IM approximately well in the arbitrary reference frame is given by.

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(\frac{3PL_m}{4L'_r}\left(\lambda'_{dr}i_{qs} - \lambda'_{qr}i_{ds}\right) - \left(F\omega_m + T_L + T_d\right)\right) \tag{3.15a}$$

$$\frac{di_{ds}}{dt} = -\gamma i_{ds} + \omega i_{qs} + \frac{\omega_r L_m}{L_m L_r \sigma}\lambda'_{qr} + \frac{L_m R_r}{L_s L_r^2 \sigma}\lambda'_{dr} + \frac{1}{L_s \sigma}Vds \tag{3.15b}$$

$$\frac{di_{qs}}{dt} = -\gamma i_{qs} - \omega i_{ds} + \frac{\omega_r L_m}{L_m L_r \sigma}\lambda'_{dr} + \frac{L_m R_r}{L_s L_r^2 \sigma}\lambda'_{qr} + \frac{1}{L_s \sigma}V_{ds} \tag{3.15c}$$

$$\frac{d\lambda'_{qr}}{dt} = -\frac{R_r}{L_r}\lambda'_{qr} + \frac{L_m R_r}{L_r}i_{qs} - (\omega - \omega_r)\lambda'_{dr} \tag{3.15d}$$

$$\frac{d\lambda'_{dr}}{dt} = -\frac{R_r}{L_r}\lambda'_{dr} + \frac{L_m R_r}{L_r}i_{ds} - (\omega - \omega_r)\lambda'_{qr} \tag{3.15e}$$

Where $\gamma = \frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r^2}$, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ and $\omega r = \frac{P}{2}\omega_m$

Assigning the speed of reference frame equal to synchronous speed, we get IM model in a synchronously rotating frame as in equation (3.16a-3.16e).

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(\frac{3PL_m}{4L'_r}\left(\lambda'_{dr}i_{qs} - \lambda'_{qr}i_{ds}\right) - \left(F\omega_m + T_L + T_d\right)\right) \tag{3.16a}$$

$$\frac{di_{ds}}{dt} = -\gamma i_{ds} + \omega_s i_{qs} + \frac{\omega_r L_m}{L_m L_r \sigma}\lambda'_{qr} + \frac{L_m R_r}{L_s L_r^2 \sigma}\lambda'_{dr} + \frac{1}{L_s \sigma}Vds \tag{3.16b}$$

$$\frac{di_{qs}}{dt} = -\gamma i_{qs} - \omega_s i_{ds} + \frac{\omega_r L_m}{L_m L_r \sigma}\lambda'_{dr} + \frac{L_m R_r}{L_s L_r^2 \sigma}\lambda'_{qr} + \frac{1}{L_s \sigma}V_{ds} \tag{3.16c}$$

$$\frac{d\lambda'_{qr}}{dt} = -\frac{R_r}{L_r}\lambda'_{qr} + \frac{L_m R_r}{L_r}i_{qs} - (\omega_s - \omega_r)\lambda'_{dr} \tag{3.16d}$$

$$\frac{d\lambda'_{dr}}{dt} = -\frac{R_r}{L_r}\lambda'_{dr} + \frac{L_m R_r}{L_r}i_{ds} - (\omega_s - \omega_r)\lambda'_{qr} \tag{3.16e}$$

3.3 IM MATLAB/SIMULINK simulation

Before using this model for controller design, it needs to verify whether this model accurately represents the motor or not. Then the IM SIMULINK model in the synchronous reference frame [$x = [\lambda_{qr} \quad \lambda_{dr} \quad i_{qs} \quad i_{ds}]^T$] as state variables is given in figure (3.2). the detailed MATLAB/SIMULINK model is given in APPENDIX A.

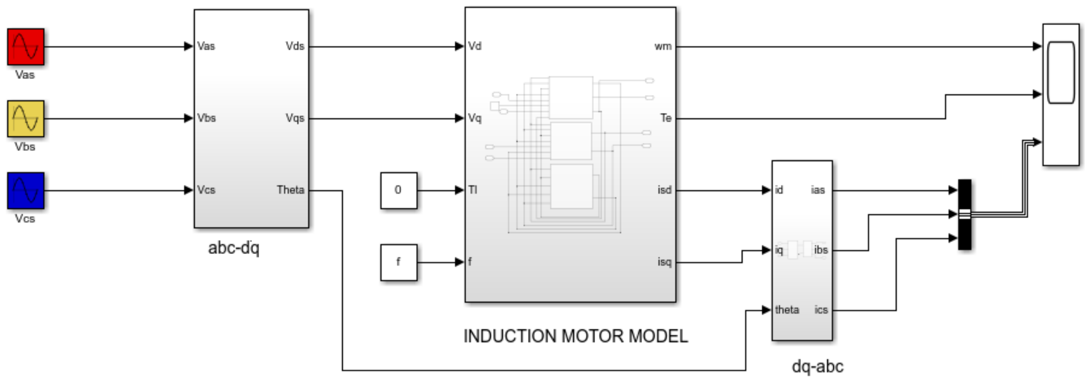


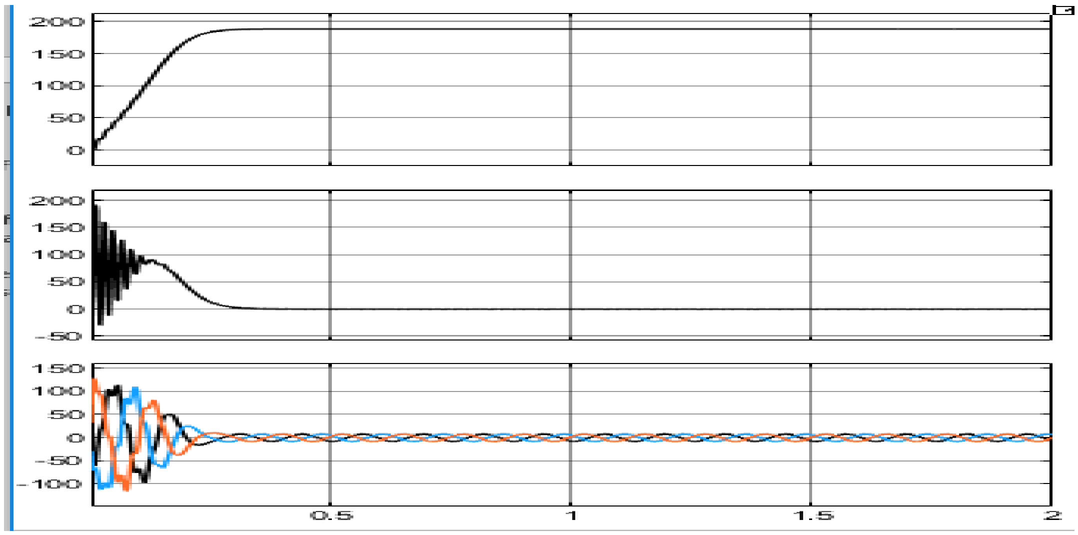
Figure 3. 2 IM MATLAB/SIMULINK model

The simulation of IM in the synchronous reference frame is shown in figure (3.2). As shown in figure (3.2) the three-phase supply, load torque, and friction force are inputs to the motor and speed, electromagnetic torque, and stator currents are the output of the motor. The model is verified using two IMs, the response for two IM, 0.18 kW, and 2.24KW, with the corresponding parameters given in table (3.1), is given in figure (3.3(a & b)). The data was obtained from reference [28]and [11] respectively.

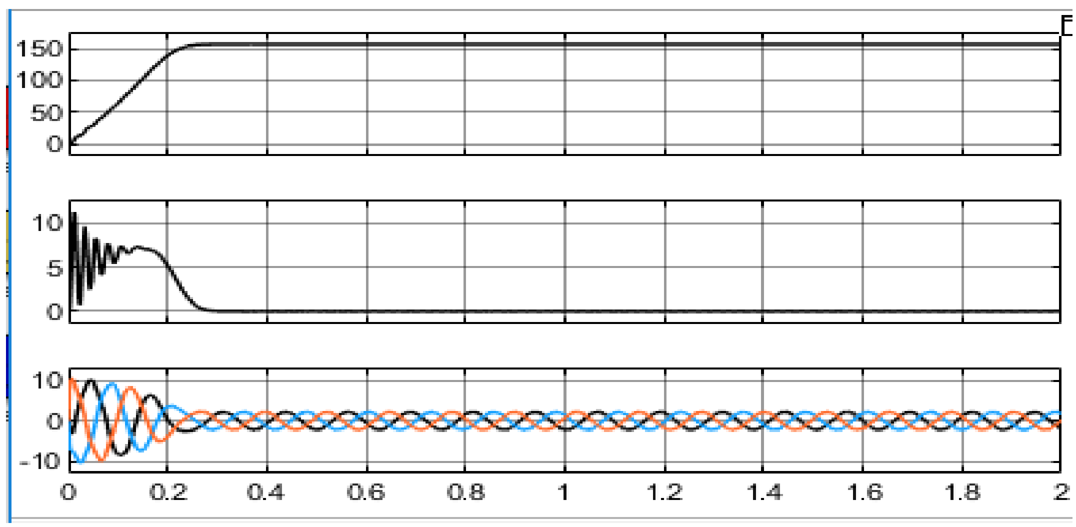
Motors	Stator resistance (Ω)	Stator inductance (Hennery)	Rotor resistance (Ω)	Rotor inductance (Hennery)	Mutual inductance (Hennery)	Moment of inertia (Kg.m^2)	Friction coefficient (N.m.s)
0.18KW	6.11	0.316423	11.05	0.316423	0.2939	0.009	0.00061
2.24KW	0.435	0.0020	0.816	0.0020	0.0692	0.089	0

Table 3. 1 IM parameters

The response at no load applying full voltage supply and at supply frequency is shown in figure (3.3).



a) For 2.24 KW, at 220V/p, and 60Hz



b) 0.18KW motor, at 220V/p, and 50Hz

Figure 3. 3 IM behavior at no-load applying full supply

Conclusion

From the graph, one can observe at full supply main the motor rotates near to the motor rated speed specified by the manufacturer. Therefore, the model represents the motor accurately well. Therefore, the model developed above can be used to PID controller parameter calculation. In addition, the model can be used to FLC design using simulation.

3.4 Controller design

The controller design comprises the design of the two internal loop controllers (flux and torque producing current controllers) and the outer loop (speed controller). For simplicity, normal PI controllers control the flux and torque producing current.

Rotor flux oriented control

As it is the original vector control, the rotor flux oriented technique is used in this design. Rotor flux oriented control has many advantages over the other vector control strategies.

1. Provides complete decoupling of flux producing current and torque producing current no decoupling circuit needed.
2. Possibility of both DFOC (use of direct measurement sensors) and IFOC (through estimation and observer).

The rotor flux oriented control is obtained by considering a non-commonly used rotating reference frame the one whose d-axis coincides with the rotor flux, λr as shown in figure (3.4). This is by the alignment of the d-axis of the synchronously rotating reference frame to the rotor flux space vector.

Analytically given by:

$\lambda_{dr} = \lambda_r \qquad \lambda_{qr} = 0$, and $\frac{d\lambda_{qr}}{dt} = 0$

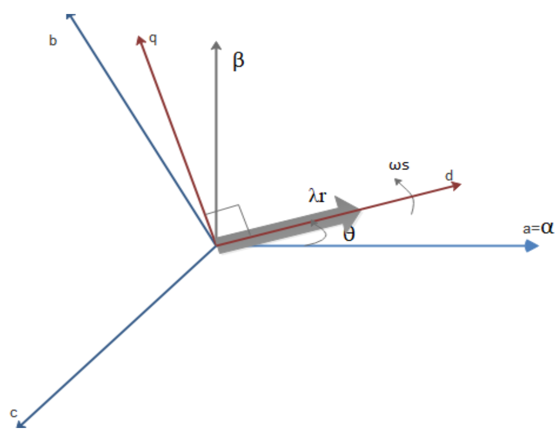


Figure 3. 4 Vector diagram in the stationary and rotating reference frame

Substituting the above in the synchronously rotating reference frame IM model above we get a fourth-order state-space equation representing the motor behavior.

