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Title:

Speed Control of Induction Motor Using Three Fuzzy-Logic-Based Controllers

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Abstract:

This work portrays the methods for controlling an induction motor using three different types of fuzzy controllers: single-stage fuzzy controller; fuzzy-PID controller and adaptive-fuzzy-PID controller. The comparative performance of these three techniques has been presented and analyzed in this work. The proposed scheme uses indirect field oriented control and is simulated using MATLAB.

The IFOC accepts two inputs: the reference torque from the speed controller and the measured current feedback. Using the Clark and Park transformations, the current is transformed from the three phase to the rotating reference frame. The new reference currents are then measured before being transformed back to the three phase using inverse Park and Clark. The new reference current will be fed to the hysteresis current controller for current tracking then to the three-phase inverter. Finally, the inverter is connected to the squirrel cage induction motor.

The first speed controller consists of a simple single-stage fuzzy controller. This fuzzy controller regulates the output torque depending on the error and error ratio ranges, which are chosen according to the if-then rules. The second controller demonstrates the speed control using a fuzzy-PID control. A PID controller is connected to the fuzzy controller. The gain parameters of the PID are fixed. The third controller displays the Adaptive-fuzzy PID controller. It is also called multiple-stage controller since three fuzzy blocks are used. Each controller is used to adjust the gain values of the PID, depending on the changes in the error and error ration. The ranges of the membership functions are determined using error-and-trial method. Then the PID uses these gain values, alongside the error value to calculate the torque value.

Keywords: Induction Motor; Fuzzy; Fuzzy-PID; Adaptive-Fuzzy-PID; FOC

Dedication

Praise to God, the supreme for leading us in our study path, and for allowing us to realize this work.

I dedicate this work to all my family members: my father and mother, who dedicated their lives to raise me, no words can describe my love to you and how much I want to make you feel proud of your daughter so that you witness the fruit of your education along all these years. Also, I want to dedicate this work to my younger brother who brought joy to my life.

My sincere gratitude goes to my dear grandmother; my angel who I really love. I remember whenever I go back home tired of studies, I look at her baby face with warm smile, and I feel all that fatigue vanishes. May Allah preserve you for us.

I want to dedicate this work to my uncle and my aunt. Your presence in my life is vital, without your encouragement and support; I would not be where I am now. Your constant care, wise advices and pure love is the secret behind my success during my university cursus. Only Allah know how much I love you, and how deep is my desire to make you feel happy and proud.

Finally, I cannot forget to mention my dear friends, the ones who had always been around me and supported me, especially my lovely cousin Houda, my best friend Hana and my amazing partner Hadjer. You three are the best!

Amina Yahia

In the name of Allah, the most beneficent and merciful, I dedicate this work foremost to my dear parents for their endless love, support and encouragement throughout my life. Words would never be enough to express my endless gratitude and appreciation for all the things that they provided for me. I also want to dedicate this work to my brother, who brought joy to my life. May God bless them all.

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List of Abbreviations:

AC	Alternating Current
AFC	Adaptive Fuzzy Controller
AFPID	Adaptive Fuzzy PID
AI	Artificial Intelligence
Al	Aluminum
ANN	Artificial Neural Network
CSI	Current Source Inverter
Cu	Copper
d-axis	Direct-axis
DC	Direct Current
DFOC	Direct Field Oriented Control
E	Error
Emf	Electro-motive force
ER	Error Ratio
FL	Fuzzy Logic
FLC	Fuzzy Logic Controller
FOC	Field Oriented Control
FPID	Fuzzy PID
GA	Genetic Algorithm
IFOC	Indirect Field Oriented Control
IGBT	Insulated Gate Bipolar Transisitor
IM	Induction Motor
MF	Membership Function

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
O	Output
PID	Proportional-Integral-Derivative
PSO	Particle Swarm Optimization
PWM	Pulse Width Modulation
q-axis	Quadrature-axis
S	Switch
U	Universe of Discourse
VSI	Voltage Source Inverter
W	Weight

Symbols

μ	Membership Function
n_{sync}	Synchronous speed
n_m	Mechanical speed
n_{slip}	Slip speed
f_e	Power source frequency
P	Number of poles
I	Current
Φ	Flux
L	Inductance
U	Voltage
R	Resistance
W_e	Stator angular frequency

LIST OF ABBREVIATIONS

W_r	Rotor angular frequency
p	Differential operator
T_e	Torque
K	Torque coefficient
θ_e	Angular position
ω_{act}	Rotor speed (rotational)
ω_m	Slip frequency speed (rotational)
ω_{ref}	Reference speed (rotational)
x	Fuzzy coordinate
a,b,c,d	Fuzzy parameters
c	Membership function center
σ	Membership function width
A,B	Fuzzy sets
Kp	Proportional gain
Ki	Integral gain
Kd	Derivative gain
Ti	Integral time constant
Td	Derivative time constant
N.m	Newton.meter
Rad/sec	Radian/second

Subscripts

a	Phase A
b	Phase B

LIST OF ABBREVIATIONS

c	Phase C
d	Direct
l	Leakage
m	Mutual
r	Rotor
q	Quadrature
s	Stator

Content

General Introduction:

Induction machines are widely used in the industry as they provide a definite advantage with respect to cost and reliability when compared to other motors. They have a rugged structure that is insensitive to dusty and explosive environment and they do not require a periodic maintenance. Besides these, they are cheaper than the other types of electrical motors. Although the induction motor has many advantages, it is, however, difficult to control due to its complex mathematical model, its non-linear behavior during saturation effect and the electrical parameter oscillation, which depends on the physical influence of the temperature. [7]

Unlike induction motor, it is fairly easy to control DC motors. However, DC motors have many disadvantages such as the big size of the motor, the high maintenance cost and the short life span. Researches were developed to emulate the DC characteristics of the orthogonal relationship between the torque and the flux in induction motors; thus creating the Field Oriented Control.

The FOC is the most suitable way in achieving a high performance control for induction machines. Estimating the magnitude and phase of rotor flux is very crucial for the implementation of field oriented control method. Direct ways of sensing the rotor flux by implementing suitable hardware around the machine have proved to be inaccurate and impractical at speed and torque. Indirect methods of sensing the rotor flux employ a mathematical model of induction machine by measuring state variables, like currents and voltages. [2]

In the conventional IFOC, PI regulators are used to control the flux magnitude and rotor speed. It is well known that standard regulators with fixed parameters may be insufficient to achieve good static and dynamic performance when the induction motor drives systems is subjected to large variation of inertia during their normal operating cycles . In this case, more sophisticated controllers are required such as fuzzy controllers which are very useful when the controlled plant have some uncertainties or unknown variations. [23]

The fuzzy logic control (FLC) has been an active research topic in automation and control theory since Mamdani proposed in 1974 based on the fuzzy sets theory of Zadeh to deal with the system control problems that are not to model. The fuzzy logic can serve as a tool in developing intelligent control systems. It has ability to plan via decomposition of a complex task into manageable subtasks and adapt to new situations.[29]

While non-adaptive fuzzy control has proven its value in some applications, it is sometimes difficult to specify the rule base for some plants, or the need could arise to tune the rule-base parameters if the plant changes. This provides the motivation for adaptive fuzzy control, where the focus is on the automatic on-line synthesis and tuning of fuzzy controller parameters. [5]

The main objective of this work is to create three different speed controllers. This will be achieved by modelling the induction motor drives using MATLAB/SIMULINK, and to perform time domain simulations of the drive system in order to analyze and compare the performance of each fuzzy logic speed controller.

This work consists of five chapters. The first chapter represents general overview for the induction motors. The second chapter discusses the induction modeling, its mathematical equations in addition to the Indirect Field Oriented Control. Chapter three introduces in depth the fuzzy logic. Furthermore, it investigates the fuzzy and fuzzy-PID controller modeling, results and discussion. In addition to that, chapter four concerns the Adaptive-fuzzy-PID controller modeling, results, simulation and discussion. Finally, the conclusion and recommendations for future work according to the work done are summarized in chapter five

Chapter I: Generalities

1.1 Overview:

Induction motors (IMs) are broadly utilized for converting electric energy into mechanical energy. IMs are significant in daily life and available as single and three phase IMs. Centrifugal pumps, washing machines, dryers, mixers, fans, air conditioners, and refrigerators are examples of IM applications.

The invention of the IM happened in the last quarter of the nineteenth century by Nikola Tesla. There has been a significant improvement in the IM construction and performance. Using high conductivity materials such as copper as an alternative to standard steel in the squirrel cage rotor decreases motor power losses. In addition, the use of silicon steel sheets that shape the stator core minimizes the hysteresis losses and eddy currents [1].

Nowadays, induction machines are widely used in various industries as prime workhorses to produce rotational motions and forces. Generally, they are used for electrical transportation systems, such as cars and trains. They are also used in ventilation and heating systems and in many other electrical domestic apparatus [2].

The most popular induction motor drive control method has been the field oriented control (FOC) in the past two decades. Furthermore, the recent trend in FOC is towards the use of sensorless techniques that avoid the use of speed sensor and flux sensor [3].

FOC is one of the most effective vector controls of induction motor due to the simplicity of designing and construction.

Artificial Intelligence (AI), such Artificial Neural Networks (ANN), Genetic Algorithm (GA) and Fuzzy Logic Control (FLC) or a combinations among them are become an important techniques to extract the ultimate performance from modern motors. Fuzzy logic control is used and implemented in this thesis because of its simple structure and good results in the area of control. Fuzzy logic control is the process of employing fuzzy logic concept in system control applications. The fuzzy logic approach allows the designer to handle efficiently very complex closed-loop control problems, reducing in many cases, engineering time and cost. In addition, it supports nonlinear design techniques that are now being used in motor control application. Moreover, FLC relatively needs less computation than ANN and GA [3].

In the last decade, fuzzy logic control has found extensive applications for systems that are complex. In most of these applications, the rule base of the fuzzy controller is constructed from expert knowledge. However, it is sometimes difficult to build the rule base of some plants, or the need may arise to tune the controller parameters if the plant dynamics change [4].

This provides the motivation for adaptive fuzzy control, where the focus is on the automatic on-line synthesis and tuning of fuzzy controller parameters (i.e., the use of on-line data to continually “learn” the fuzzy controller, which will ensure that the performance objectives are met) [5].

Research in adaptive control started in the early 1950s [6], and it has been gaining a lot of interest due to its interesting characteristics that facilitate dealing with control systems. Our work will focus on this method in the next chapters.

1.2 Induction Motors Types:

The two names for the same type of motor, *Induction motor* and *Asynchronous motor*, describe the two characteristics in which this type of motor differs from DC motors and synchronous motors. Induction refers to the fact that the field in the rotor is induced by the stator currents, and asynchronous refers to the fact that the rotor speed is not equal to the stator frequency. No sliding contacts and permanent magnets are needed to make an induction motor work, which makes it very simple and cheap to manufacture. As motors, they are rugged and require very little maintenance. However, their speeds are not as easily controlled as with DC motors. They draw large starting currents, and operate with a poor lagging factor when lightly loaded. [7]

Three-phase AC induction motor are widely used in many fields. They are classified in two categories:

- Squirrel cage motor
- Wound-rotor motor [8]

Squirrel cage motor is without any doubt the most common and widely used. Its electric circuit consists of uninsulated metal bars forming the squirrel cage which resembles the rotating cages used in bygone days to exercise small rodents, this is the reason it gives that name to the rotor. These metal bars installed into the slots, commonly made of Cu or Al, are short-circuited at their two ends by conducting end-rings.

Induced winding is a poly-phase winding, with equal or different number or phases to the stator, but with the same number of poles. This type of winding is internally connected in star and has free phase terminals connected to slip rings arranged on the shaft. Hence, the rotor circuit is open. This opening allows the increase in resistance in each phase of the rotor circuit by adding additional rotor resistance for several purposes, such as raising the torque in the start-up or decreasing the initial current. [10]

1.2.1 Comparison Table

Table 1.1: Comparison between Slip Ring Motors and Squirrel Cage Motor.[9]

Basis For Comparison	Slip Ring Motor	Squirrel Cage motor
Definition	The rotor of the motor is constructed as a slip ring type.	The rotor of the motor is a squirrel cage type.
Rotor	Cylindrical laminated core with parallel slots and each slot consist one bar.	The slots of the rotor are not parallel, but are skewed.
Other name	Phase wound rotor	Cage motor
Construction	Complicated	Simple
Resistance	Added external to the rotor	The rotor bar is permanently shorted at the end of the ring, thus it is not possible to add any external resistance.
Starter	The rotor resistance starter can be used.	Rotor resistance starter cannot be used.
Starting Torque	High	Low
Brushes	Present	Absent
Maintenance	Frequent maintenance required	Less maintenance required
Copper Loss	High	Low
Efficiency	Low	High
Speed Control	Possible	Not Possible
Power Factor	Low	High
Cost	Costly	Cheap
Starting Current	Low	High
Uses	Use in hoist, cranes, elevator where high torque is required.	Use in lathe machines, fan, blower, profiting machines, etc.

1.2.2 Advantages of the Squirrel Cage induction motor

90% of the three-phase AC Induction motors are squirrel cage motors because of their lower cost and the possibility of starting heavier loads with respect to wound-rotor motors [8]. They are also very robust, efficient, and reliable. The slip ring motor has very little application in industries. Rarely 5% – 10% slip ring motors are used in industries because it has several disadvantages, as it required frequent maintenance, having a high copper loss. [9]

1.3 Induction motor construction and operation

Induction motors are the most important electrical motors since they have a lot of advantages; such as its simple design, reliable operation, the simplicity of speed control and the high efficiency. Induction motor main components are the stator and the rotor. The rotor is constructed of a number of conducting bars running parallel to the axis of the motor and two conducting rings on the ends. The assembly -Figure 1.1- resembles a squirrel cage, thus this type of motor is often called a squirrel-cage motor. The stator –which is the outer body of the motor- contains a pattern of copper or aluminum coils arranged in windings – Figure 1.1-a -.