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(\frac{3PL_m}{4L_r'}(\lambda_r' i_{qs}) - (F\omega_m + T_L + T_d)\right) \tag{3.17a}$$

$$\frac{di_{ds}}{dt} = -\gamma i_{ds} + \omega_s i_{qs} + \frac{L_m R_r}{L_s L_r^2 \sigma}\lambda_r' + \frac{1}{L_s\sigma}Vds \tag{3.17b}$$

$$\frac{di_{qs}}{dt} = -\gamma i_{qs} - \omega_s i_{ds} + \frac{\omega_r L_m}{L_m L_r \sigma}\lambda'_{\ r} + \frac{1}{L_s\sigma}V_{ds} \tag{3.17c}$$

$$\frac{d\lambda_r'}{dt} = -\frac{R_r}{L_r}\lambda_r' + \frac{L_m R_r}{L_r}i_{ds} \tag{3.17d}$$

From the equation, (3.16d) the slip speed is given by $(\omega_s - \omega_r) = \frac{L_m R_r}{L_r \lambda_r} i_{qs} = \omega_{sl}$, by adding this slip speed with rotor speed, rotor flux position can be determined.

Rotor flux field-oriented control also classified into two types [4], [25], [29].

1) Direct field-oriented control, and
2) Indirect field-oriented control

Direct field-oriented control

It depends on the generation of unit vector signals from the stator voltage and current signals. The stator flux component can be directly computed from stator quantity. This type of field-oriented control is an optimum choice for medium and high-speed applications. In the direct field-oriented control, the rotor flux may be measured directly using a Hall Effect sensor mounted in the air gap so it is problematic in terms of cost and installation problem.

Indirect field-oriented control

In indirect field-oriented control, the rotor field angle is obtained indirectly by integrating the summation of the rotor speed and slip speed. Indirect field-oriented control also has a problem associated with robustness. Indirect field-oriented control is an optimal choice for low-speed applications. The general block diagram of indirect and direct FOC block diagram are shown in figure 3.5 and 3.6 respectively.

In this thesis work, an indirect field-oriented control is proposed in which the rotor flux position is not directly measured rather it is estimated from stator current.

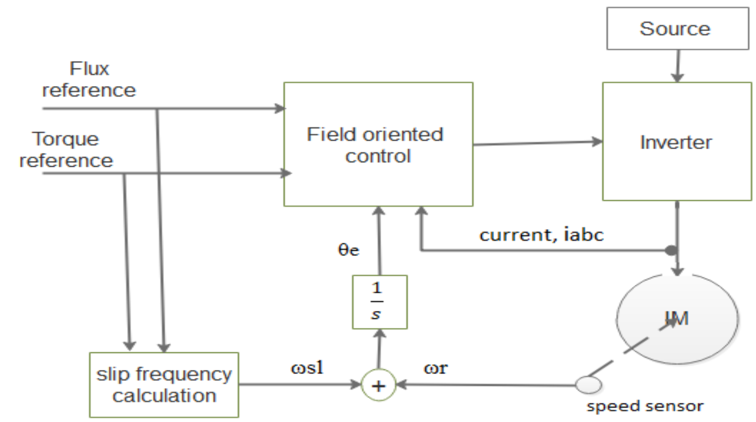


Figure 3. 5 Indirect field-oriented control simplified block diagram

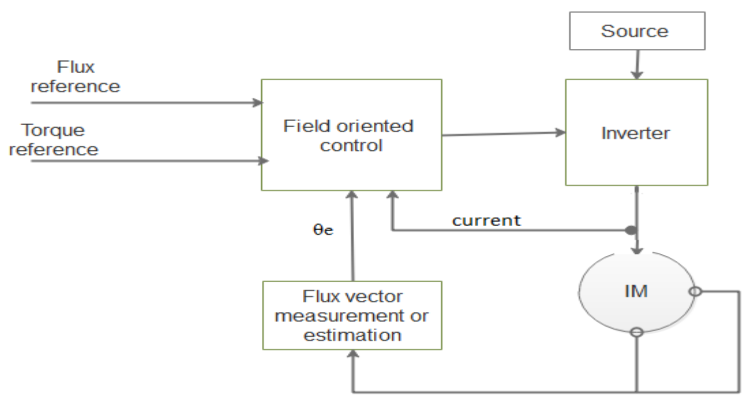


Figure 3. 6 Direct field-oriented control simplified block diagram

Reference current calculation

For IFOC the quadrature current in the rotor flux oriented synchronous reference frame given by equation (3.18) below.

$$i^*{}_{qs} = \frac{4L_r}{3PL_{m\lambda'_r}}T_e \tag{3.18}$$

Assuming constant rotor flux for fast response time the direct stator current is given by equation (3.19) below.

$$i^*_{ds} = \frac{1}{L_m}\lambda_r' \quad (3.19)$$

Rotor flux position calculation

The rotor flux position is then the integral or summations of rotor speed and slip speed.

$$\theta_{field} = \int (\omega_{sl} + \omega_r)dt$$

$$\theta_{field} = \int (\frac{L_m R_r}{L_r \lambda_r} i_{qs} + \frac{P}{2}\omega_m)dt$$

3.5 PID controller design

To design the PID controller the linearized mathematical model is required. For this purpose, the motor is modeled in the synchronous reference frame. Since once the motor is modeled in synchronous reference frame MATLAB/SIMULINK toolbox can linearize and determine the PID controller parameter automatically. The IM model to be controlled was simulated in MATLAB/SIMULINK and the validation was cheeked before using it in PID controller parameter tuning. IFOC control of IM using PID controller is given in figure (3.7).

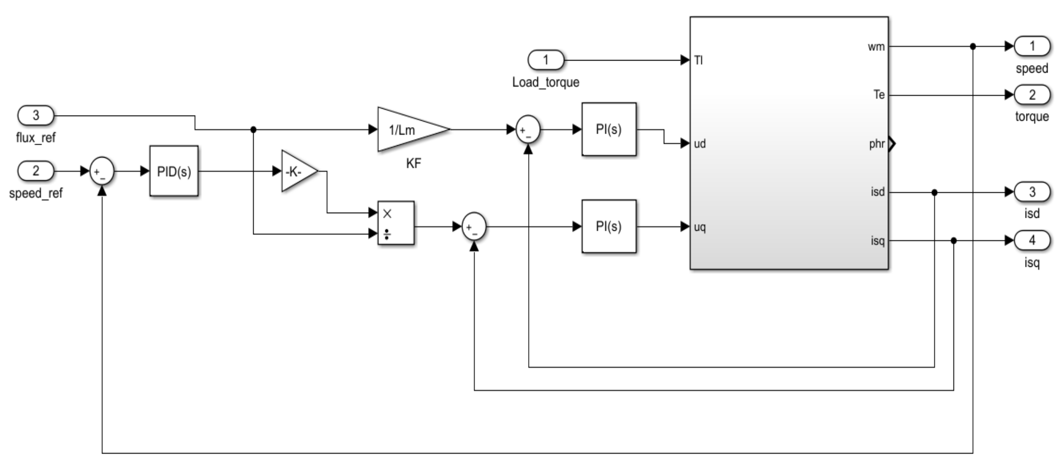


Figure 3. 7 PID control system SIMULINK model

3.5.1 PID controller tuning

The tuning of the PID controller is a matter of finding the optimum combination of effects overshoot, settling time, steady-state error, and damping effect of the transient response. This in turn, means finding the best-balanced combination of the three gain terms kp, ki, and kd. To tune the PID controller parameters MATLAB/SIMULINK auto tuner was used. After many tuning the optimal combination of the PID controller parameters ($kp, ki, kd,$ and N) are given in table (3.2) below. If one tries to design a faster PID controller results in a higher overshot and scarifies the damping effect. In addition, if one tries to design a robust PID controller it results in too low speed of response.

Parameters	Speed control	Torque control	Flux control
P (proportional gain)	0.35656	25.446	10.40186
I (integral gain)	2.56564	24625.386	6635.8529
D (derivative gain)	0.0009024	0	0
N (filter coefficient)	419.5886	0	0

Table 3. 2 PID controller parameters obtained from the auto tuner

3.6 Fuzzy logic controller design

Fuzzy logic control system design essentially contains performing the following tasks [18], [19].

1) Choosing the fuzzy logic controller inputs and outputs
2) Choosing the preprocessing that is needed for the controller inputs and possibly, post-processing that is needed for the controller outputs
3) Design each of the four components of the fuzzy controller (choice of fuzzification, inference mechanism, rule base, and defuzzification)

The fuzzy logic control design procedure

Steps to follow in designing a fuzzy logic controller for the system are the following [18], [19].

1. Identify the variables (inputs, outputs, and states) of the plant. Here the inputs to FLC are error and error rate of speed and the output is torque as shown in figure (3.10).
2. Determine the universe of discourse (min and max values) for each input and output variable. Here ranges for each input and output variables is determined by tuning via input and output scaling.
3. Partition the universe of discourse or the interval spanned by each variable into a number of fuzzy subsets and assigning each a linguistic level. Here each variable (error, error rate, and output signal) has seven trigonometric membership function having a linguistic level negative big (NB), negative medium (NM), negative small (NS), about zero (Z), positive small (PS), positive medium (PM), and positive big (PB).
4. Determine a membership function for each fuzzy subset. For an acceptable computational burden, each fuzzy subset is a trigonometric membership function as shown in figure (3.9). The variables (error, error rate, and control signal) are normalized in the range (-1, 1).
5. Forming a fuzzy rule base. The rule base for the system is better to tabulate as in table (3.3) below 7x7 a total 49 set of control rules are obtained for this system.
6. Determine the inference mechanism and defuzzification [because of its popularity Mamdani type inference mechanism and center of area defuzzification method is used for this design]

The rule base is constructed so that it represents a human expert in the loop. Hence, the rule base came from human expert who has spent a long time learning how best to control the process. In another situation, there is no such human expert, and the designer simply studies the plant dynamics (using modeling and simulation) and write down a set of control rules that make sense.

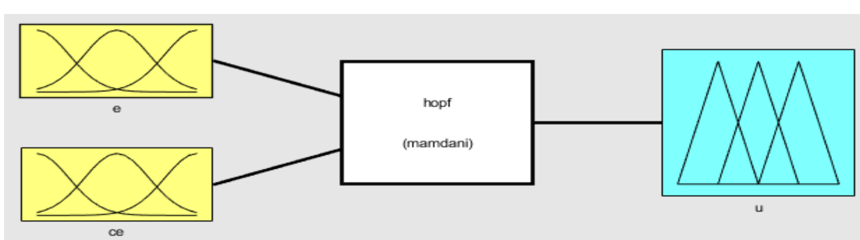


Figure 3. 8 FIS editor for fuzzy logic control

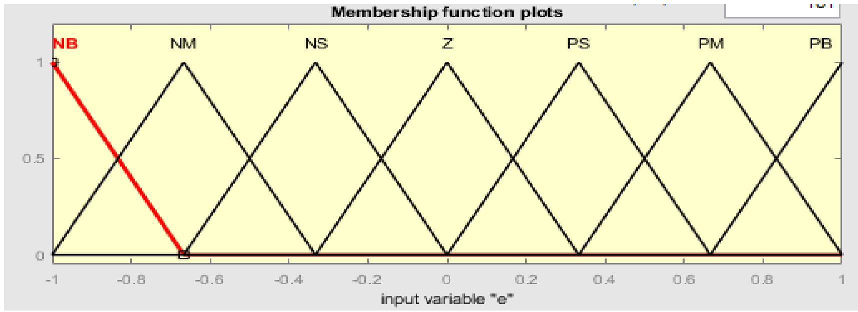


Figure 3. 9 Normalized membership plot for error, error rate, and control output

In a fuzzy logic controller design, the following basic assumptions are considered [19].

1. The plant is observable and controllable
2. There exist a body of knowledge comprising a set of linguistic rules, engineering common sense, intuition, or a set of input-output measurements data from which rules can be extracted.
3. The designer is looking for a good enough solution, not necessarily the optimum one.
4. The controller will be designed within an acceptable range of precision.
5. Problems of optimality and stability are not addressable explicitly, etc.

3.6.1 Choosing fuzzy controller inputs and outputs

Here the designer wants to control the speed of an IM. So that the designer can make input to the FLC to be speed error and rate of speed error and the controlled-output signal is obviously an electromagnetic torque, which is a reference input to the inner control loop because IM has a multivariable nature. Here the error rate gives information about the error. Information is as if speed error is constant, increasing very fast or slowly, or decreasing very fast or slowly are determined based on sign and magnitude of error rate so that the decision made to be more tight or accurate.

For this design of FLC IM control, error and error rate can be used as the variables on which to base decisions.

$$e(t) = r(t) - y(t)$$

And

$$\frac{de(t)}{dt} = -\frac{dy(t)}{dt}$$

Certainly, there are many other choices (e.g., the integral of the error $\int e(t)dt$ could be also used) but this choice makes good intuitive sense. Next, we must identify the controlled variable, for the IM the controlled variable is a torque, which is input to the inner control loop.