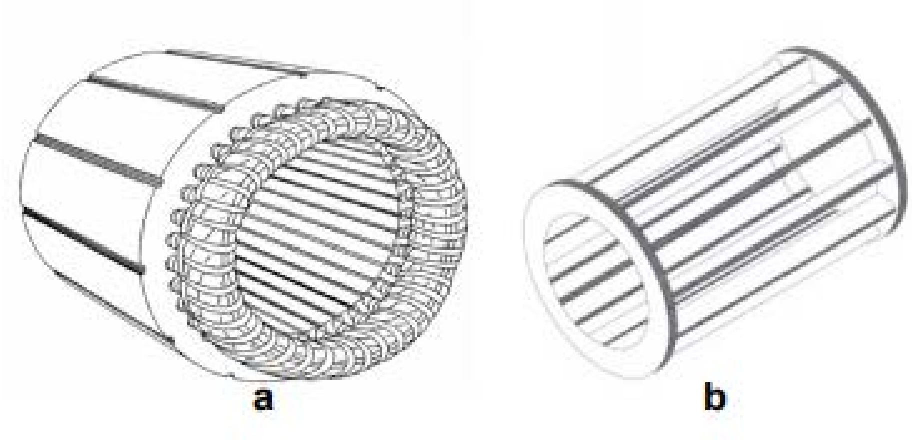


Figure 1.1 (a) A typical structure of stator core and **(b)** the rotor in squirrel-cage induction motor.

As alternating current (AC) is passed through the stator windings, a rotating magnetic field is formed near the stator; the speed of rotation is called *synchronous speed* (n_{sync}). This induces a current in the rotor, creating its own magnetic field. The interaction of these fields produces a torque on the rotor. The speed of the rotor, which is called *mechanical speed* (n_m), will be slightly less than the synchronous speed; the difference is called the *slip speed* (n_{slip}). In addition, *slip* is defined as equation 1.1. [3]

$$s = \frac{\omega_{sync} - \omega_m}{\omega_{sync}} (\times 100\%) \tag{1.1}$$

The synchronous speed is related to the number of poles of the induction motor and the frequency of power source.

$$n_{sync} = \frac{120 f_e}{P} \quad rpm \tag{1.2}$$

Where f_e is the power source frequency, P is the number of poles and n_{sync} is the synchronous speed in revolutions per minute. [11]

Figure 1.2 shows a typical induction motor. From working principle of the induction Motor, it may be observed that the rotor should not reach the synchronous speed .If the speed equals; there would be no relative velocity. So there will be no cutting of flux so no emf can be generated, means no current will be flowing. Hence, no torque will be generated. [12]

Note that there is no direct electrical connection between the stator and the rotor.

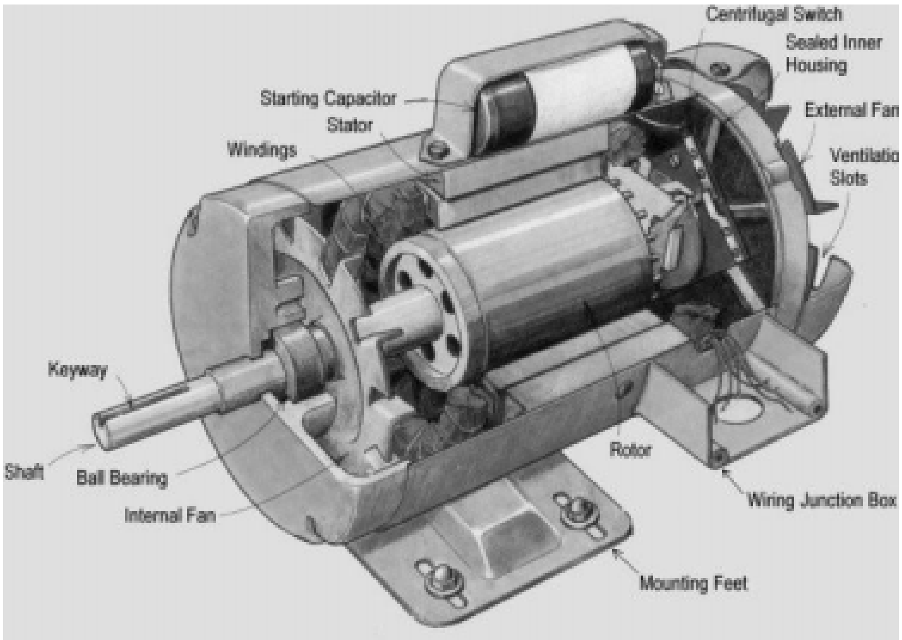


Figure 1.2 A squirrel cage induction motor

One of the main characteristics of induction motor is that the efficiency is inversely proportional to slip. A motor with a lower value of slip will be more efficient than a motor with a higher slip because of the increased losses in the rotor of the latter. The efficiency of three phase induction motors varies with type, size and load. It ranges from 85% to 99%. [3]

Chapter II: Modeling of induction motor

Induction motor is widely used in the industries due to its exclusive features such as high robustness, high reliability and efficiency as well as low cost and maintenance. This results to its increased demand in high performance applications. Using the through vector control method, the induction motor can be controlled like a DC motor. Decoupling control between the flux and torque by means of coordinate transformation eases the control action. [26]

This chapter introduces the vector control method and its specific transformations such as Clark and Park transformations, as well as establishing the mathematical model of the induction motor.

2.1. Space vector transformations: Clark/Park

Space vector notation allows the transformation of the natural instantaneous values of a three-phase system onto a complex plane located in the cross section of the motor. In this plane, the space phasor rotate with an angular speed equal to the angular frequency of the three-phase supply system. A space phasor rotating with the same angular speed, for example, can describe the rotating magnetic field. Moreover, in the special case of the steady state, where the supply voltage is sinusoidal and symmetric, and the space phasor becomes equal to three-phase voltage phasors, allowing the analysis in terms of complex algebra. It is shown in Figure 2.1 the equivalent schematic for this new model. [3]

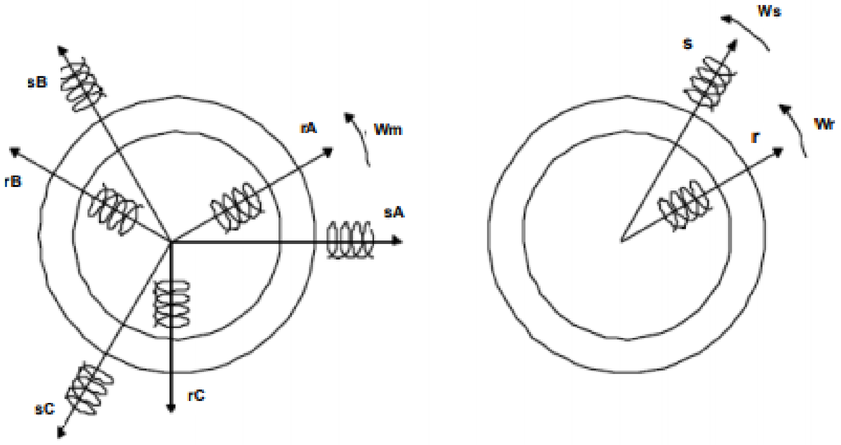


Figure 2.1 The schematic of rotating magnetic fields with rotor speed

With regard to the currents –the same could be done for any other quantity like voltages or fluxes-, the space vector can be defined as follows. Assuming the instantaneous currents in the stator phases are i_a, i_b, and i_c, then the complex phasor current is defined as in equation 2.1, and Figure 2.2 shows the space vector of the stator current and its components in three phase system axes (a, b, c). Note that $\alpha=e^{(j*2\pi/3)}$ and $\alpha^2= e^{(j*4\pi/3)}$ and the factor C usually takes two values: *2/3* or $\sqrt{(2/3)}$.

$$\underline{i_s} = C(i_a + \alpha i_b + \alpha^2 i_c) \qquad (2.1)$$

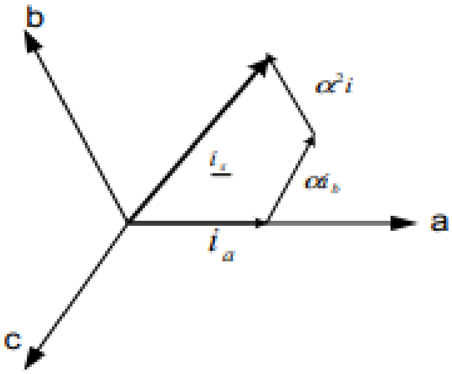


Figure 2.2 Stator current space vector and its components in (a,b,c). [3]

In order to transform $\underline{i_s}$ into a two time invariant coordinate system, two steps need to be done:

- The Clarke transformation
- The Park transformation

2.1.1. Forward and inverse Clarke transformation

In electrical engineering, the *Clarke transformation* is a mathematical tool employed to simplify the analysis of three phase circuits [16]. It converts three-phase signals such as currents, voltage, and flux from three-phase coordinate system (a, b, c) into a two-phase coordinate orthogonal system (α, β). Figure 2.3 shows the graphical construction of the current space vector and its projection into stator reference frame (α, β).

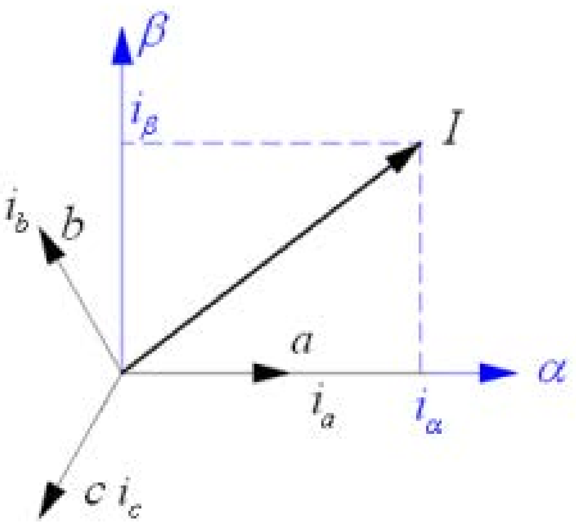


Figure 2.3 Clarke transformation of three-phase currents [15]

The projection that modifies the three phase system into the (α, β) two dimension orthogonal system is presented by equation 2.2.

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \end{pmatrix} \cdot \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \qquad (2.2) \qquad [15]$$

The (α,β) components can be easily converted from a two phase coordinate orthogonal system (α,β) into a three-phase coordinate system (a, b, c) by using the inverse Clarke transformation. The matrix equation is expressed as:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (2.3) \qquad [3]$$

2.1.2. Forward and inverse Park transformation

Park transformation modifies a two-phase orthogonal system (α, β) into the (d, q) rotating reference frame. If the d-axis is aligned with the rotor flux vector, the transformation is expressed as:

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} \quad (2.4) \qquad [15]$$

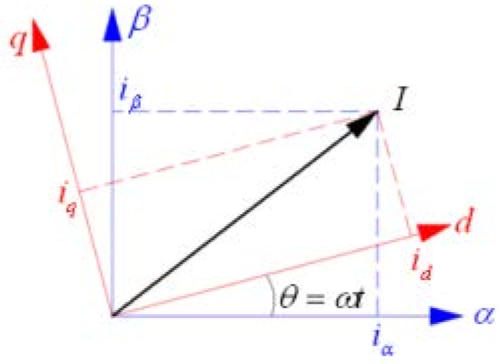


Figure 2.4 Park transformations of two-phase currents [15]

While the inverse transformation from rotating reference frame to stationary reference frame is expressed as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (2.5) \qquad [3]$$

2.2 Mathematical Modelling

Mathematical model of induction machines is represented in space vector notation, established in d-q axis coordinates reference rotating system at ω_s speed. Standard dynamic model of induction machine are available in the literature.

Assumptions:

The modeling of the AC electrical machine generally relies on several hypotheses, which allow to model the system with a reduced complexity. The hypotheses are expressed:

- The magnetomotive forces created by stator and rotor phases are distributed in a sinusoidal way in the air gap, when those windings are crossed by a constant current.
- The machine air gap is supposed to have a uniform thickness.
- Linear magnetic characteristic (no saturation).
- Parasitic effects such as hysteresis, eddy currents, skin effect and temperature are generally neglected [35].

The state-space model of the system equations related to the indirect method of vector control is described in the following sections.[2]

2.2.1 Flux Equations:

The stator and rotor fluxes are defined by the following magnetic equations:

$$\varphi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr} \quad (2.6)$$

$$\varphi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr} \quad (2.7)$$

$$\varphi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) = L_r i_{dr} + L_m i_{ds} \quad (2.8)$$

$$\varphi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) = L_r i_{qr} + L_m i_{qs} \quad (2.9)$$

L_{ls}, L_{lr} and L_m are the stator leakage inductance, rotor leakage inductance, and mutual inductance, respectively. [2]

2.2.2 Voltage Equations

The voltage equations of the induction motor in d-q coordinate are given as follows:

$$\begin{cases} u_{ds} = R_s i_{ds} + p\lambda_{ds} - \omega_e \lambda_{qs} & (2.10) \\ u_{qs} = R_s i_{qs} + p\lambda_{qs} - \omega_e \lambda_{ds} & (2.11) \\ 0 = R_r i_{dr} + p\lambda_{dr} - (\omega_e - \omega_r)\lambda_{qr} & (2.12) \\ 0 = R_r i_{qr} + p\lambda_{qr} - (\omega_e - \omega_r)\lambda_{dr} & (2.13) \end{cases}$$

Where: [27]

- **U_{ds} , U_{qs}** : d-axis and q-axis components of stator voltages
- **i_{ds}**, **i_{qs}** : d-axis and q-axis components of stator currents
- **i_{dr}**, **i_{qr}**: d-axis and q-axis components of rotor currents.
- **R_s , R_r** : stator and rotor resistances
- **λ_{ds}; λ_{qs}** :d- axis and q- axis components of stator flux
- **λ_{dr}; λ_{qr}**: d- axis and q- axis components of rotor flux
- **W_e** : stator angular frequency
- **W_r**: rotor angular frequency
- **p**: differential operator.