Once the fuzzy controller inputs and outputs are chosen, then reference inputs are needed to determine. The reference input here is the desired speed it varies from zero up to the maximum possible speed in the capability curve of the IM under control in a step-less manner. After all the inputs and outputs for the fuzzy control system are defined, we can specify the fuzzy control system. The fuzzy control block diagram of the system is given in figure (3.10) [18], [19].

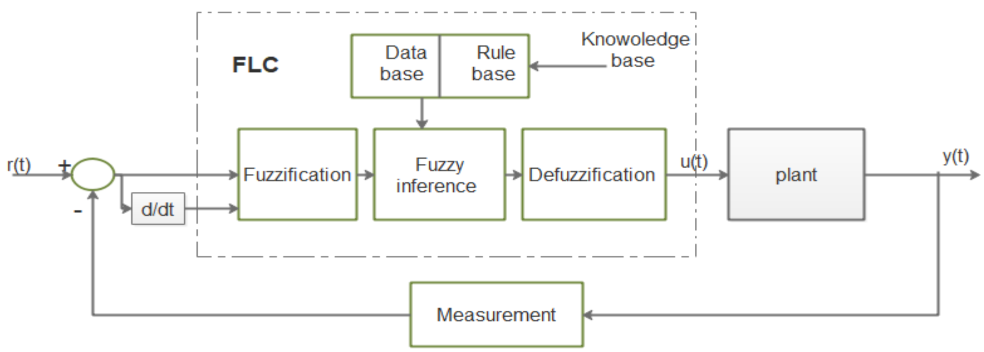


Figure 3. 10 Fuzzy controllers for IM

In the above block diagram, the plant contains the IM dynamics, and the internal flux and torque control loop. Then the IFOC speed control algorithm using fuzzy is depicted in figure (3.11).

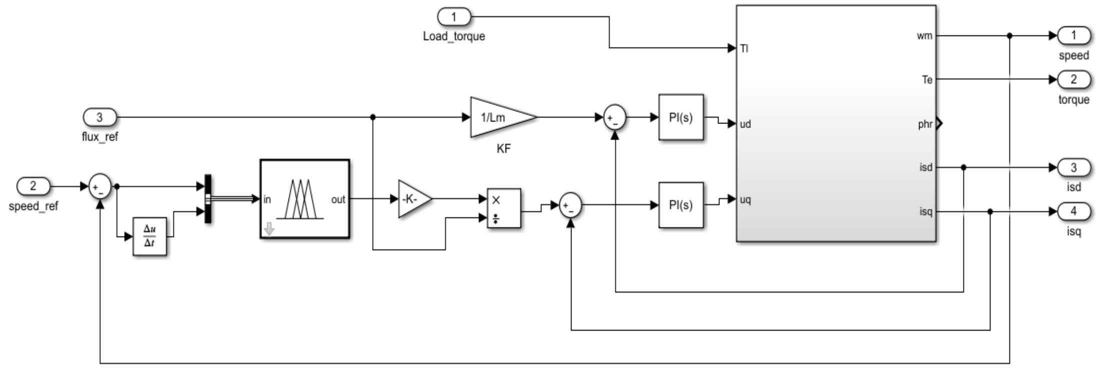


Figure 3. 11 Fuzzy control system SIMULINK model

3.6.2 The fuzzy rule bases

The fuzzy rule base consists of a set of antecedent-consequent linguistic rules of the form IF error is A AND error rate is B THEN control signal is C. This type of conditional statement is often called a 'Mamdani' type rule, after Mamdani (1776) who first used it as fuzzy rule base to control steam plant. The two seen sets of fuzzy input give a possible 7x7 set of control rules. It is convenient to tabulate it as in table (3.3).

Generally, in fuzzy controller design, the rule base is constructed from a priori knowledge from the following sources.

1. The physical law that governs the system dynamics
2. Data from existing (PID) controller
3. Expert knowledge about the plant

The expert knowledge about the system is obtained as follows

From the general conventional control, the error is given by $e(t) = r(t) - y(t)$, and assuming a constant set point one can arrive at $\frac{de(t)}{dt} = -\frac{dy(t)}{dt}$

Where $r(t)$ =reference/ desired output signal

$e(t)$ = error signal

$y(t)$= actual output signal

$e(t) =$ negative, Means the motor speed is greater than the desired speed so that the motor needs to decrease its speed.

$e(t) =$ positive, Means the motor speed is less than the desired speed so that the motor needs to speed up until it reaches the desired speed or until error is zero.

$\frac{dy(t)}{dt}$ = negative, Means speed is decreasing this implies $\frac{de(t)}{dt}$ = positive. Therefore, a positive change in the error rate indicates the speed is decreasing.

$\frac{dy(t)}{dt}$ = positive, Means speed is increasing this means $\frac{de(t)}{dt}$ = negative. Therefore, a negative change in the error rate indicates the speed is increasing.

And also by looking at PID control, one can observe that the control signal is positive large for positive large error, negative large for a negative large value of error signal, and the control signal goes to zero as the error signal goes to zero. The rule base was formed using the above knowledge together with the general working principle of IM. The fuzzy rule base is tabulated as shown in table (3.3). As we see the table, it forms a certain symmetrical pattern.

“Output” U		“error” e						
		NB	NM	NS	Z	PS	PM	PB
“Error rate” ce	NB	NB	NB	NB	NM	Z	PS	PM
	NM	NB	NB	NM	NS	PS	PM	PS
	NS	NB	NB	NM	NS	PS	PM	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NM	NS	PS	PS	PM	PB
	PM	NM	NM	NS	PS	PM	PB	PB
	PB	NM	PS	Z	PM	PB	PB	PB

Table 3. 3 Fuzzy rule base

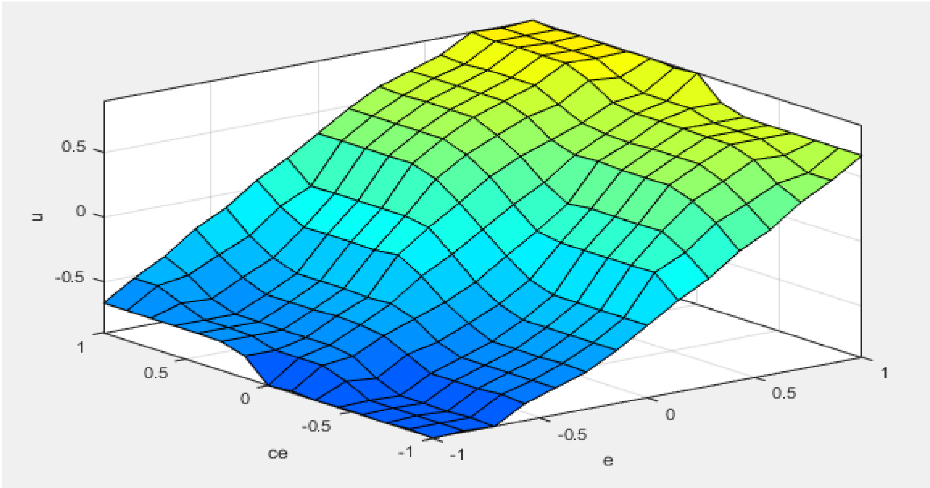


Figure 3. 12 Fuzzy logic controller control surface

The complete set of rules is shown in tabulated form in the table (3.3). In table (3.3), the linguistic values found in the top row represents the premises for the input error e, the linguistic values in the left-most column represents the input premises change in error rate ce, and the linguistic values representing the consequents u, for each of the 49 rules are found in the intersection of the rows and columns of the appropriate premises.

Example: Rule 1: IF error is NB AND error rate is NB THEN control signal u is NB

3.6.3 Fuzzy logic controller tuning

The rule base above developed from expert knowledge about the system may not give a good performance. Thus after the rule base is formed using the above insight, the controller may need to tune. Generally, there are varieties of parameters can be tuned. The controller may be tuned using input and output scaling by introducing gain in the proportional and derivative term, and at the same time putting gain between the controller and the plant as shown in figure (3.13). In addition, some rules may need to tune, and shape, position, and the number of membership functions may need to tune. In the fuzzy controller input-output scaling tuning method, input scaling less than one $h_0 < 1$and $h_1 < 1$expand the input universe of discourse by a factor $\frac{1}{h_0}$ for error and $\frac{1}{h_1}$ for error rate and output scaling greater than one $h_2 > 1$ expand output universe of discourse uniformly by h_2 [18].

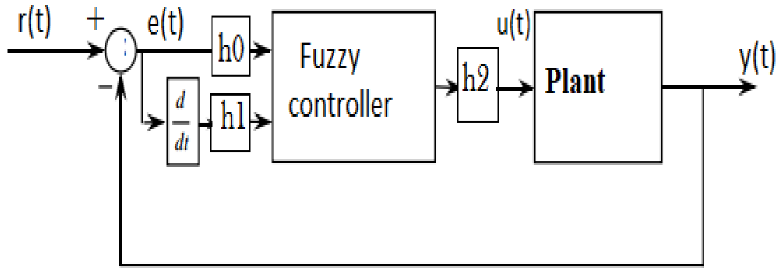


Figure 3. 13 Fuzzy control tuning by input and output scaling

For this work to have a good performance like insensitivity to parameter variation, quick torque response, and reference tracking over a wide speed range the designed values for the gain are $\mathrm{h0} = 0.002, \mathrm{h1} = 0.0002,$ and $\mathrm{h2} = 100$. This means the range of universe of discourse for error is [-500, 500], for error rate [-5000, 5000], and for the control output is [-100, 100].

CHAPTER FOUR

Result and Discussion

4.1 Introduction

This section presents the simulation results of the designed control system and discussions on the result obtained. The main objective of this thesis was to undergo a comparative analysis of the fuzzy and PID controller for IM speed control. The comparison of these controllers based on results obtained for different conditions using MATLAB/SIMULINK simulation is presented in this section. For comparison, the desired and actual speed for both fuzzy and PID controllers are plotted on the same scale for each possible case. The MATLAB/SIMULINK model for both controllers (PID and FLC) is shown in figure (4.1). The controllers are designed for 0.18KW IM with its parameters given in the table (3.1). As shown in figure (4.1) reference speed, load torque, and reference flux are inputs to the system, and desired speed, stator current, and electromagnetic torque are outputs for the system. For further information, the result using the SIM SCAPE model is given in APPENDIX B.

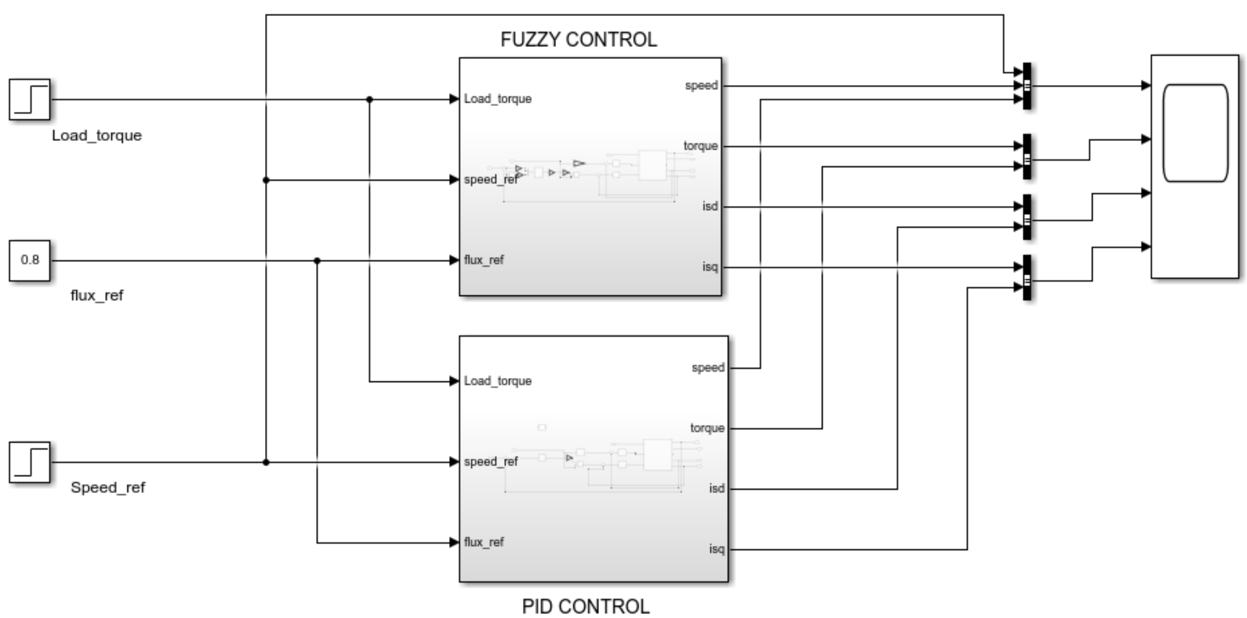


Figure 4. 1 FLC and PID control MATLAB/SIMULINK model

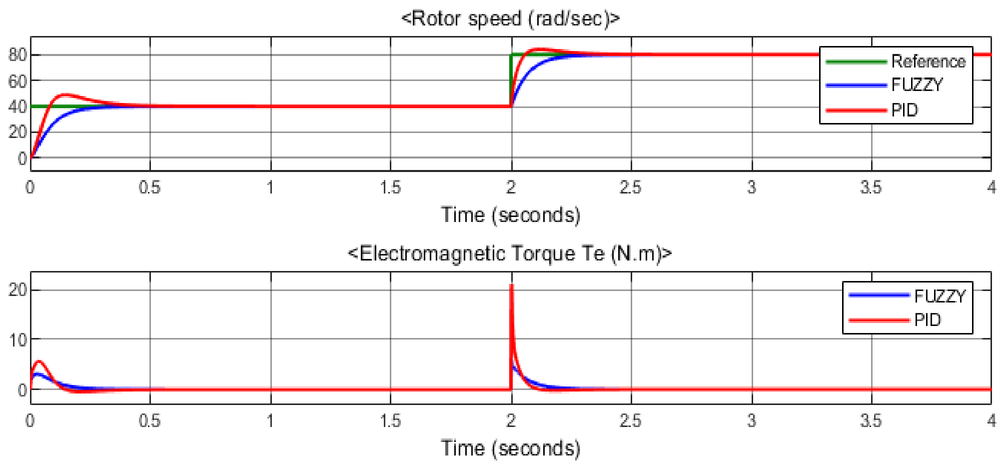
4.2 Results

Based on the problem of IM control the following criteria's are used to evaluate the performance of the designed PID and Fuzzy logic controllers.

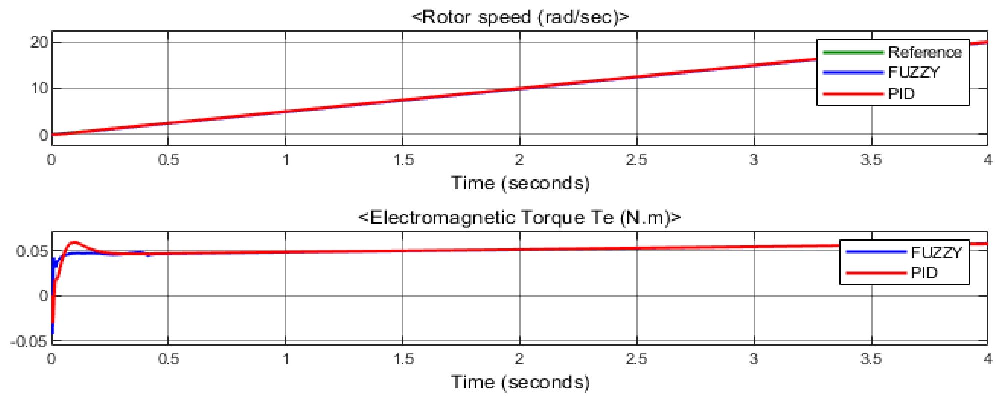
1. Setpoint tracking with no load
2. Setpoint tracking with load
3. Low-speed tracking, and
4. Parameters variation

4.2.1 Setpoint tracking with no load

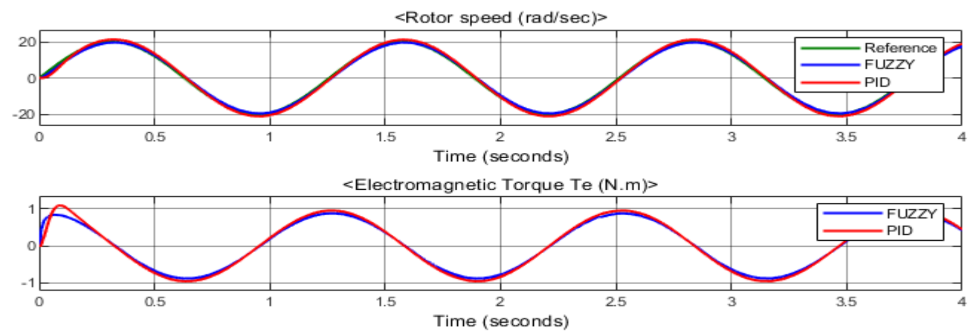
In the feedback control system, a good controller is that in which the output of the system tracks or follows the reference signal with an acceptable transient response specification (settling time, overshoot, steady-state error, etc.). In figure 4.2 (a-c), one can see that the system output tracks different reference signals (step, ramp and sinusoidal test signals). Here the response of the system for various speed setpoint has been checked. As shown in figure (4.1 a) the response for PID control has 0.3sec settling time and with 10% overshoot. Whereas for FLC the settling time is 0.2sec and with 0% overshoot. The electromagnetic torque and stator current i_{qs} also varies according to the speed request to provide the torque requirement.



a) Step setpoint tracking



b) Ramp setpoint tracking

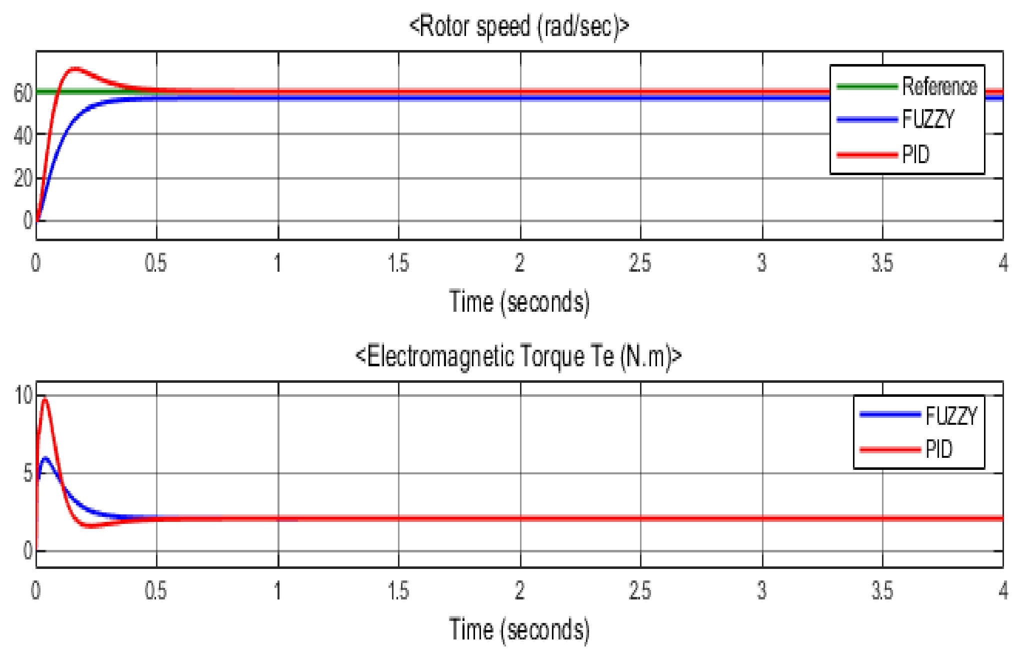


c) Sinusoidal setpoint tracking

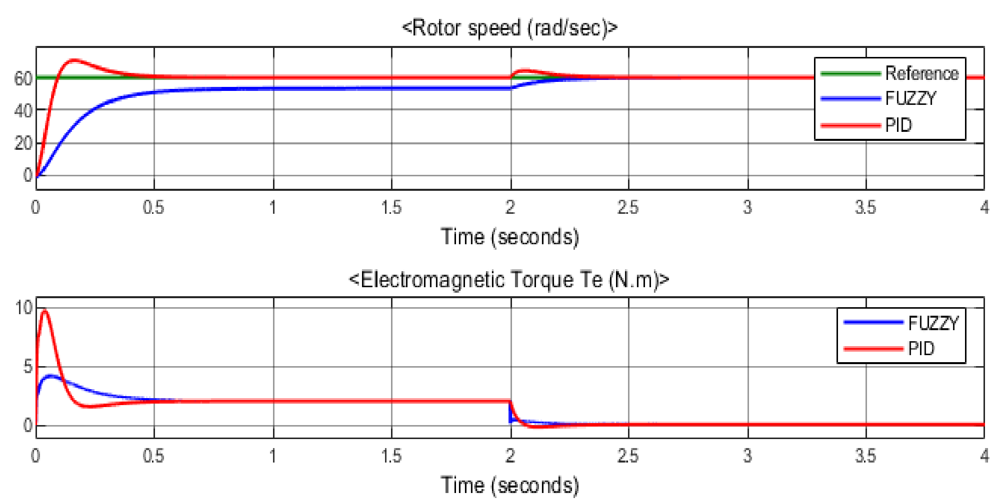
Figure 4. 2 Response of FLC and PID controller for different speed setpoint with no load

4.2.2 Setpoint tracking with load

The other problem associated with the speed control of the IM is the load variation. Loads for electric motors can be constant torque type or variable torque type. The best controller is that in which not too much affected by these properties of the load. The response for different loads is shown in figure (4.3(a&b)). In figure (4.3a) load torque TL= 2N.m is added at t=0sec, one can see that the FLC has about 3rad/sec steady-state error. Figure (4.3b) shows the case when load torque TL=2N.m is added at t=0.0sec and removed at t=2sec when the motor is in a steady-state condition. From figure (4.3b), one can see that the speed for PID control is increased above the setpoint, and for the fuzzy controller, the speed increases until the steady-state error caused by the load become zero. Moreover, for both FLC and PID controllers the electromagnetic torque decreases to maintain the torque demand for the system so that the speed tracks the reference.



a) Response with TL=2N.m is added at t=0sec

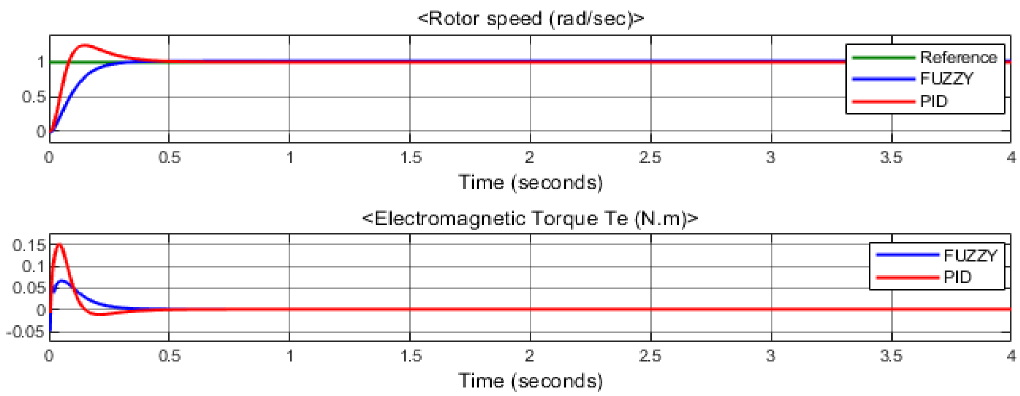


b) response with TL=2N.m is added at t=0sec and removed at t=2sec

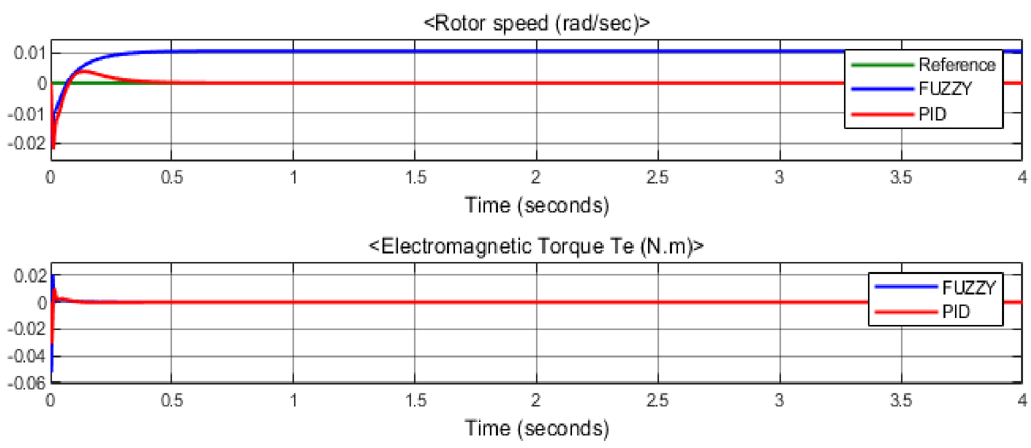
Figure 4. 3 Response in the presence of load