2.2.3 Torque Equations

The electromagnetic torque is produced by the interaction of current and magnetic field. Using two current quantities (stator current and rotor current) and three fluxes (stator flux, mutual flux and rotor flux), the torque can be expressed in six different forms [14]:

$$T_e = K_1 \Psi_s \times I_r \qquad (2.14)$$

$$T_e = K_2 \Psi_m \times I_r \qquad (2.\ 15)$$

$$T_e = K_3 \Psi_r \times I_r \qquad (2.16)$$

$$T_e = K_4 \Psi_s \times I_s \qquad (2.17)$$

$$T_e = K_5 \Psi_m \times I_s \qquad (2.18)$$

$$T_e = K_6 \Psi_r \times I_s \qquad (2.19)$$

(2.20)

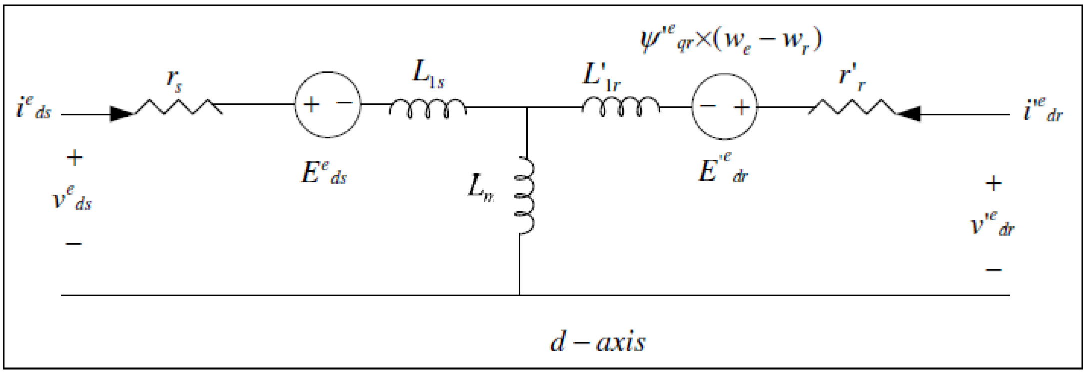
Where K_1 to K_6 are the torque coefficients. Also, the system motion equation is given by [14]:

$$T_e = T_L + \frac{J}{n_p} \cdot \frac{d\omega}{dt} \tag{2.21}$$

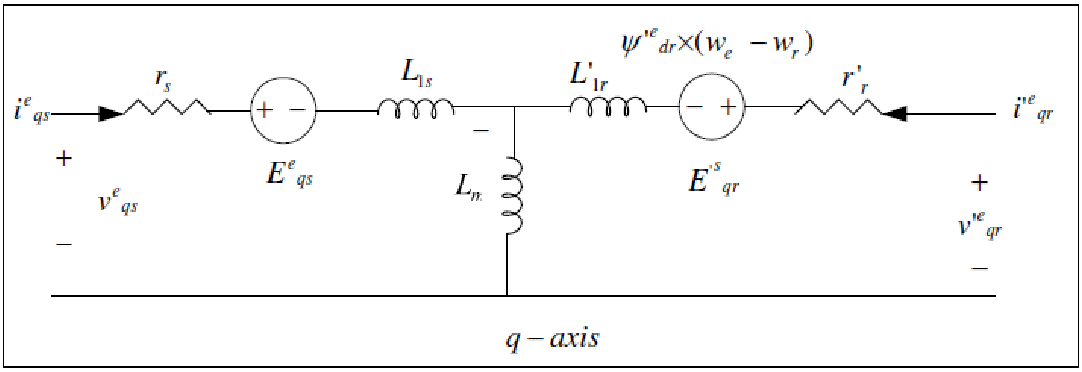
Where T_L is the load torque, ω is the rotor rotating speed, and n_p is the poles numbers, and J is rotor's moment of inertia.

2.3 Induction motor Equivalent Circuit

The equivalent induction machine circuits in the synchronous reference frame are given in the following figures [7]:



(a)



(b)

Figure 2.5 Model of an induction machine in the synchronous frame **(a)** in the d-axis; **(b)** in the q-axis [7]

2.4 Field Oriented Control

2.4.1 Overview

Blaschke in 1972 has introduced the principle of field orientation to realize DC motor characteristics in an induction motor drive. For the same reason, he has used decoupled control of torque and flux in the motor and gives its name transvector control. In DC machines, the field flux is perpendicular to the armature flux. Being orthogonal, these two fluxes produce no net interaction on one another. Adjusting the field current can therefore control the DC machine flux, and the torque can be controlled independently of flux by adjusting the armature current. An AC machine is not so simple because of the interactions between the stator and the rotor fields, whose orientations are not held at 90 degrees but vary with the operating conditions.

We can obtain DC machine-like performance in holding a fixed and orthogonal orientation between the field and armature fields in an AC machine by orienting the stator current with respect to the rotor flux to attain independently controlled flux and torque. Such a control scheme is called flux-oriented control or vector control. Vector control is applicable to both induction and synchronous motors. [15]

Field orientation is a method of control in which the stator currents of a three-phase AC electric motor are identified as two orthogonal components that can be visualized with a vector. One component defines the magnetic flux of the motor, the other the torque. The control system of the drive calculates the corresponding current component references from the flux and torque references given by the drive's speed control [13].

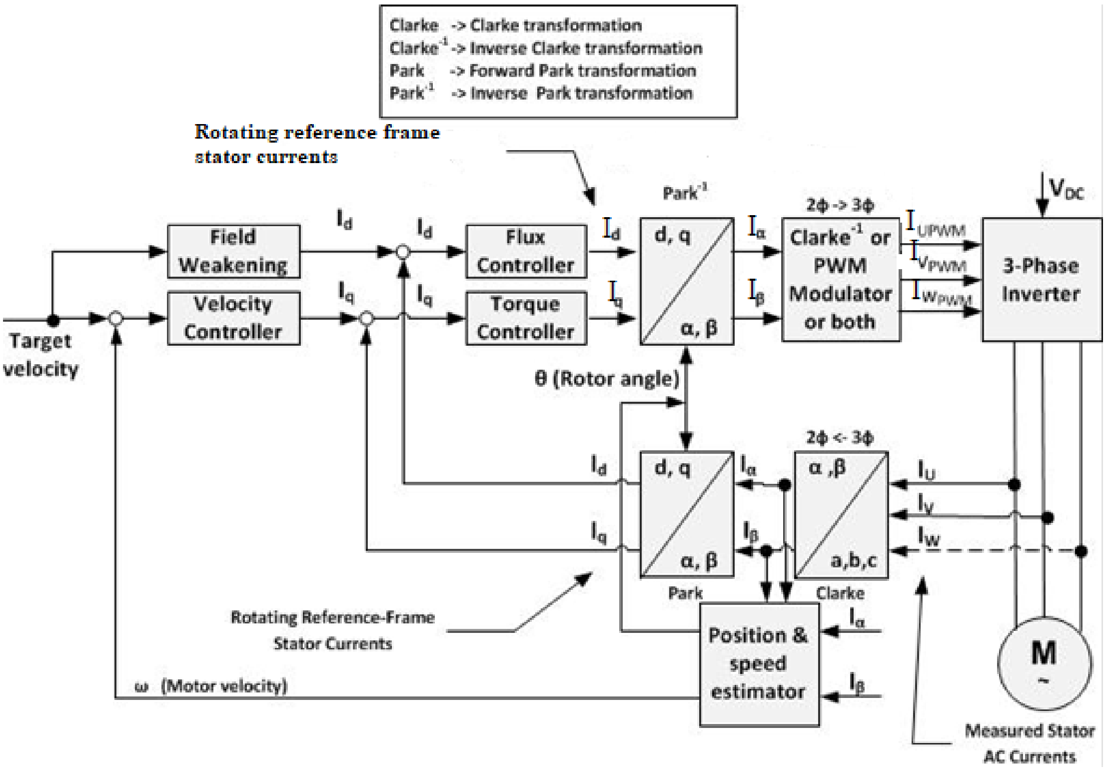


Figure 2.6 Sensorless FOC Block Diagram [13]

2.4.2 Direct and Indirect Field Orientation Control

Knowledge of the instantaneous rotor flux position (angle), with which the revolving reference frame is aligned, constitutes the necessary requirement for proper transformation from stationary reference frame to rotating reference frame, or vice versa, in field orientation. In fact, if there is an error in this variable, the d-axis is not aligned with the rotor flux vector. Thus, I_d and I_q are incorrect flux and torque components of the stator currents. There are two general methods to measure the rotor flux vector angle. One, called the direct or feedback method was invented by Blaschke, and the other, known as the indirect or feed-forward method was invented by Hasse. The two methods differ in the way the rotor angle is determined: [31] and [32]

DFOC (Direct Field Oriented Control): rotor flux vector is either measured by means of a flux sensor mounted in the air-gap or measured using the voltage equations starting from the electrical machine parameters [8]. The direct FOC obtains the orientation of the mutual flux by installing a hall-effect sensor inside the induction motor. However, using these type sensors is expensive and inconvenient, because special modifications need to be made in order to place the flux sensors. Furthermore, it is impossible to sense the rotor flux, so we have to sense the mutual flux directly and then calculate the rotor flux information. [14]

IFOC (Indirect Field Oriented Control): rotor flux vector is estimated using the field oriented control equations (current model) requiring a rotor speed measurement [8]. It is based on estimating the rotor flux orientation. By using the signals from the motor terminals such as three phase currents and rotor rotating speed, the rotor flux orientation can be estimated using motor state equations. Indirect FOC does not have the problems that direct FOC does, which makes it popular in most applications. [14]

IFOC can be implemented as follows:

1. Stator phase currents are measured, converted to complex space vector in (a,b,c) coordinate system.
2. Current is converted to (α,β) coordinate system. Transformed to a coordinate system rotating in rotor reference frame, rotor position is derived by integrating the speed:

$$\theta_e = \int_0^t \omega_{sl}\, dt + \omega_{act}\, dt \qquad (2.22)$$

3. Rotor flux linkage vector is estimated by multiplying the stator current vector with magnetizing inductance L_m and low-pass filtering the result with the rotor no-load time constant L_r/R_r, namely, the rotor inductance to rotor resistance ratio.
4. Current vector is converted to (d,q) coordinate system.
5. The motor speed, ω_{act}, is compared with the reference speed ω_{ref} and the error produced is fed to the speed controller. The output of the speed controller is electromagnetic torque T_e^*.
6. d-axis component of the stator current vector is used to control the rotor flux linkage, it is obtained by:

$$I_d^{*}\text{[1]} = \frac{\Psi_r^{*}}{l_m} \qquad (2.23)$$

---

[1] (*) stands for reference

7. The imaginary q-axis component is used to control the motor torque, it is obtained by:

$$I_q^{e*} = \left(\frac{2}{3}\right)\left(\frac{2}{p}\right)\left(\frac{L_r}{L_m}\right)\left(\frac{T_e^*}{\Phi_r}\right) \qquad (2.24)$$

8. Voltage components are transformed from (d,q) coordinate system to (α,β) coordinate system.
9. Voltage components are transformed from (α,β) coordinate system to (a,b,c) coordinate system or fed in Pulse Width Modulation (PWM) modulator, or both, for signaling to the power inverter section. [13], [33] and [34].

2.5 Three phase inverter

The induction motor can be connected directly to a standard fixed frequency, fixed voltage three phase power source. Under these conditions, the motor speed and slip will only be determined by the load torque. With no load, the slip is small so the rotor speed is close to synchronous speed. Using a variable frequency inverter in the induction motor driving system, both the magnitude and frequency of the voltage inputs can be adjusted based on certain control method. [14]

Three-phase inverter supplying voltage and current of adjustable frequency and magnitude to the stator is an important element of adjustable speed drive system employing induction motor. Inverters are dc-ac power converters and based on semiconductors power switches. Depending on the type of the dc power supplying, the inverter can be classified as voltage source inverter (VSI) or current source inverter (CSI).

In practice, the dc is usually a rectifier typically of three-phase bridge configuration with the dc link connected between the rectifier and the inverter. The dc link is a simple capacitive, inductive, or inductive-capacitive low pass filter. Since neither the voltage through the capacitor nor the current through the inductor can change instantaneously, a capacitor output dc link is used for a VSI and an inductive output link is employed in CSI. However, the dc link is still used as an interface either to impose the current source input to a CSI, or to protect the battery from the high frequency component of the supply current of VSI. VSIs can be either voltage or current controlled. In a voltage-controlled inverter, it is the frequency and magnitude of the fundamental of the output voltage that adjusted. [3]

The standard three-phase inverter has as its genesis, the hex-bridge. There are two kinds of switches that are considered for this range of power applications, Insulated Gate Bipolar Transistors (IGBTs) or MOSFETs. The hex-bridge takes a DC voltage and uses six switches (MOSFETS) arranged in three phase legs as shown in Figure 2.7. The power circuit consists of six self-commuted semiconductor switches S1 to S6. The switch pairs (S1, S4), (S3, S6), and (S5, S2) form three legs of the inverter. The switches in the same leg conduct alternately. Sometime must elapse before the turn-off of one switch and turn on of another to ensure that both do not conduct simultaneously. Their simultaneous operation will cause a short circuit of the dc source resulting in a very fast rise in current. This fault, known as short-through fault can only be cleared by fast-acting fuse links. [28]

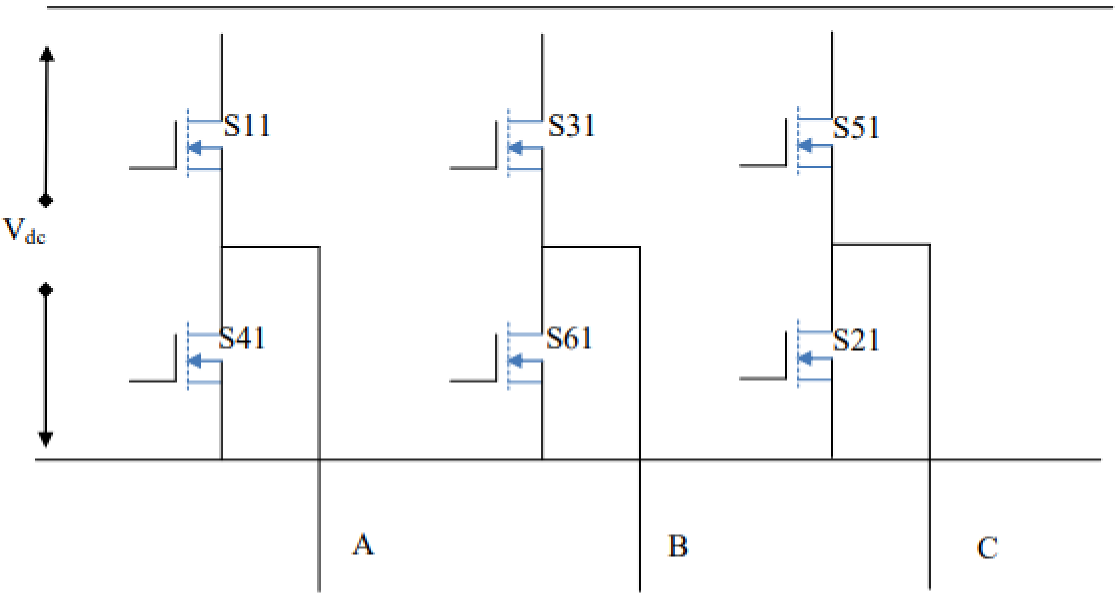


Figure 2.7 Hex Bridge of inverter

2.6 Hysteresis-band current controller

Hysteresis current control is a method of controlling a voltage source inverter so that an attempt current is generated which follows a reference current waveform. This method controls the switching in an inverter asynchronously to ramp the current through an inductor up and down so that it follows a reference. [25]