4.2.3 Low-speed tracking

IMs are highly efficient near to rated speed at rated supply voltage and frequency. Traditionally, as speed decreases IM efficiency also scarifies. However, FOC is expected to avoid this limitation of IM. To check this behavior so that IM to work from zero speed up to above base speed, the response for low speed has been tested using simulation. The response for low speed at 1rad/sec and 0rad/sec are shown in figure (4.5(a-b)). From figure (4.5a and b) one can see that the present overshoot increases for PID but for fuzzy; the response is the same to that of at high-speed performance.



a) Response for 1rad/sec reference speed

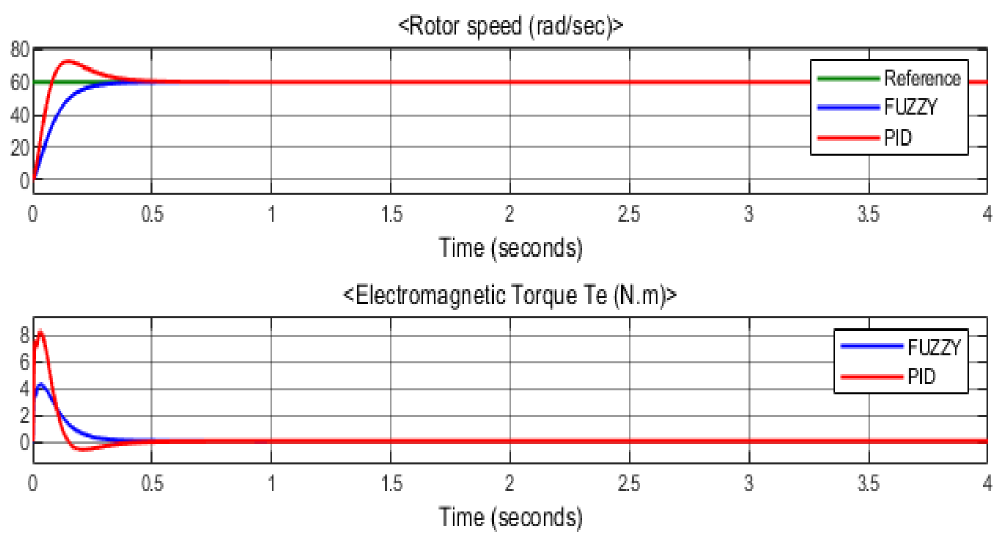


b) Response for 0rad/sec reference speed

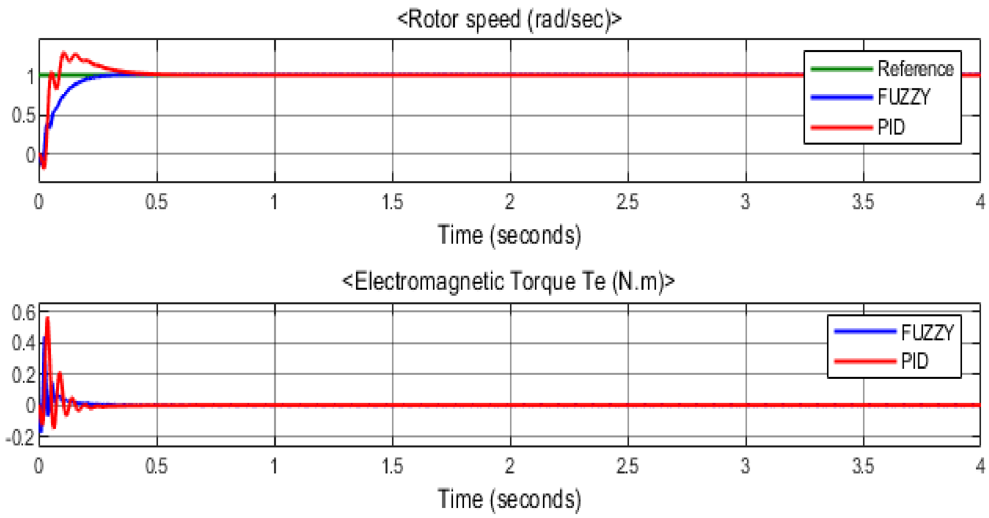
Figure 4. 4 Response of the system for low-speed reference

4.2.4 Parameter variation

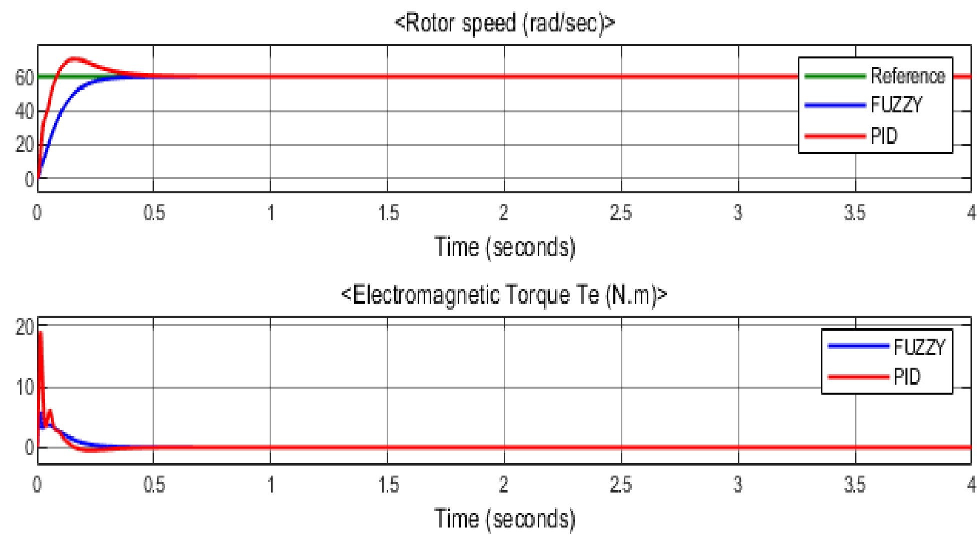
Besides the nonlinear nature of the IM, some of the parameters like rotor inductances are time-variant. In addition, the resistance of an IM winding may vary due to temperature variation or the parameter may not be exact due to measurement error. On the other hand, the designer may not know anything about the values of parameters at designing the controller. This uncertain nature of IM parameters makes it a far difficult problem to control IM. Due to the smooth control behavior of the FLC, it is considered best for parameter variation due to vagueness and lack of information. To check this nature of the controllers the parameters purposely changed to new parameters. The response of the controller for different parameters with the controller kept at the original design is shown in figure (4.6). From the result, one can observe parameter variation has an effect on PID controller performance. Generally, parameter variation alters performance on PID controller like increase overshot and settling time see figure (4.6 a-g) below. From figure (4.6 b & g) one can observe parameter variation produces oscillation for a low-speed response. However, the performance of fuzzy control is not altered by parameter variation.



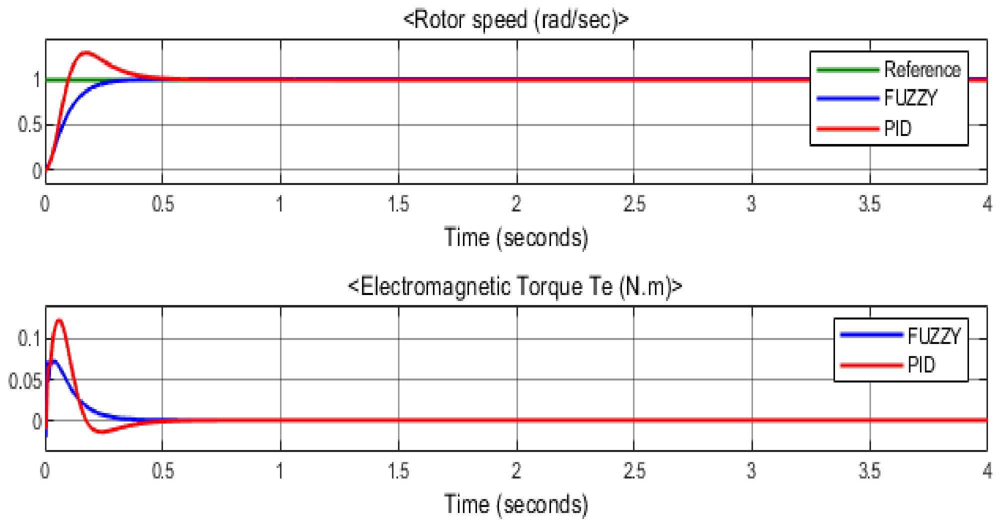
a) 50% Decrease in stator resistance, Rs



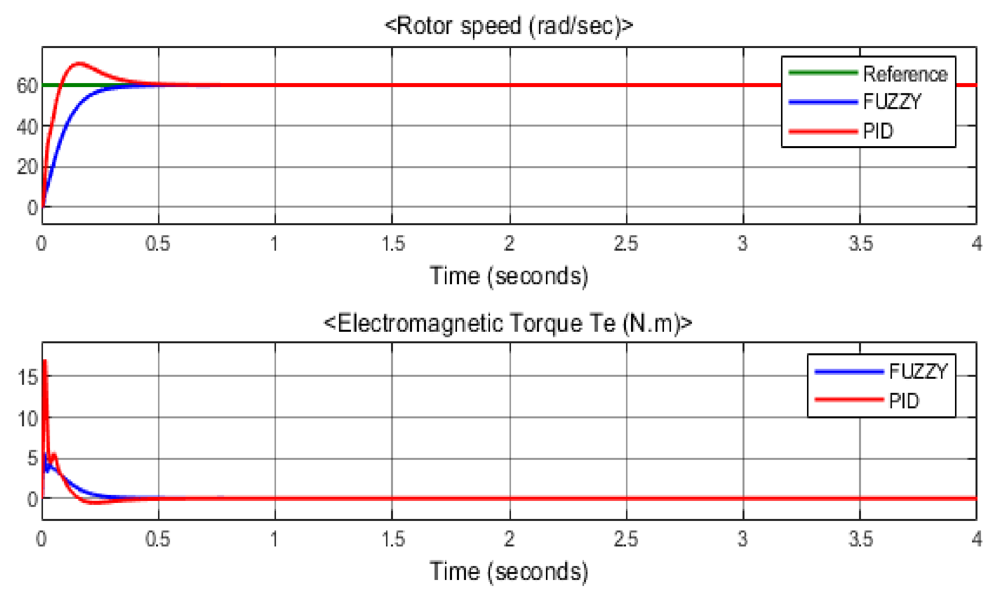
b) 50% increase in stator inductance, Ls