The hysteresis or bang-bang current control is among the simplest PWM technique. The advantages of this technique are the simple implementation and fast transient response. The hysteresis current control is fundamentally a feedback of current control based on PWM technique. The actual current persistently tracks the reference current within a specified band around the desired level of current. [26]

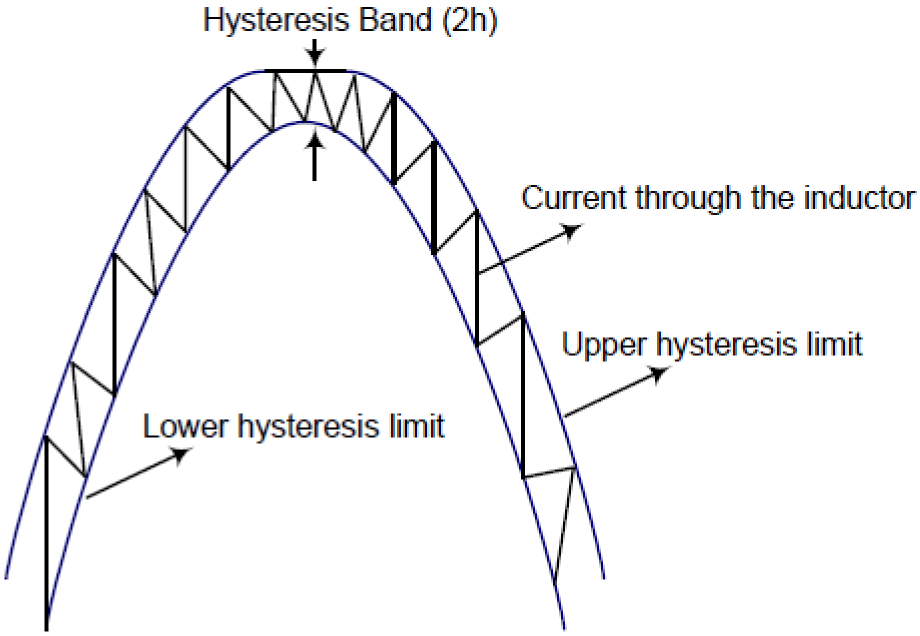


Figure 2.8 Hysteresis current waveform for one phase [25]

Chapter III: Fuzzy / Fuzzy-PID Controller

3.1 Fuzzy logic basics

3.1.1 Definition

The Fuzzy theory was first put forward by L.A. Zadeh in 1965. He felt that the classical theory concentrates much on precision rather than easy and efficient controlling mechanism [16], this is why we define fuzzy logic as a superset of Boolean logic which has been extended to handle the concept of partial truth- truth values between "*completely true*" and "*completely false*". It is the logic basic modes of reasoning which are approximate rather than exact. Fuzzy logic replicates human thinking into control logic; this is achieved through the concept of degree of membership. The essential characteristics of fuzzy logic as founded by Zadeh are as follows: [12]

- Any logical system can be fuzzified.
- In fuzzy logic, knowledge is interpreted as a collection of elastic or, equivalently, fuzzy constraint on a collection of variables
- No need of any exact mathematical model.

Precisely, the key mechanisms of fuzzy system's knowledge base are a set of IF-THEN rules attained from human knowledge [17]. This latter is going to be further explained in the next section.

3.1.2 Membership functions:

A membership function is a curve that defines how each a point in the input space is mapped to a membership value (or degree of membership) [3]. In order to define fuzzy membership function, designers choose many different shapes based on their preference. Different classes of parameterized membership functions commonly used are [12]:

- **Triangular MF**: A triangular MF is specified by three parameters {a, b, c} as follows:

$$\text{Triangle}(x;\, a,b,c)=\begin{Bmatrix} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0, & c \le x \end{Bmatrix} \tag{3.1}$$

The parameters {a, b, c} (with a < b < c) determine the x coordinates of the three corners of the underlying triangular MF.

- **Trapezoidal MF:** A trapezoidal MF is specified by four parameters {a, b, c, d} as follows:

$$\text{Trapezoid}(x;a,b,c,d)=\begin{Bmatrix} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \frac{d-x}{d-c}, & c \le x \le d \\ 0, & d \le x \end{Bmatrix} \tag{3.2}$$

- **Gaussian MFs** A Gaussian MF is specified by tow parameters :

$$\text{Gaussian}(x;c,\sigma)=e^{-\frac{1}{2}\left(\frac{x-c}{\sigma}\right)^2} \tag{3.3}$$

A Gaussian MF is determined complete by c and σ; c represents the MFs center and σ determines the MFs width.

- **Generalized bell MFs** A generalized bell MF (or Bell-shaped Function) is specified by three parameters {a, b, c}:

$$\mathrm{Bell}(x;a,b,c)=\frac{1}{1+\left(\frac{x-c}{a}\right)^{2b}} \tag{3.4}$$

Where, the parameter b is usually positive. The Gaussian MFs and bell MFs achieve smoothness; they cannot specify asymmetric MFs, which are needed in some applications.

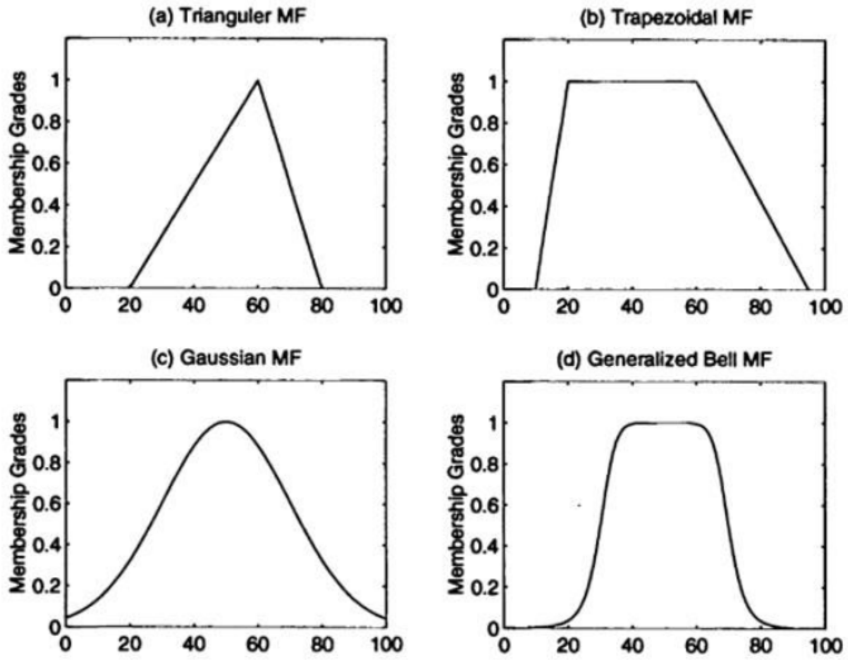


Figure 3.1: Examples of four classes of parameterized MFs: **(a)** triangle (x; 20, 60, 80); **(b)** trapezoid (x; 10, 20, 60, 95); **(c)** Gaussian (x; 50, 20); **(d)** bell (x; 20, 4, 50) [12]

3.1.3 Operations on fuzzy sets

Consider two Fuzzy A and B sets such that A, B ∈ U. Where, U is the Universe of Discourse. Main set operations are: [16]

1. Complement

2. Intersection

3. Union.

Complement: The Complement of a fuzzy set can define as a fuzzy set with the membership function shown below:

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x) \qquad (3.5)$$

Intersection: It can be defined as the biggest fuzzy set in both A and B, which contains both the elements in A, and B. It can be written as ‘A ∩ B’. The membership function for intersection is defined as:

$$\mu_{A\cap B}(x) = \mu_A(x) \cap \mu_B(x) \qquad (3.6)$$

Union: It can be defined as the smallest set, which contains all elements in ‘A’, or ‘B’. It can be written as ‘A + B’ or ‘A U B’. The membership function for union is defined as:

$$\mu_{A\cup B}(x) = \mu_A(x\mu_B) \cup (x) \qquad (3.7)$$

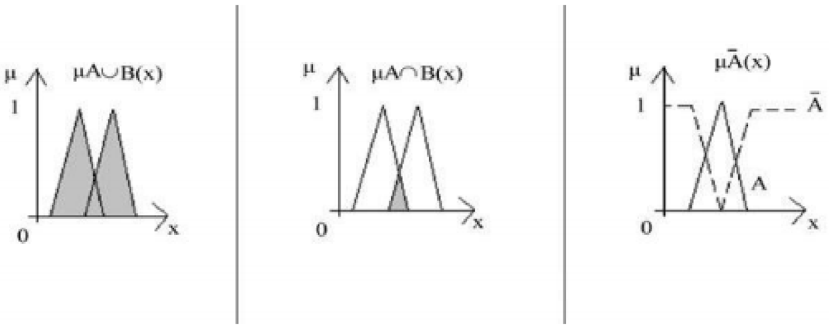


Figure 3.2: Membership functions of **a)** Union **b)** Intersection **c)** Complement

3.1.4 If-Then rules:

Fuzzy sets depend on certain rules. The rule base is the most important requirement for the fuzzy logic. The rule base generally consists of various cases of If-Then rules. First the fuzzy sets and the membership functions are declared. Then the If-Then rules for the membership functions are decided for the particular control. The output is controlled by these rules on input. A typical If-Then rule consists of two parts. They are 1) Antecedent and 2) Consequence or Conclusion. The ‘If’ statement is the Antecedent and the ‘Then’ statement is the Consequence.

If - (Antecedent) & Then - (Consequence).

Examples:

- If the fan is slow, then increase the speed.
- If the temperature is high, then decrease the setting on an air conditioner [16].

3.1.5 Fuzzy Control Method

Fuzzy logic control mainly depends upon the rules formed by the linguistic variables. Fuzzy logic control is free of complex numerical calculations, unlike other methods. It only uses simple mathematical calculations to control the model. Despite relying on basic mathematical analysis, it provides good performance in a control system. Hence, this method is one of the best methods available and easiest one to control a plant. [16]

The three main components of a Fuzzy Logic controller are

- Fuzzification,
- Fuzzy Rule base and Interfacing engine,
- Defuzzification.

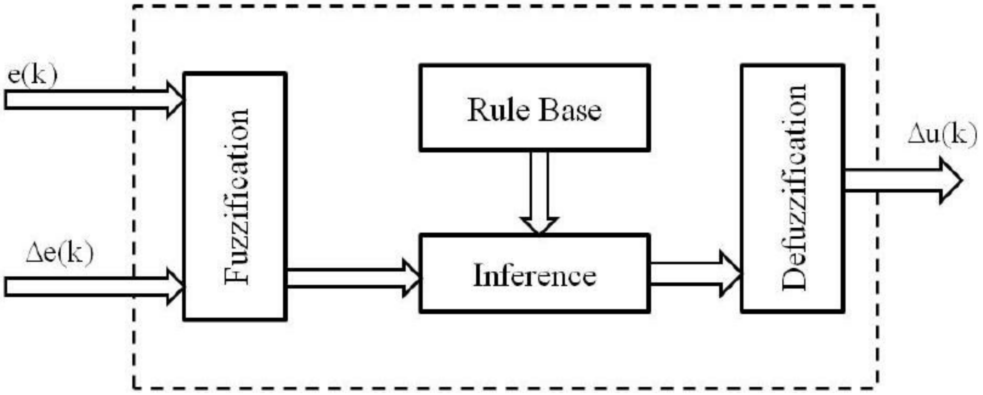


Figure 3.3: Fuzzy Controller Internal Block Diagram

Fuzzification module:

The most important step in formulating a design for the fuzzy controller is to identify the state variables, which efficiently control the plant. After determining the state variables, they are to be passed through the fuzzification block to fuzzify the inputs as the FLC works with only the fuzzy inputs. As the fuzzy rule base employs rules on only linguistic variables, the numerical inputs have to be converted to fuzzy linguistic variables first. This process of converting a numerical state variable into a fuzzy input linguistic variable is called *Fuzzification process*. The variables are generally used to comprise the state error, the rate of change of state error (derivative of state error), or the area of a state error (integral of state error). The membership function is the graphical representation of the degree of belonging of an element to the fuzzy set. We can use different membership functions for an input and output depending on the requirement of the precision to be provided. Generally, the mostly used membership functions are triangular and trapezoidal membership functions.

For a number of membership functions, the accuracy of control increases and the control works effectively. Complexity and time delay due to calculations increase with the number of membership functions taken for a linguistic variable. Hence, the number of membership functions to be used is a judgment that has to be made considering the quickness and efficiency of control to be delivered. [3]

Fuzzy Rule Inference:

Fuzzy inference is of two methods. They are Mamdani and Sugeno [6]. They are explained as below:

- Mamdani Method:

Mamdani’s method of the fuzzy interface is the most commonly used method. It was among the first control systems built using fuzzy set theory. This inference method expects the output variable to be fuzzy sets. It is more advantageous to use a single membership function of a linguistic variable instead of number of fuzzy sets, which can be tedious in some cases. This method of using a single linguistic variable in output is called a Singleton output mechanism. It enhances the *Defuzzification process* because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of the two-dimensional function. However, the Sugeno type of inference can be used to model any inference system in which the output membership function is either linear or constant.

- Sugeno Method:

The first two parts namely, fuzzifying the inputs and applying the fuzzy operator, of the Sugeno method are similar to the Mamdani method.

If the first input is x and the second input is y, then the Output is of the linear form

$$O = Kx + Ly + M \qquad (3.8)$$

For a zero-order Sugeno model, the output O will be a constant (K = L = M).

The output level Oi of each rule is only weighted by the weightage Wi of the rule. [3]

Defuzzification:

General methods adopted for Defuzzifying are:

1. Center of Gravity Method,
2. Bisector of Area Method,
3. Mean of minimum Method.

The Fuzzy Logic Controller (FLC) produces output in a linguistic variable (fuzzy number). This process is called *Defuzzification*. As indicated by true prerequisites, the linguistic variables must be changed to crisp output. Center of gravity strategy is the best understood Defuzzification system and utilized as a part of this exploration work. It acquires the center of gravity of a region involved in the fuzzy set.

Defuzzification is the methodology of delivering a quantifiable result in the fuzzy form. A fuzzy control system has certain rules that change various variables into a "fuzzy" form, that is, the outcome is shown as membership functions and their degree of membership in fuzzy sets. The easiest but not much useful technique is to select the fuzzy set with the highest membership belonging, for this situation. The disadvantage of this methodology is that some data gets lost in this process. The rules that performed "Reduce Pressure" might as well have been absent with this process.

A helpful Defuzzification procedure should first include the outcomes of the results together somehow. The most average fuzzy set enrolment capacity has the shape of triangle.

Suppose, if this triangle were to be cut in a straight level line, some place between the top and the base, and the top segment were to be removed, the remaining figure is in the shape of a trapezoid. This procedure removes parts of the figures to give trapezoids if the membership function used earlier was triangular (or different shapes if the initial shapes were not triangles). Generally, these trapezoids are superimposed one upon another, giving a single shape. Finally, the centroid of this is computed. The abscissa of the centroid gives the defuzzified output. [3]

3.2 Proportional-Integral-Derivative (PID)

The most popular controller used in the process industries for closed loop control is Proportional Integral Derivative (PID) controller, as it can assure satisfactory performances with simple algorithm for a wide range of processes. [18]

PID controllers are widely used in industries for speed control purpose. A PID controller calculates an “error” value as the difference between the measured process value and the desired set point. The PID controller calculation involves three separate constants and is accordingly called three-term control i.e. the proportional, integral and the derivative value, which is denoted by PID as show in figure 3.4 below. [19]

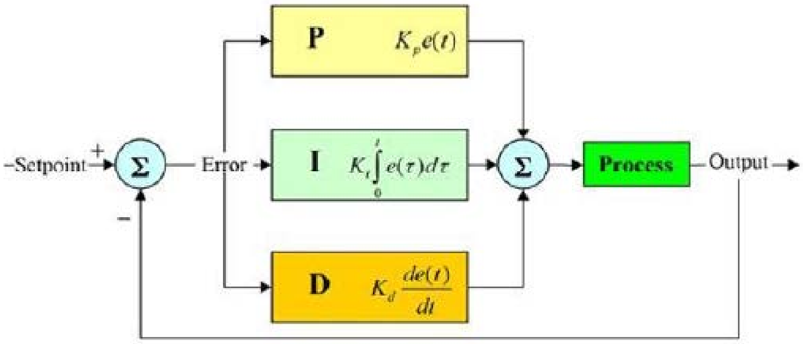


Figure 3.4: Block diagram of PID controller

A standard PID controller is also known as the “three-term” controller, whose transfer function is generally written in the “parallel form” given by (3.9) or the “ideal form” given by (3.10) [20]

$$G(s) = K_P + K_I \frac{1}{s} + K_D s \qquad (3.9)$$

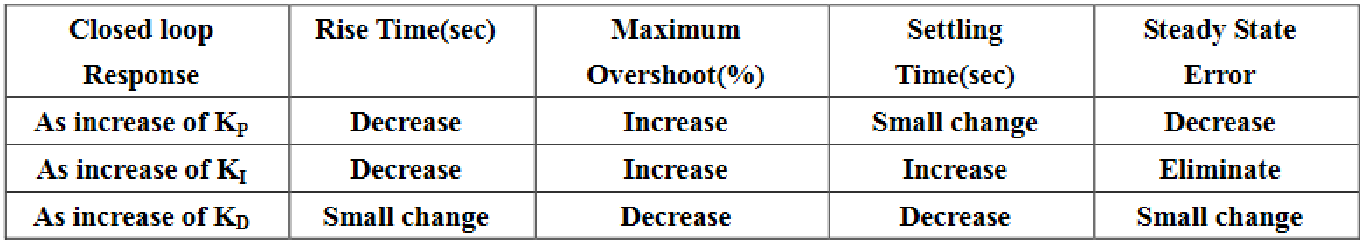
$$= K_P \left(1 + \frac{1}{T_I s} + T_D s\right) \qquad (3.10)$$

Where K_P is the proportional gain, K_I the integral gain, K_D the derivative gain, T_I the integral time constant and T_D the derivative time constant. The following highlight the “three-term” functionalities:

- The proportional term—providing an overall control action proportional to the error signal through the all-pass gain factor.
- The integral term—reducing steady-state errors through low-frequency compensation by an integrator.
- The derivative term—improving transient response through high-frequency compensation by a differentiator.

The individual effects of these three terms on the closed-loop performance are summarized in Table (3.1)

Table 3.1: Effects of PID controllers parameters k_P, k_I and k_D on a closed loop system [21]



Closed loop Response	Rise Time(sec)	Maximum Overshoot(%)	Settling Time(sec)	Steady State Error
As increase of K_P	Decrease	Increase	Small change	Decrease
As increase of K_I	Decrease	Increase	Increase	Eliminate
As increase of K_D	Small change	Decrease	Decrease	Small change

3.3 Fuzzy logic Speed Controller

3.3.1. Design

The Simulink of the fuzzy logic speed controller is shown in figure 3.5. As it can be seen, the fuzzy controller is fed with two input values: the error (E) and the error ration (ER). Since our aim is to control the speed of the induction motor, a speed error is used.

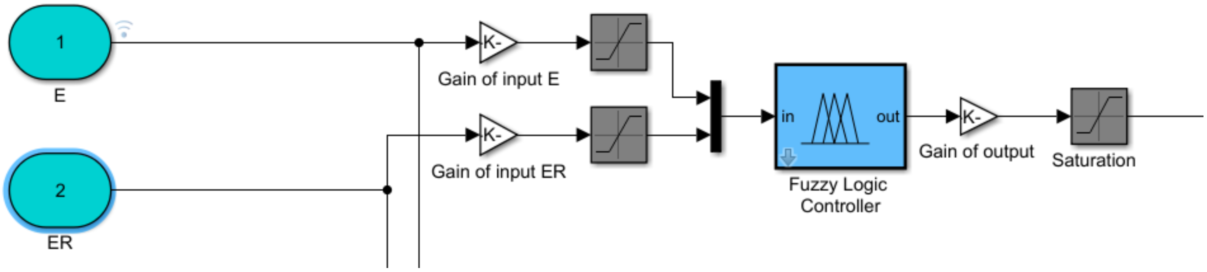


Figure 3.5: Simulink model for FLC

The speed error E is equal to the reference speed *Wm** minus the current speed of the motor *Wm*. Its mathematical equation is expressed in (3.11). The current speed of the induction motor is taken from a tacho-generator attached to the shaft of the motor. This method is called the feedback mechanism.

$$\mathrm{E} = \omega_m^* - \omega_m \qquad (3.11)$$

Feedback is defined as the process of returning part of the signal output from a circuit or device back to the input of that circuit or device. In control systems, the desired result is either to increase the input (positive or regenerative feedback) or to decrease the input (negative or degenerative feedback). [24]

The error ration (ER) is calculated by dividing the error E over the speed reference. It can be expressed mathematically in (3.12)

$$\mathrm{RE} = \frac{E}{\omega_m^*} \qquad (3.12)$$

The two inputs, E and ER, are fed to the fuzzifier for fuzzification. The inference system then processes these two fuzzy inputs using the fuzzy control rules and the database, which are defined by the programmer based on the chosen membership function and fuzzy rule table. The fuzzy output, is thus obtained and defuzzified by the defuzzifier to give a crisp value, i.e. the Torque Reference (*Te**).

The two inputs, E and ER, and the output, Te^*, membership functions are shown in figures (3.6) and (3.7) respectively.

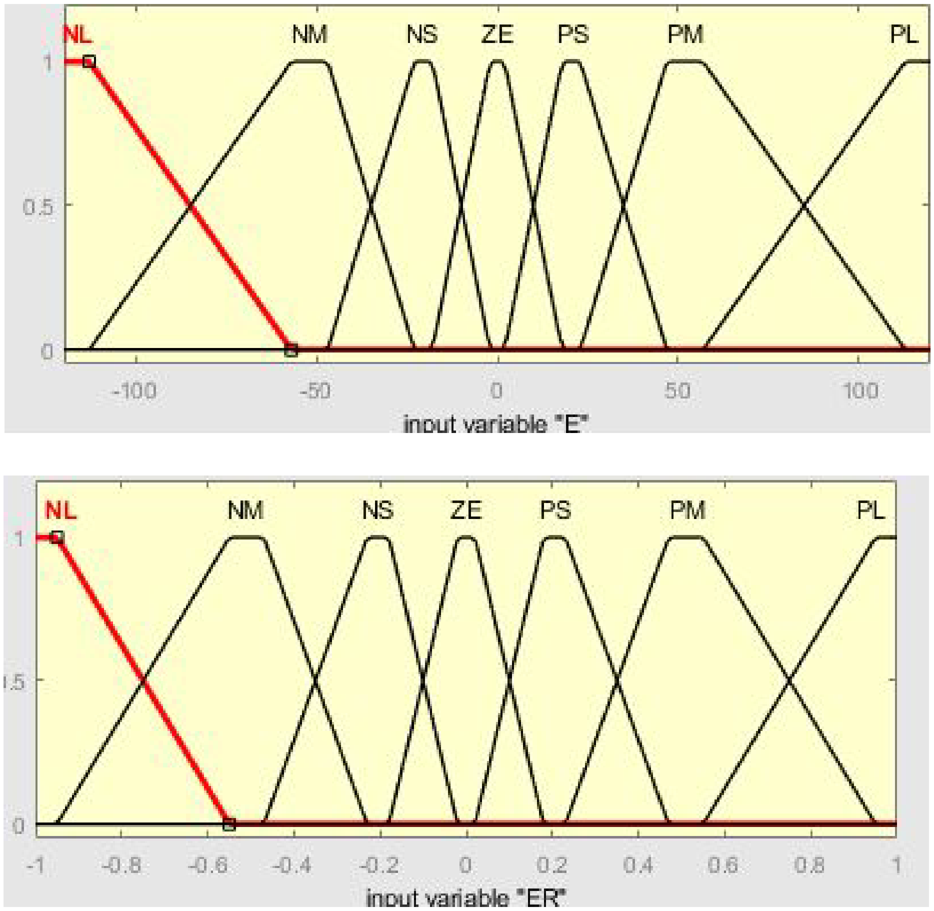


Figure 3.6: Input membership functions for FLC

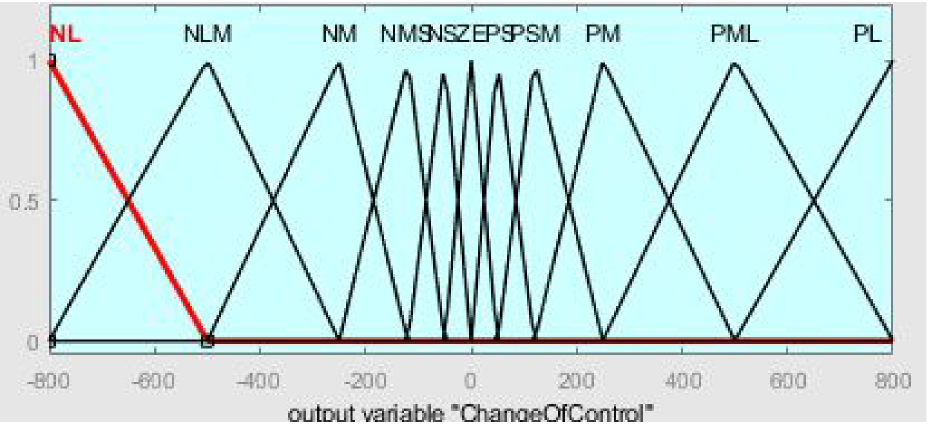


Figure 3.7: Output membership function for FLC

The Rule Base for deciding the output of the inference system consists of 49 If-Then rules in this case since there are seven fuzzy sets in each of the inputs. The output, on the other hand, has nine fuzzy sets.

Table 3.2: Fuzzy rule table for output (Te^*)

E/ER	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NLM	NM	NMS	NS	ZE
NM	NL	NLM	NM	NMS	NS	ZE	PS
NS	NLM	NM	NMS	NS	ZE	PS	PMS
ZE	NM	NMS	NS	ZE	PS	PMS	PM
PS	NMS	NS	ZE	PS	PMS	PM	PLM
PM	NS	ZE	PS	PMS	PM	PLM	PL
PL	ZE	PS	PMS	PM	PLM	PL	PL

Abbreviations:

NL: Negative Large

NM: Negative Medium

NS: Negative Small

ZE: Zero

PS: Positive Small

PM: Positive Medium

PL: Positive Large

NLM: Negative Large Medium

NMS: Negative Medium Small

PMS: Positive Medium Small

PLM: Positive Large Medium

3.3.2. Simulation Results:

- ***Constant Torque - Step Speed:***

The dynamic performance of the Fuzzy controller is analyzed by applying 100 N.m torque load and step change in reference speed, from 120 rad/sec to 40 rad/sec, at second interval time. The red curve represents the reference speed while the blue curve represents the measured speed.

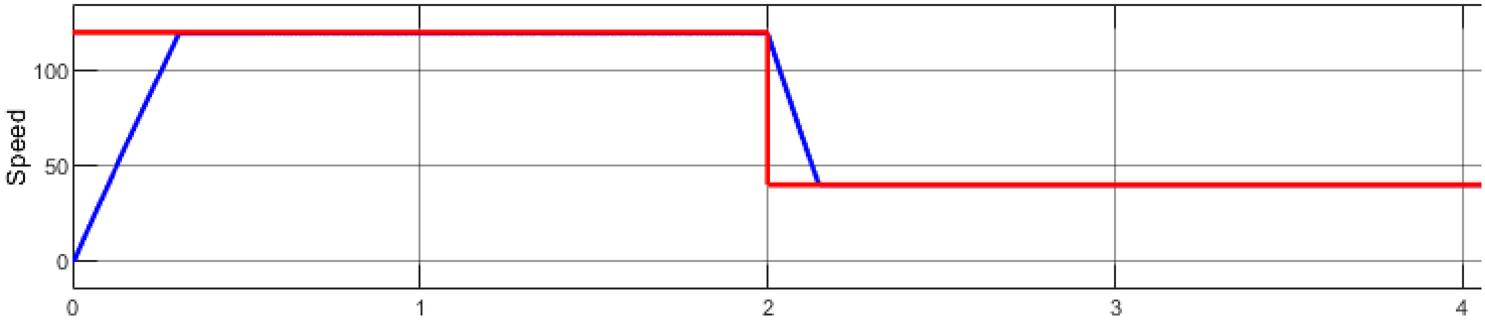


Figure 3.8: Simulation result of the fuzzy controller for a Constant Torque and Step Speed.