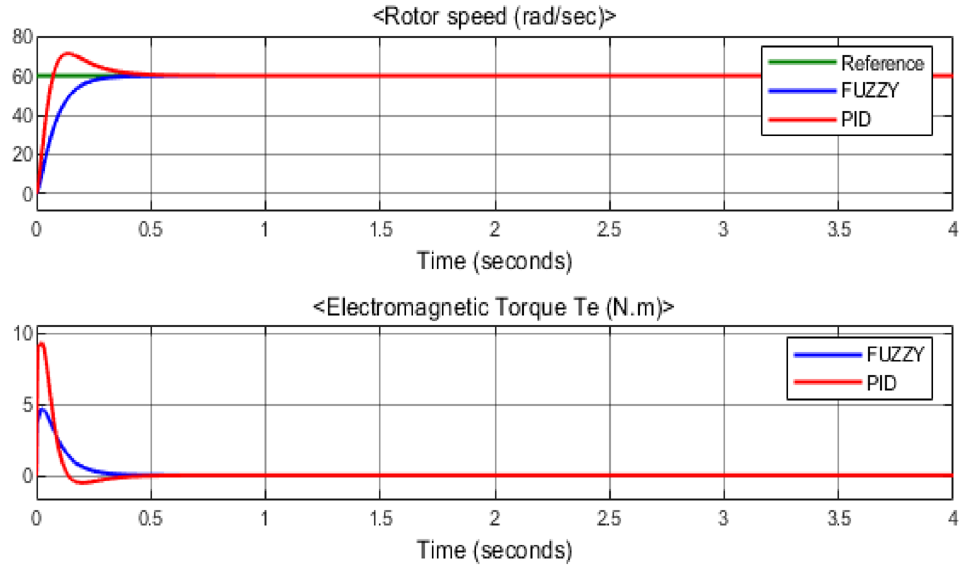
c) 50% increase in rotor inductance, Lr



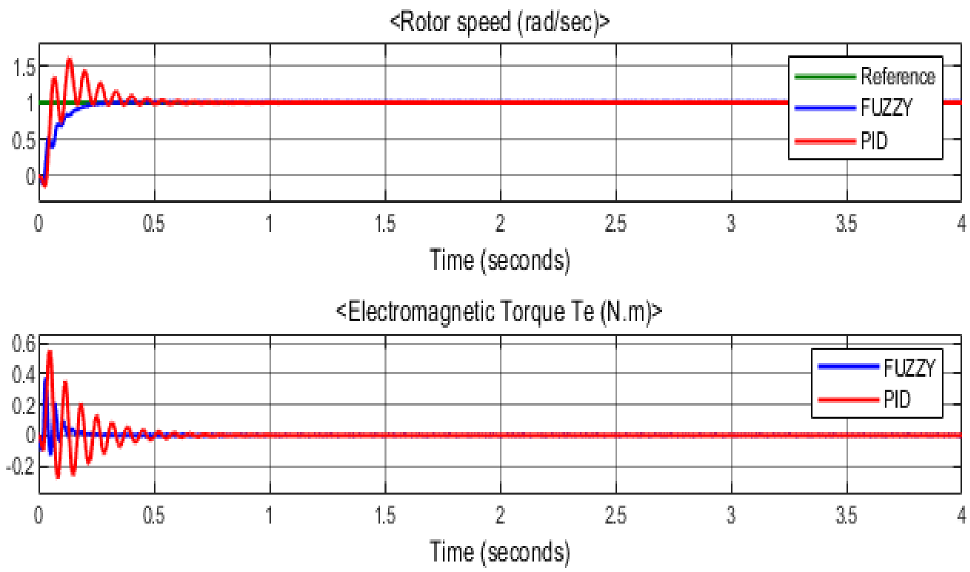
d) Decrease Rs and Rr by 50%



e) 50% increase in stator resistance, Rs



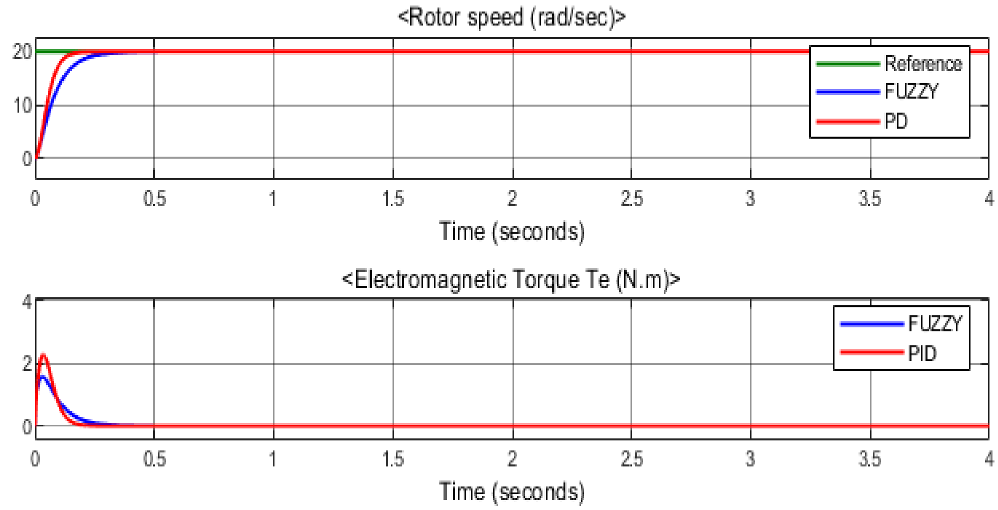
f) 50% increase in rotor resistance, Rr



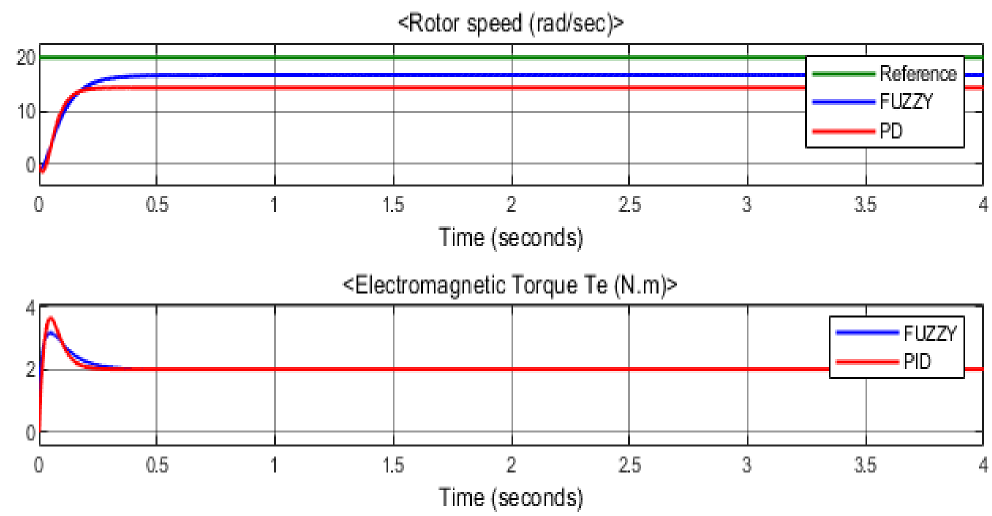
g) 50% increase in rotor and stator inductance, Ls and Lr

Figure 4. 5 Response for parameter variation

Actually one can design a more robust PD controller but in this case, the transient performance is too poor see figure (4.6 a and b).



a) Response with no load



b) Response with load torque Tl=2N.m

Figure 4. 6 Comparisons of fuzzy and PD controller

CHAPTER FIVE

Conclusion and Future Work

5.1 Conclusion

In this thesis, a comparative analysis of FLC and PID controller for IM speed control has been done. FLC and PID control are compared using transient response performance. From design perspectives, FLC is difficult than PID especially if the designer is new for the system. For FLC mathematical model is not necessary is not the case for IM. IM model was necessary for both PID and FLC control design. For FLC IM model was used to construct expert knowledge about the system and to determine the universe of discourse for FLC inputs and output. In FLC control, even the first design of PID control may need to study the system behavior. In general, from the result, one cannot say PID is inferior to FLC.

From the performance point of view, the PID and FLC have been compared using MATLAB /SIMULINK simulation based on reference tracking, load change, low-speed tracking, sensitivity to parameter variation, and speed reversal. In the PID controller, speed of response has an undershot, and overshoot but the FLC is more robust than PID. Moreover, the PID controller performance is reduced at low speed, but the FLC control performance is good in the whole speed range. In fuzzy logic control, the response has good performance with zero overshoot and good speed of response. In fuzzy logic control, the addition of load introduces small steady-state error and the range at which the system can track is decreased. PID control is affected by parameter variation, but fuzzy control is not affected by parameter variation.

FLC controllers, when well designed, can behave like a nonlinear controller or even like a set of linear PID controllers that operate differently according to the inputs. Fuzzy control is more efficient than PID as it represents many equations represented by rule bases. However, PID control represents a single equation. However, if not well designed, fuzzy controllers can lead to mistakes. The fuzzy control system is more robust and flexible, but the design of FLC needs expert knowledge so that it is even normal to design an FLC that performs less than that of PID, as it initially happened in this thesis.

The conclusion depends on the application are. For example, for aircraft landing control fuzzy is better than PID because zero overshoot is mandatory to avoid crashing. However, for mixing and ventilating application PID control is enough. In addition, if the system parameters are not known fuzzy control is the best option.

5.2 Future work

Future research suggestion is in the following direction

In this thesis comparative analysis of PID and FLC has been done. Both fuzzy and PID control has its advantages and disadvantages. Even though FLC is better than PID in control performance, it is difficult to design; it needs expert knowledge and may lead to mistakes. However, the PID control has well-defined design procedures, easy to tune, so one can design the maximum possible PID control. Therefore, to combine the advantages of many different controllers, for the future research directions is on hybrid Fuzzy-PID, ANFIS, and Fuzzy SMC. In this thesis, the comparison is analyzed based on performance, therefore another research direction is on power consumption analysis of different controllers.

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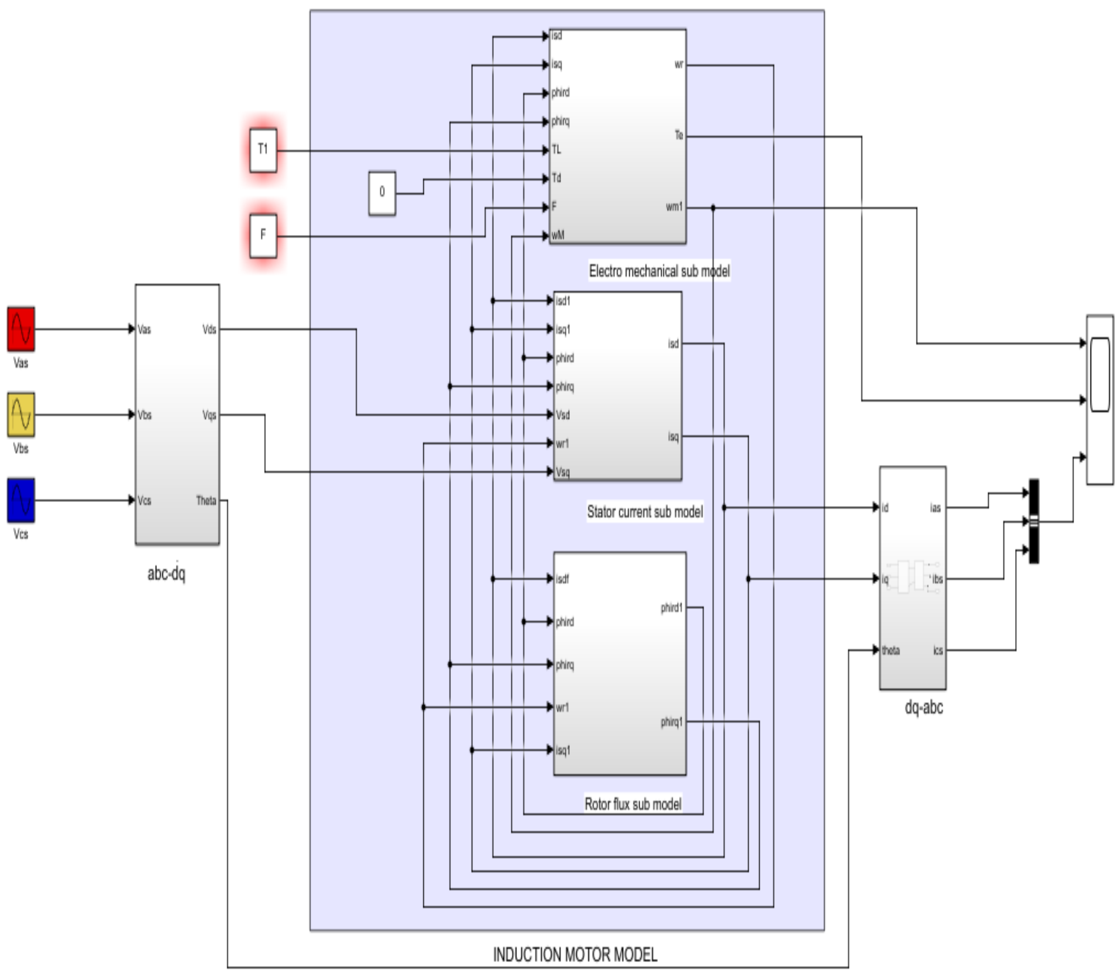
APPENDIX