- ***Step Torque- Constant Speed:***

The dynamic performance of the Fuzzy controller is analyzed by applying step change in torque load, from 50 N.m to 350 N.m at third interval time, and a constant speed reference of 120 rad/sec.

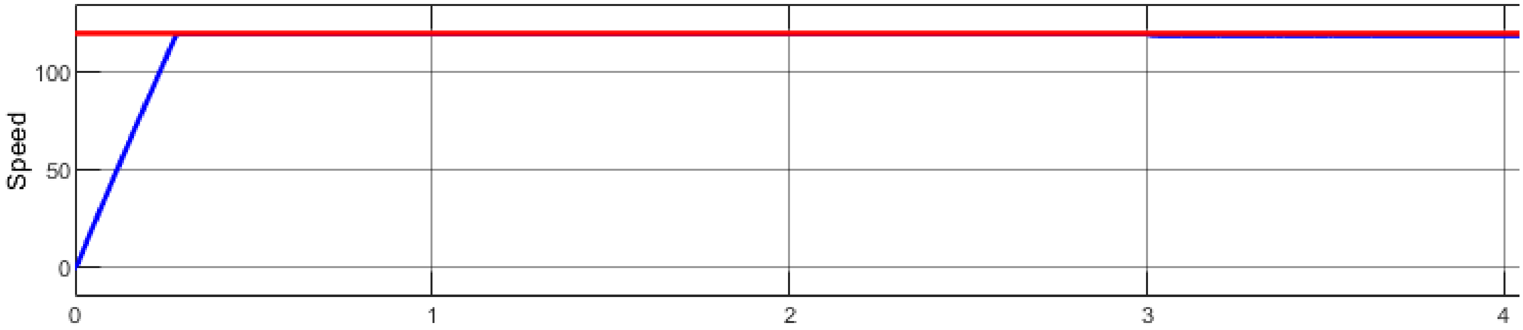


Figure 3.9: Simulation result of the fuzzy controller for a Step Torque and Constant Speed.

✓ *Discussion and Results:*

By analyzing fig 3.8, it has been found that the measured speed follows the reference speed in a linear behavior. The measured speed reaches the reference speed after approximately 0.3 to 0.4 sec and remains constant at a value of 120 rad/sec. As the reference speed drops to a value of 40 rad/sec after 2 sec, the measured speed consequently slides until it reaches the reference speed and remains unchanged.

By analyzing fig 3.9, it has been found that the measured speed follows the reference speed in a linear behavior. When the measured speed reaches the reference speed after approximately 0.3 to 0.4 sec, it remains constant at 120 rad/sec.

The fuzzy controller presents a good performance and a remarkable flexibility. Because of the variety of the fuzzy if-then rules, the smallest change in the error is detected. Hence, the fuzzy controller is capable to adjust the measured speed according to the reference speed in a timely manner.

3.4 Fuzzy-PID controller:

3.4.1. Design

The proposed controller design is shown in figure 3.10; it is a two level controller. The first level is a fuzzy network and the second level is a PID controller. The structure of the classical FPID controller in which the PID controller gains are tuned online for each of the areas, where we have chosen the three gains of PID to be: $K_P= 200$; $K_I= 30$; $K_D= 1$.

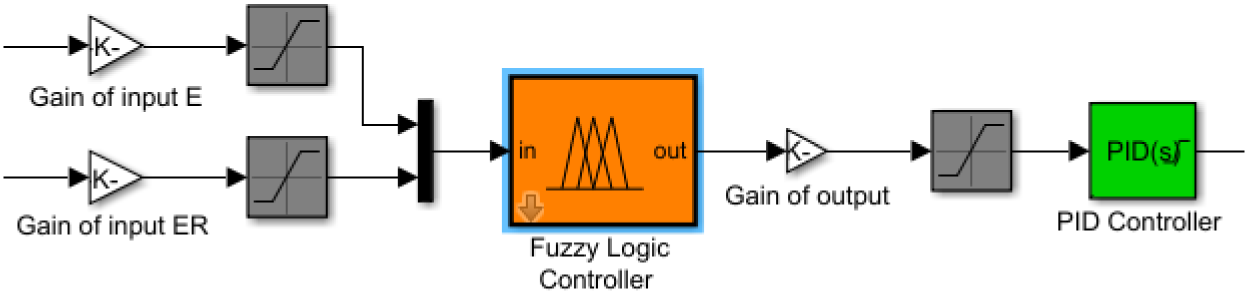


Figure 3.10: Simulink model for FPID

The fuzzy logic controller has the same inputs and output as the previous one.

The membership functions of input and output variables are shown in figures 3.11 and 3.12 respectively.

The Rule Base for deciding the output of the inference system T_e^* is similar as the previous FL controller.

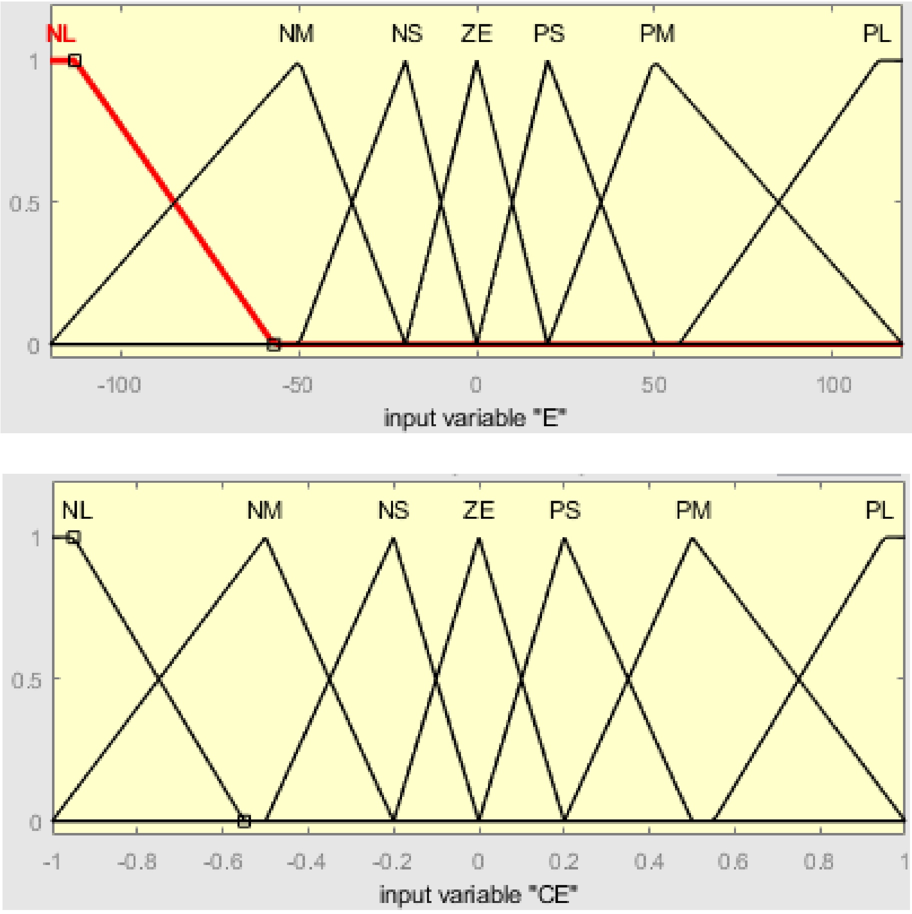


Figure 3.11: Input membership functions for FPID controller

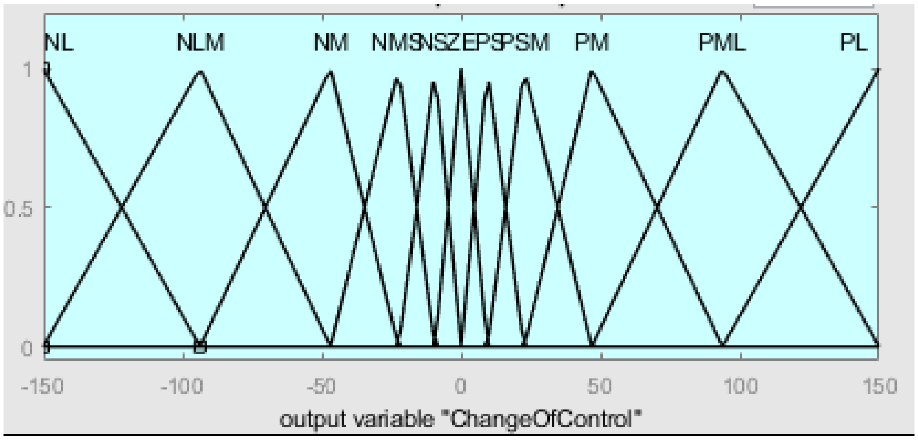


Figure 3.12: Output membership function for FPID controller

3.4.2. Simulation Results:

- ✓ **Constant Torque and Step Speed:**

The dynamic performance of the Fuzzy-PID controller is analyzed by applying 100 N.m torque load and step change in reference speed, from 120 rad/sec to 40 rad/sec, at second interval time.

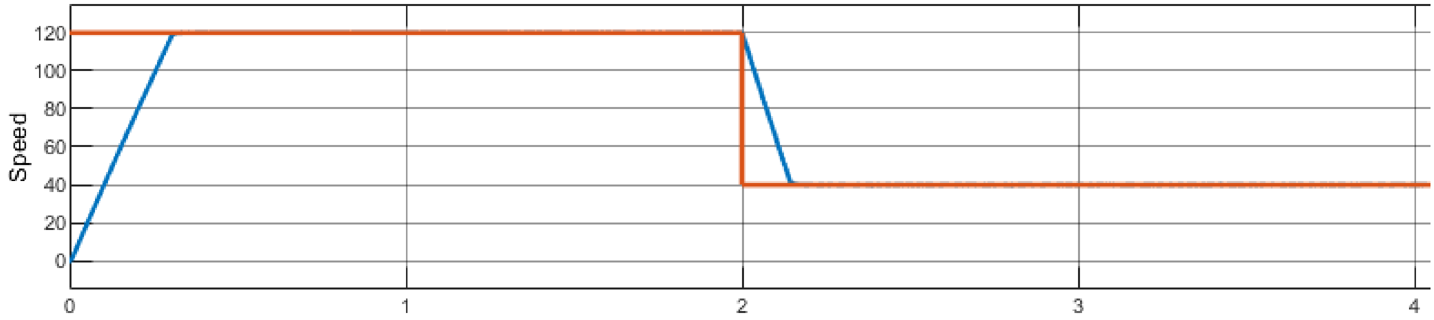


Figure 3.13: Simulation result of the fuzzy-PID controller for a Constant Torque and Step Speed.

- ✓ **Step Torque- Constant Speed:**

The dynamic performance of the Fuzzy-PID controller is analyzed by applying step change in torque load, from 50 N.m to 350 N.m at third interval time, and a constant speed reference of 120 rad/sec.

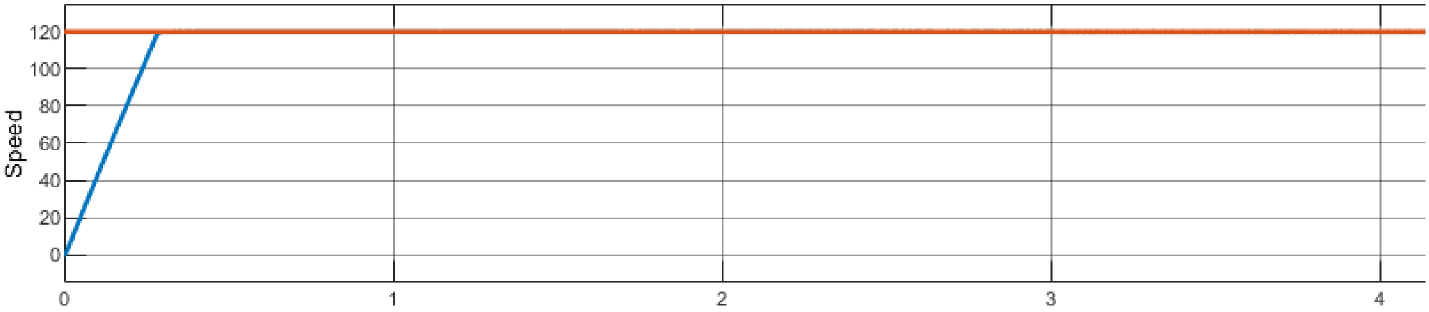


Figure 3.14: Simulation result of the fuzzy-PID controller for a Step Torque and Constant Speed.

- ✓ **Discussion and Results:**

By analyzing fig 3.13, it has been found that the measured speed follows the reference speed in a linear behavior. The measured speed reaches the reference speed after approximately 0.3 to 0.4 sec and remains constant at a value of 120 rad/sec. As the reference speed drops to a value of 40 rad/sec after 2 sec, the measured speed consequently slides until it reaches the reference speed and remains unchanged.

By analyzing fig 3.14, it has been found that the measured speed follows the reference speed in a linear behavior. When the measured speed reaches the reference speed after approximately 0.3 to 0.4 sec, it remains constant at 120 rad/sec.

The fuzzy-PID controller provides a higher flexibility due to the presence of the PID block. This latter improves the performance of the controller as the user can customize the gain parameters K_P, K_I and K_D according to his needs.

Chapter IV: Adaptive Fuzzy Logic PID Controller

4.1 Definition

In the past decade, the fuzzy logic control (FLC) strategy has been the focus of many studies and research for the control of induction motor. However, in presence of real variations of the plant parameters, recourse to adaptive control is in most cases unavoidable. Adaptive fuzzy concept combines the robustness of fuzzy logic systems and the adaptation capabilities of adaptive control. Adaptive fuzzy controllers (AFC) provided an attracting approach to obtain the fuzzy parameters of an FLC by using a tuning algorithm. [23]

Structure of the Adaptive-Fuzzy-PID (AFPID) control scheme is shown in figure 4.1. Fuzzy logic plays a role to enhance capability of the PID controller to be more sensitive on the changes of the induction motor parameters and the existence of uncertainty.