Appendix: A

IM SIMULINK model

The SIMULINK model of IM is shown below

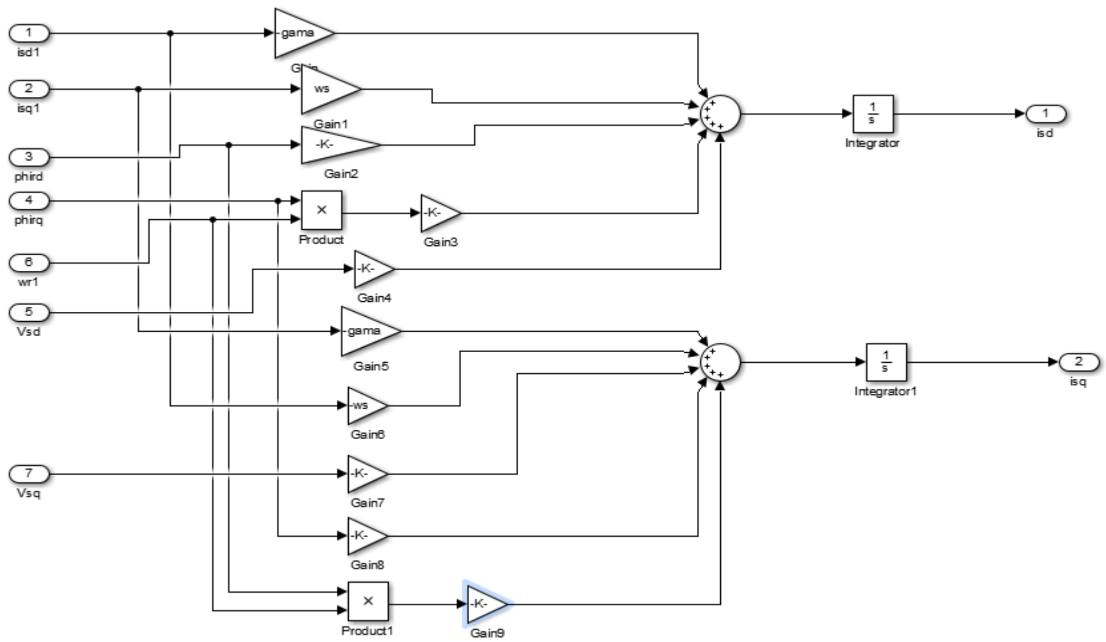


The SIMULINK model IM has three subsystems as shown above

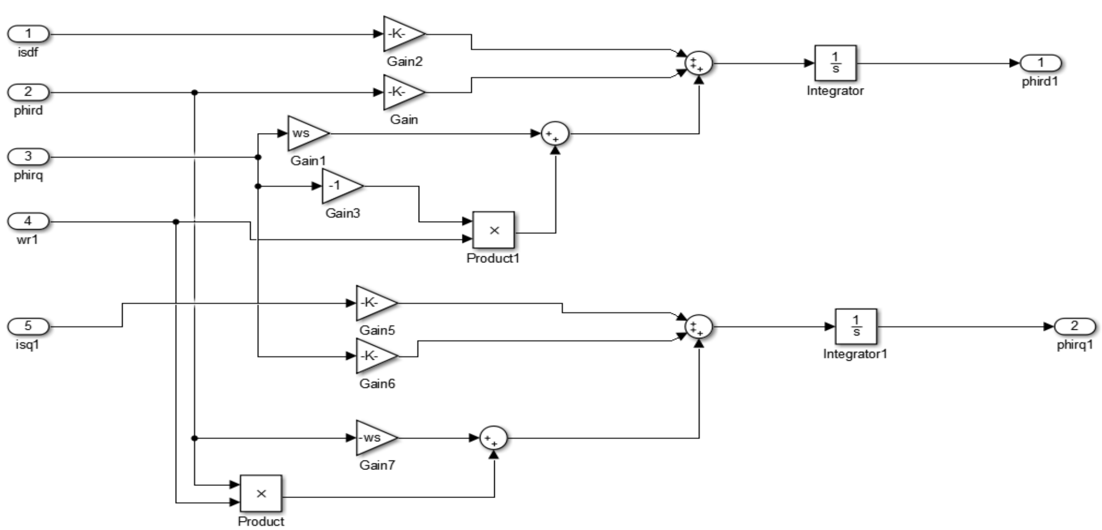
1. Electromechanical subsystem
2. Stator current subsystem
3. Rotor flux subsystem

The SIMULINK model of each subsystem is depicted below

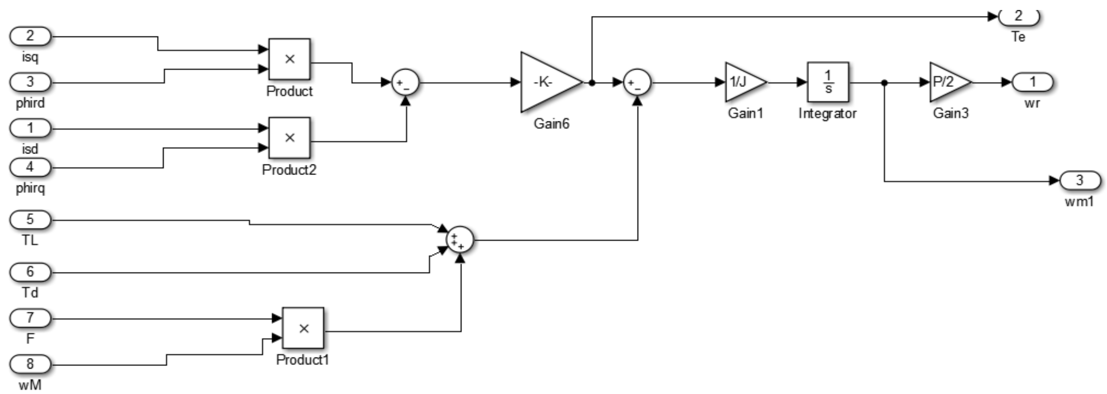
a) dq components of stator current block



b) dq components of rotor flux subsystem

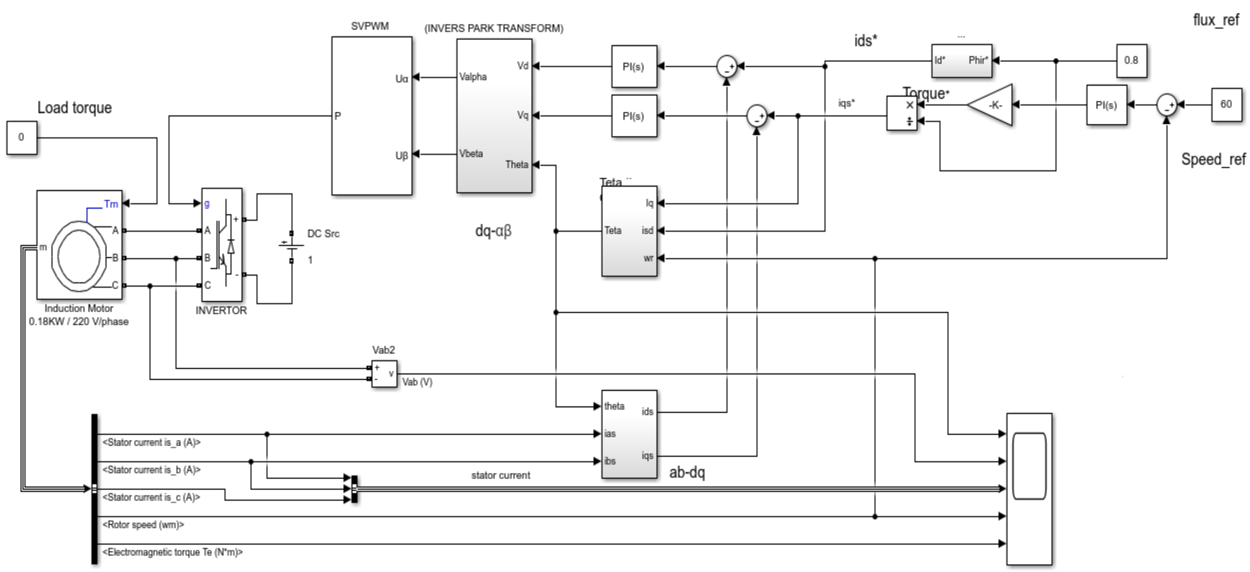


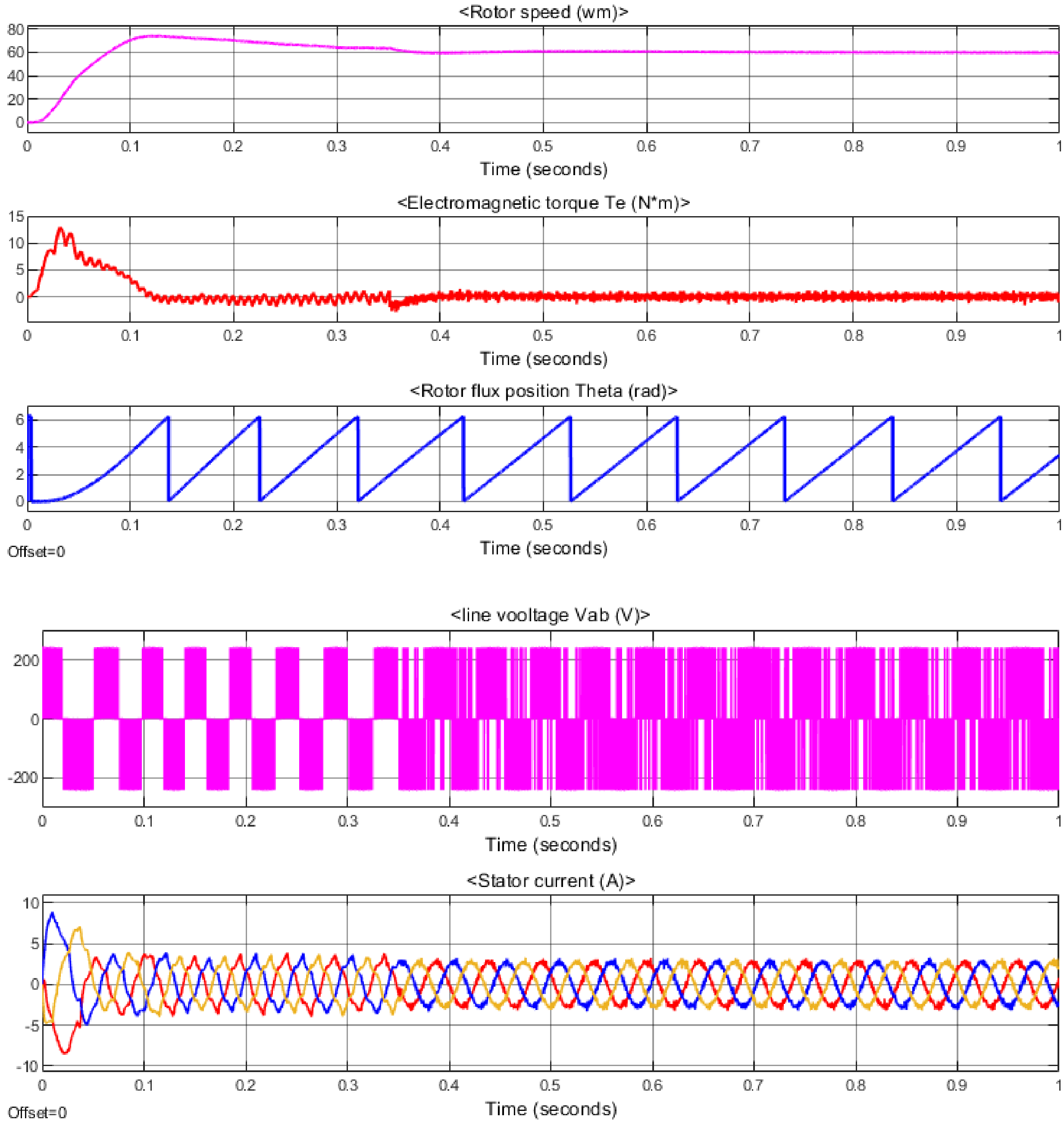
c) Electromechanical relation block



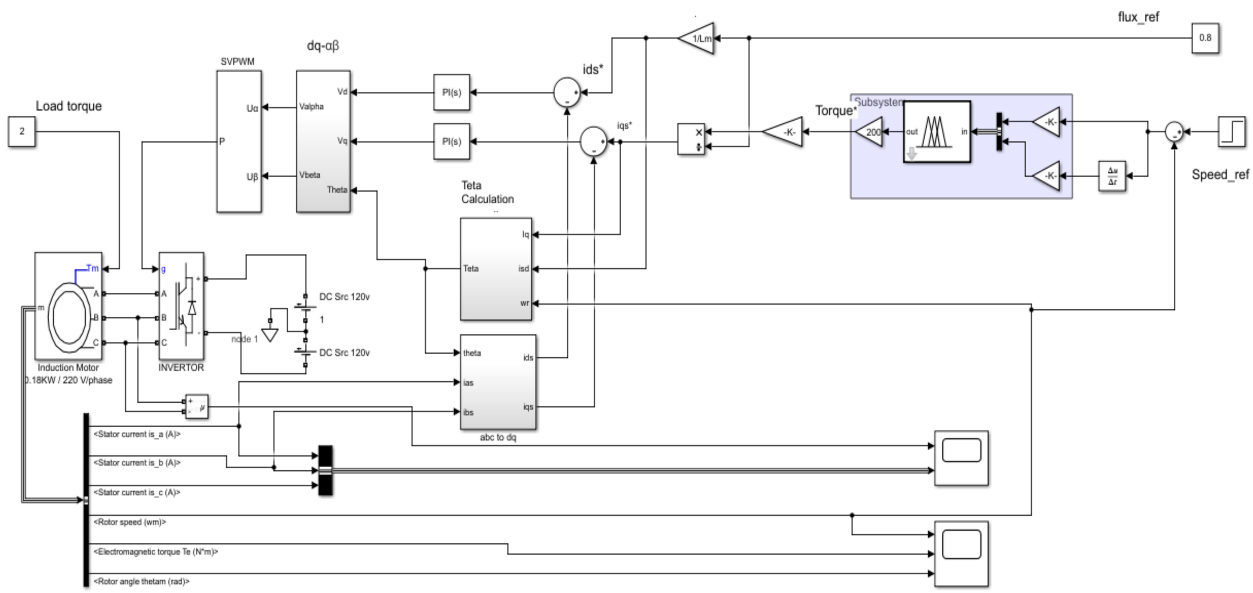
Appendix: B

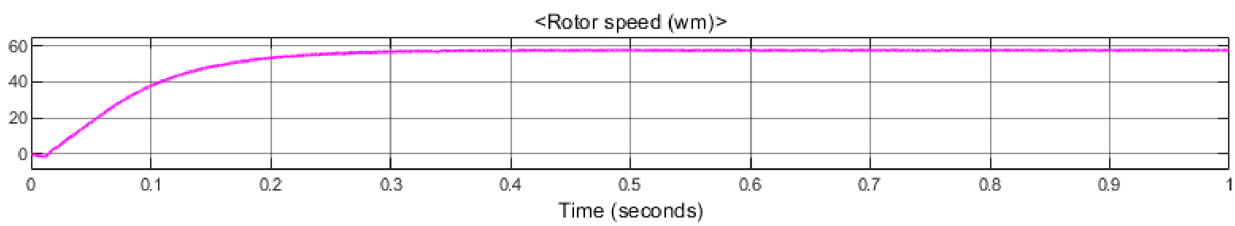
IFOC of IM MATLAB/SIMULINK Sim scape model





1) PID control SIM SCAPE model and its response for 60rad/sec reference speed


flux_ref
0.8
1/Lm
ids*
iqs*
Torque*
Subsystem
200
-K-
Speed_ref
dq-αβ
SVPWM
Load torque
2
PI(s)
PI(s)
Vd
Vq
Valpha
Vbeta
Theta
Teta Calculation
Iq
Teta
isd
wr
Induction Motor
DC Src 120v
DC Src 120v
INVERTOR
theta
ias
ibs
ids
iqs
abc to dq
<Stator current is_a (A)>
<Stator current is_b (A)>
<Stator current is_c (A)>
<Rotor speed (wm)>
<Electromagnetic torque Te (N*m)>
<Rotor angle thetam (rad)>


<Rotor speed (wm)>
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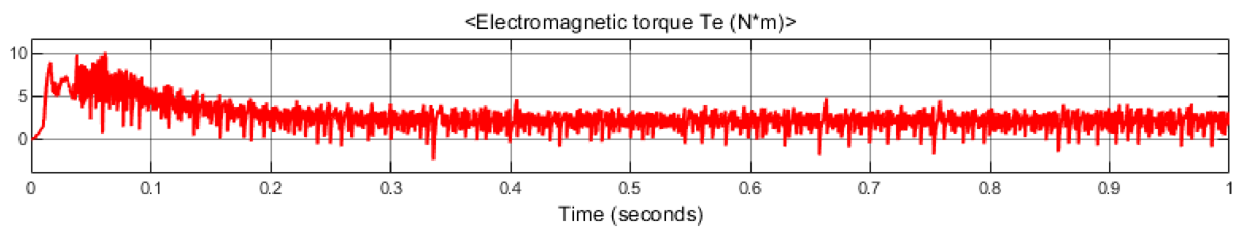
40
20
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Time (seconds)


<Electromagnetic torque Te (N*m)>
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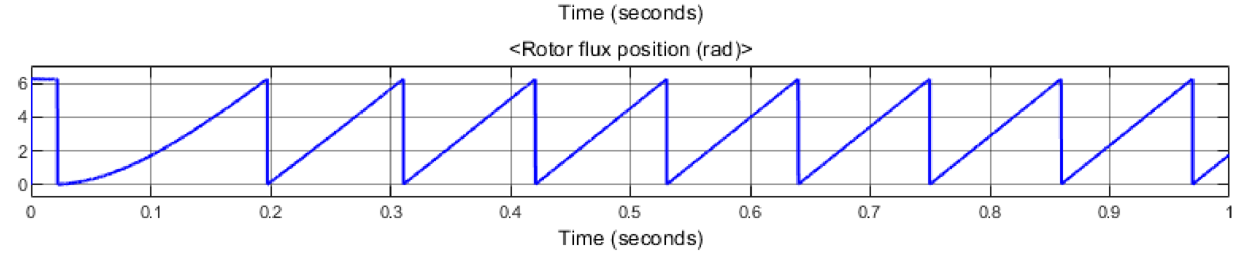
5
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Time (seconds)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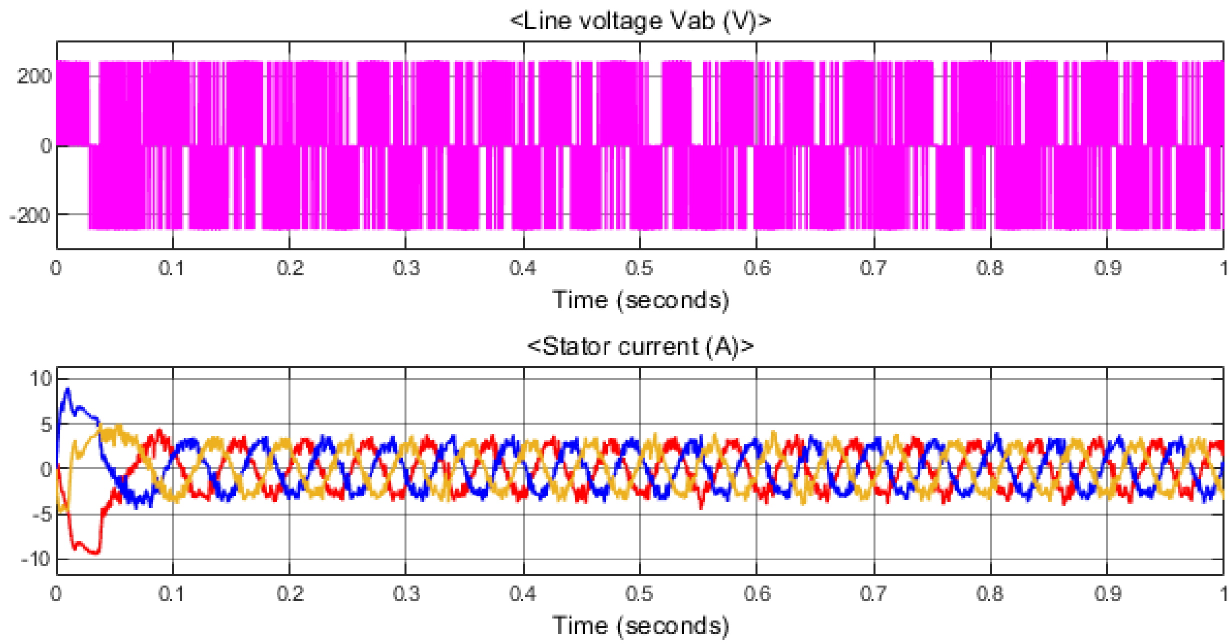
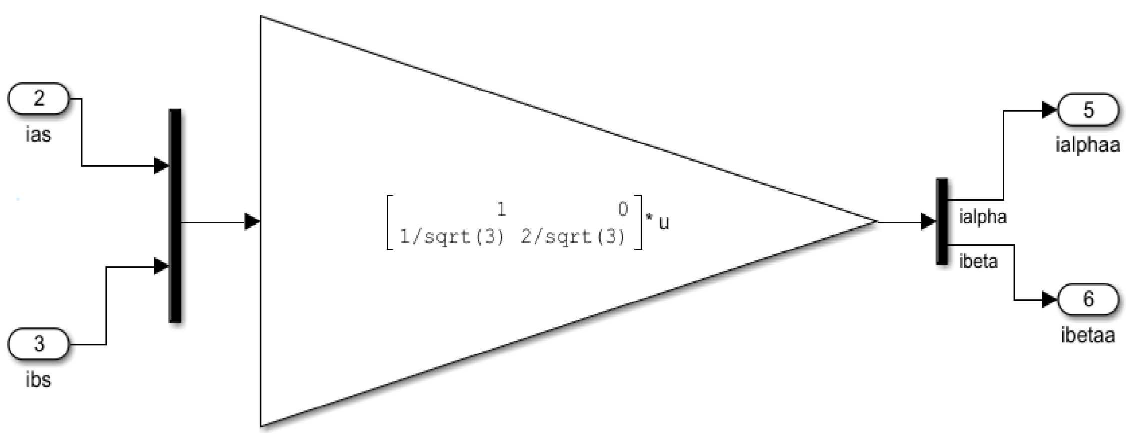
4
2
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Time (seconds)

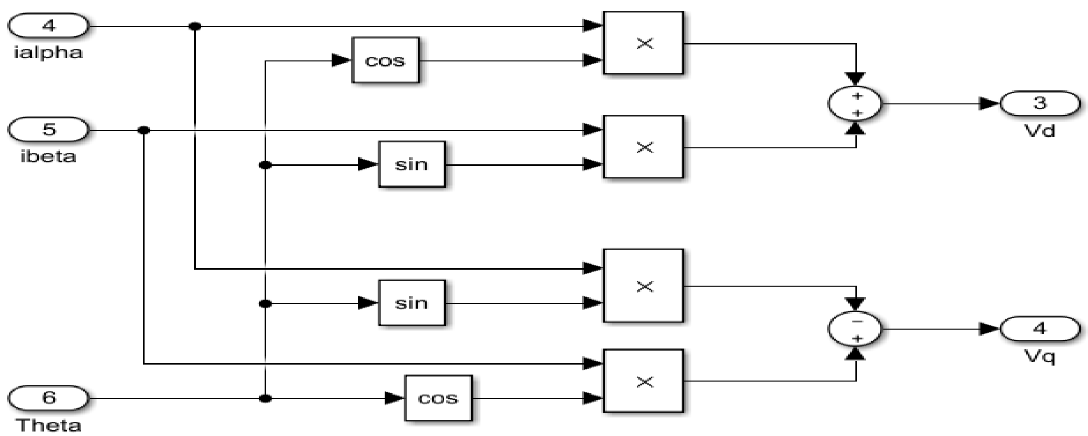


2) fuzzy control SIM SCAPE model and its response for 60rad/sec reference speed

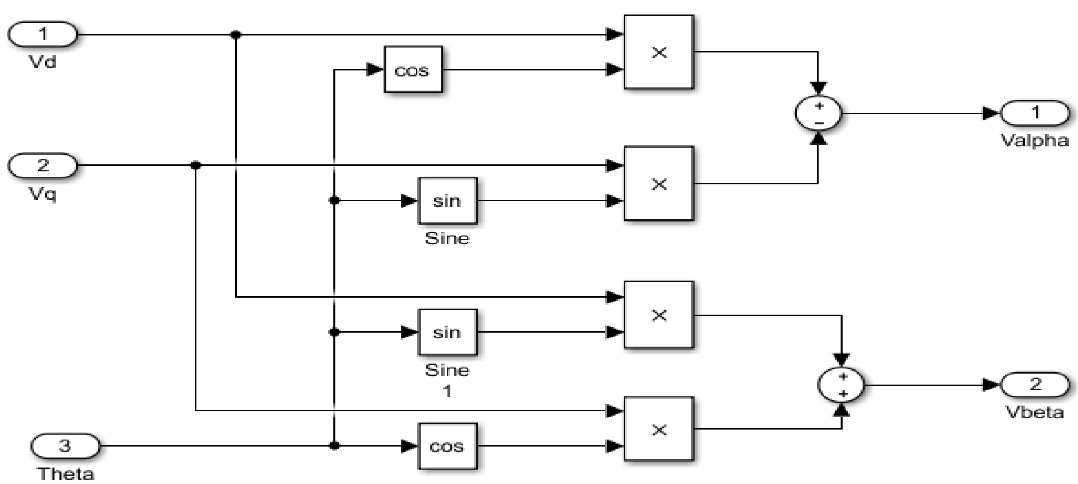
Vector transformation MATLAB/SIMULINK model



a) abc –to-αβ Clark transformation



b) αβ-to-dq Park transformation



c) dq-to- αβ invers Park transformation