Initial parameters K_P, K_I, and K_D of the PID controller are obtained by using trial-and-error tuning method. While, the fuzzy system design is arranged under the condition the system parameters change to obtain the maximum range of the system output error *E* and the error ratio ER. [22]

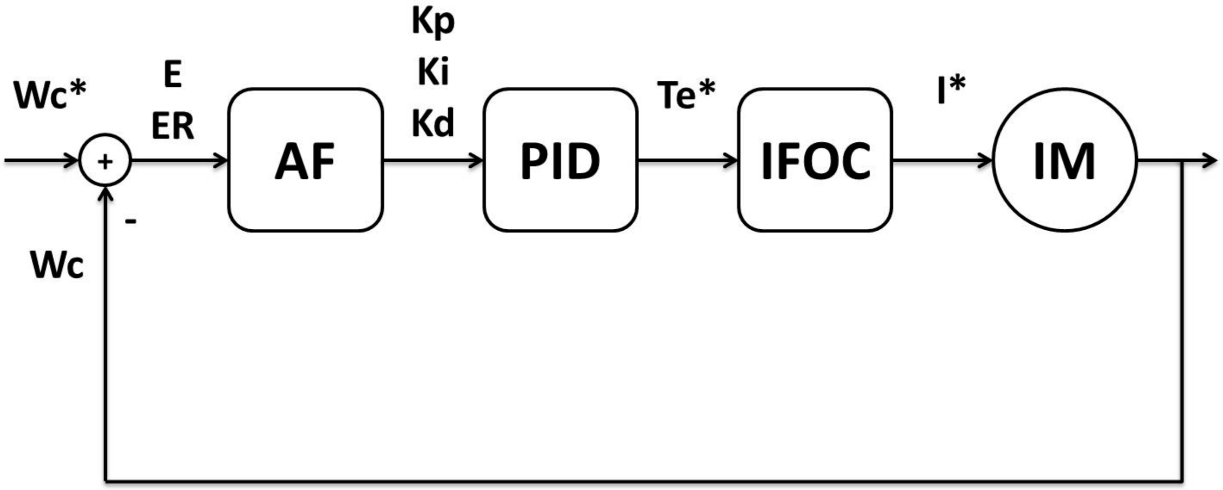


Figure4.1: Adaptive-Fuzzy-PID Control Scheme

Where I^* is the reference current.

4.2 Design

The structure of the proposed adaptive fuzzy logic PID controller is shown in figure 4.2. It consists of three FLCs, which tune the parameters K_P, K_I and K_D to improve the performance of the system.

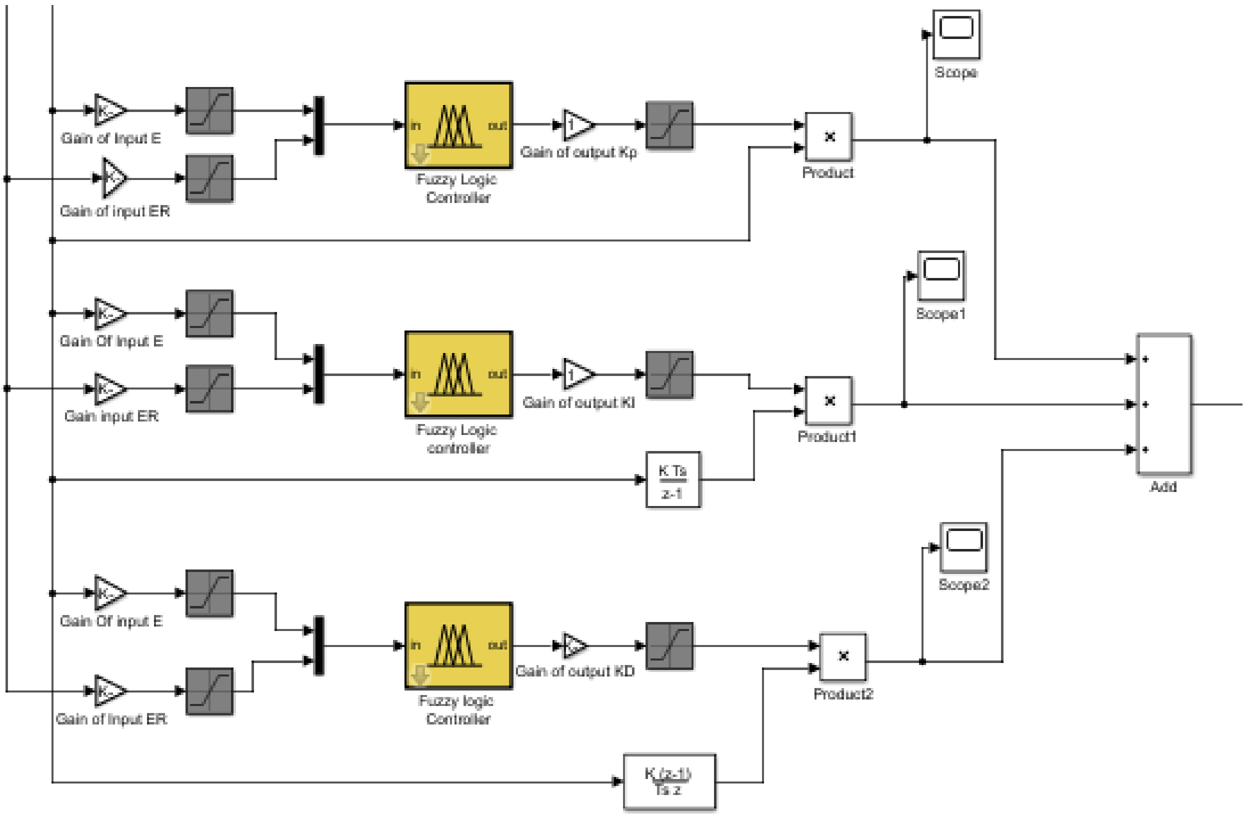


Figure 4.2: Simulink model for adaptive FLPID controller

The controller is a Mamdani-type fuzzy logic controller with a typical If-Then rule structure. Each FLC in the proposed multi-stage FLPID controller share the same inputs as the previous FLCs seen in chapter 3 i.e. Error (E) and Error Ratio (ER) and one output, either K_P, K_I or K_D which are the fuzzy tuned parameters of PID controller. These three outputs will be added together, according to equation (3.9), to constitute the PID block. This latter will generate the final output, which is the reference torque T_e^*.

The tuned parameters are a Mamdani fuzzy inference model, which provide a non-linear mapping from error (E) and error ratio (ER) to PID parameters K_P, K_I and K_D with three triangular membership functions.

The three input linguistic variables that have been used in the fuzzification stage are:

N: Negative.

Z: Zero.

P: Positive.

For the output, the three linguistic variables used are:

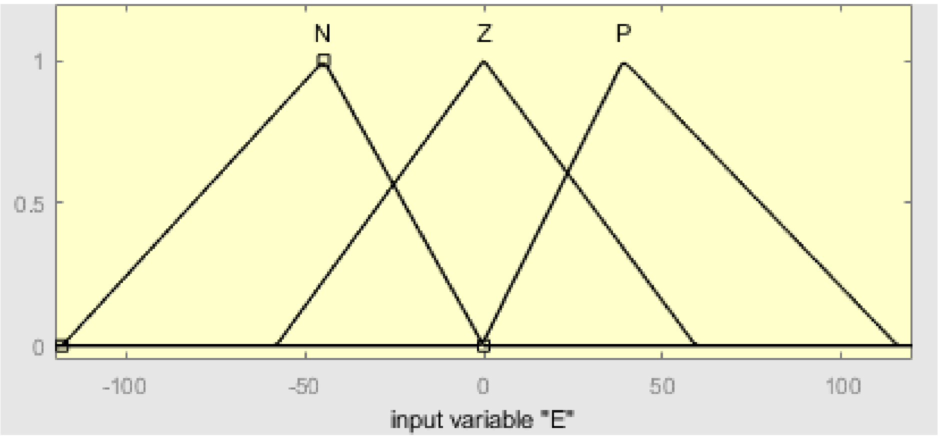
S: Small.

M: Medium.

L: Large.

The ranges of input signals are fixed from (-120 to 120) for error (E) and from (-1 to 1) for error ratio (ER), while the range of the outputs K_P, K_I and K_D is varied depending on the desired performance of the adaptive FLPID controller. The tuning of these parameters is established using the trial-and-error method.

The triangular membership functions of input and output variables are shown in figures 4.3 and 4.4 respectively.



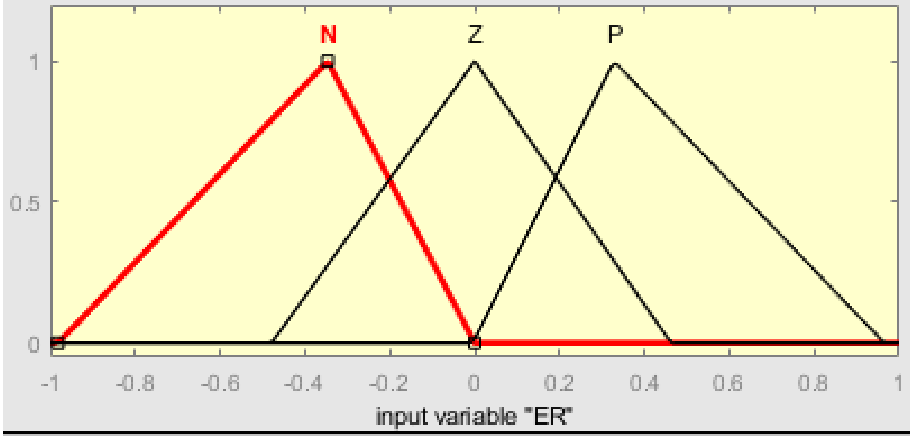
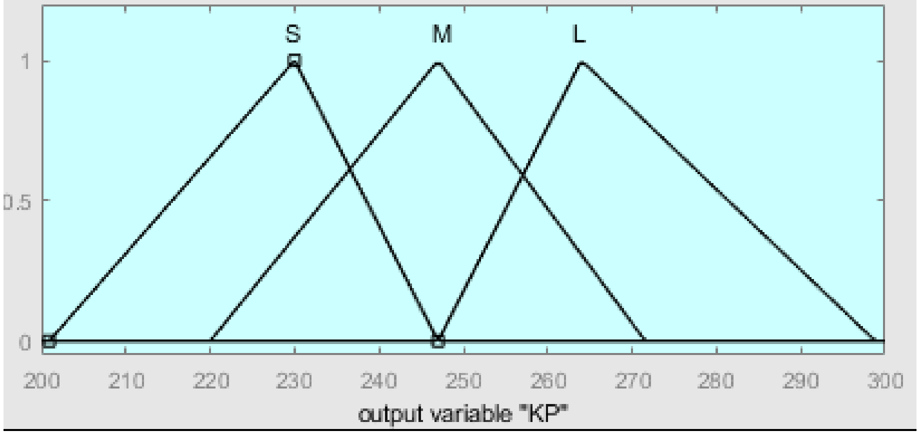
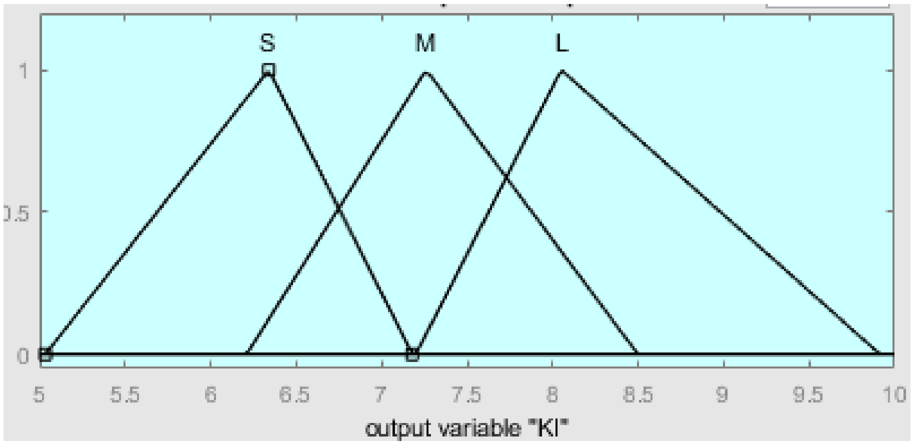


Figure 4.3: Input membership functions for adaptive FLPIDC





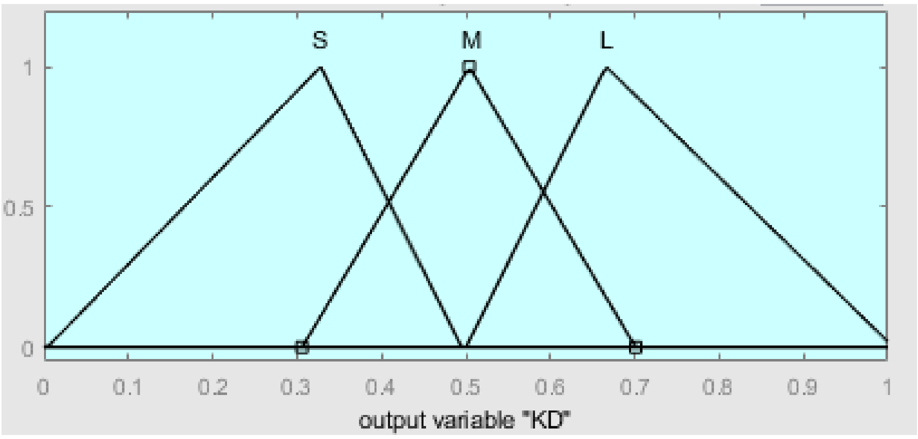


Figure 4.4: Output membership functions for adaptive FLPIDC

Since each input has three fuzzy sets, nine If-Then rules are needed to determine each of the outputs K_P, K_I and K_D. The control rules for each fuzzy logic controller are shown in tables 4.1, 4.2 and 4.3.

Table 4.1: Fuzzy rule table for output K_P

E/ER	N	Z	P
N	L	L	M
Z	L	M	S
P	M	S	S

Table 4.2: Fuzzy rule table for output K_I

E/ER	N	Z	P
N	S	S	M
Z	S	M	L
P	M	L	L

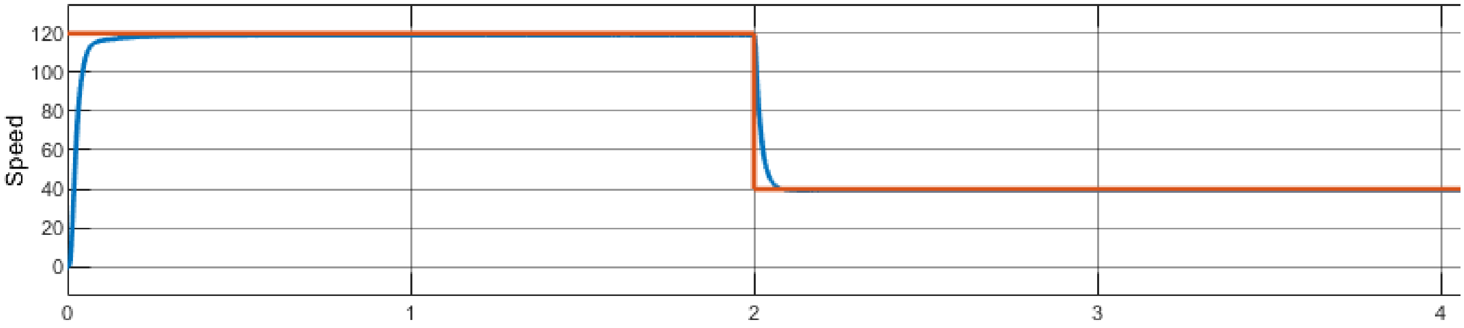
Table 4.3: Fuzzy rule table for output K_D

E/ER	N	Z	P
N	M	M	L
Z	S	S	L
P	M	M	L

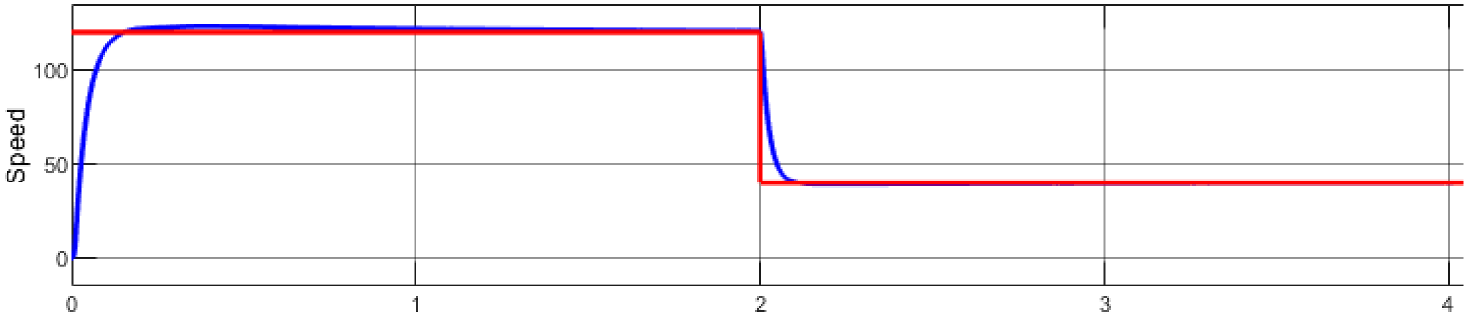
4.3. Simulation Results:

- ✓ **Constant Torque-Step Speed:**

The dynamic performances of the Adaptive Fuzzy PID controller is analyzed by applying 100 N.m torque load and step change in reference speed, from 120 rad/sec to 40 rad/sec, at second interval time.



(a) Kp=200-300 ; Ki= 5-10 ; Kd= 0-1

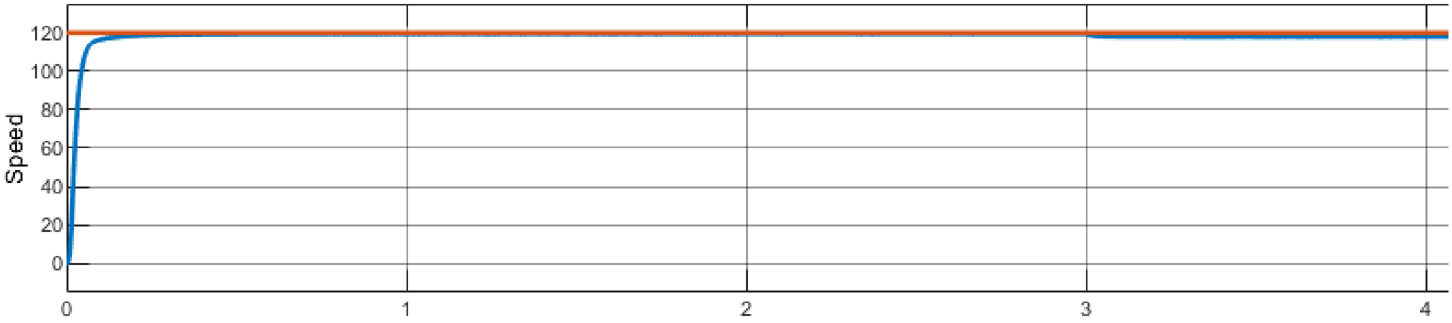


(b) Kp= 800-1000 ; Ki= 200-300 ; Kd= 2-4 ;

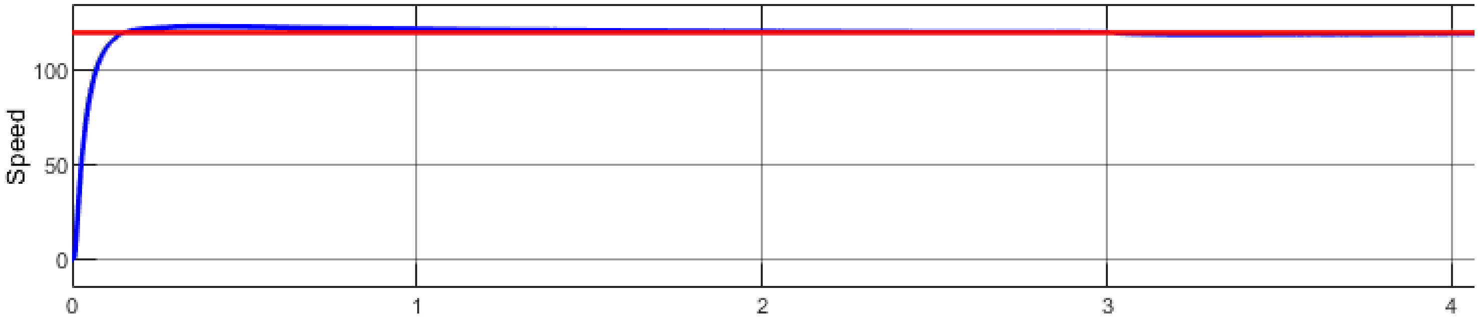
Figure 4.5: Simulation result of the Adaptive-fuzzy-PID controller for a Constant Torque and Step Speed for two different range.

- ✓ **Step Torque- Constant Speed:**

The dynamic performance of the Fuzzy controller is analyzed by applying step change in torque load, from 50 N.m to 350 N.m, and at third interval time, and a constant speed reference of 120 rad/sec.



(a) Kp= 200-300 ; Ki= 5-10 ; Kd= 0-1 ;



(b) Kp= 800-1000 ; Ki= 200-300 ; Kd= 2-4.

Figure 4.6: Simulation result of the Adaptive-fuzzy-PID controller for a Step Torque and Constant Speed for two different range.

- ✓ **Discussion and Results:**

By analyzing fig 4.5 (a) and (b), it has been found that the measured speed follows the reference speed in a fast pace. The measured speed reaches the reference speed after approximately 0.1 to 0.2 sec and remains constant at a value of 120 rad/sec. As the reference speed drops to a value of 40 rad/sec after 2 sec, the measured speed consequently falls sharply until it reaches the reference speed and remains unchanged.

By analyzing fig 4.6 (a) and (b), it has been found that the measured speed follows the reference speed in a rapid rate. When the measured speed reaches the reference speed after approximately 0.1 to 0.2 sec, it remains constant at 120 rad/sec.

Comparing the two ranges (a) and (b), it can be seen that, when employing range (a), the measured speed becomes constant as soon as it reaches the reference speed, without exceeding it. Whereas, when using range (b), a slight overshoot is detected.

As a conclusion, a suitable tuning of the adaptive fuzzy-PID gains in real time is important, since it provides excellent performance, fast response and high robustness to the system.

Chapter V: Conclusion

The objectives of this thesis are to model, simulate and analyze in real time domain the speed controller drives of the induction motor using SIMULINK.

In this work, Fuzzy logic controller was successfully designed and implemented in this thesis, as it has been enhanced by adding a PID controller then using a multi stage FLCs.

Fuzzy, Fuzzy-PID and adaptive Fuzzy-PID controllers were designed and simulated in SIMULINK. The performance and robustness of each controller have been evaluated and compared through the simulation results presented in this thesis.

Both fuzzy controller and Fuzzy-PID controller have proved their efficiency and effectiveness in driving the induction motor, with a slight difference in performance between the two controllers; since the PID block has enhanced and increased the speed of induction motor due to PID gains.

Adaptive fuzzy-PID controller revealed promising results, as it was able to tune the parameters of the PID gains independently in real time with no human intervention, and showed a higher and faster speed response comparably to the two previous controllers. Due to these interesting results achieved in this thesis, it can be concluded that the adaptive fuzzy-PID technique is more robust, more reliable and can be adopted by complex applications that require a high precision and fast response.

This work has offered several contributions in the field, where the models of the various sub-systems were integrated to form the dynamic model of the drive system. In addition, a simulation of the entire drive system was performed using the three above models. Moreover, results of the simulation were analyzed and compared.

After the good results achieved by using hybridization of fuzzy logic and conventional controllers, the need to minimize the losses in induction motor is raised. Harmonic distortion, voltage imbalance, and power factor improvements are serious problems that have to be taken into consideration in order to improve the efficiency of induction motor.

Thus, as a future work, many techniques that are common in the area of loss optimization can be developed for this thesis, such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Artificial Neural Network (ANN). These techniques are well known and differ in terms of complexity and performance.

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Appendix: Additional SIMULINK Blocks

Part I: *Speed Controller Block*

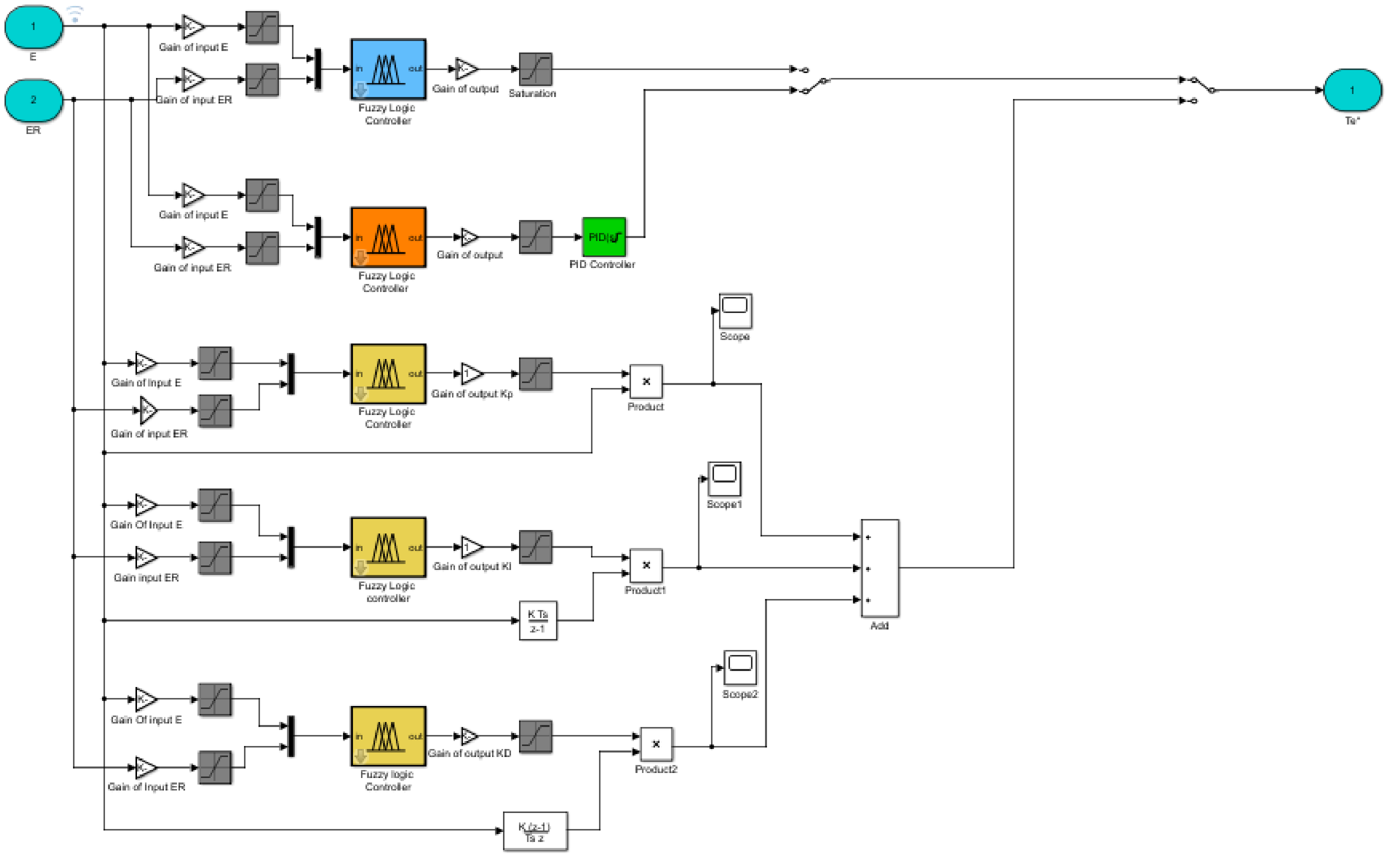

Figure A.1: Overall speed controller

Part II: *General System Block*

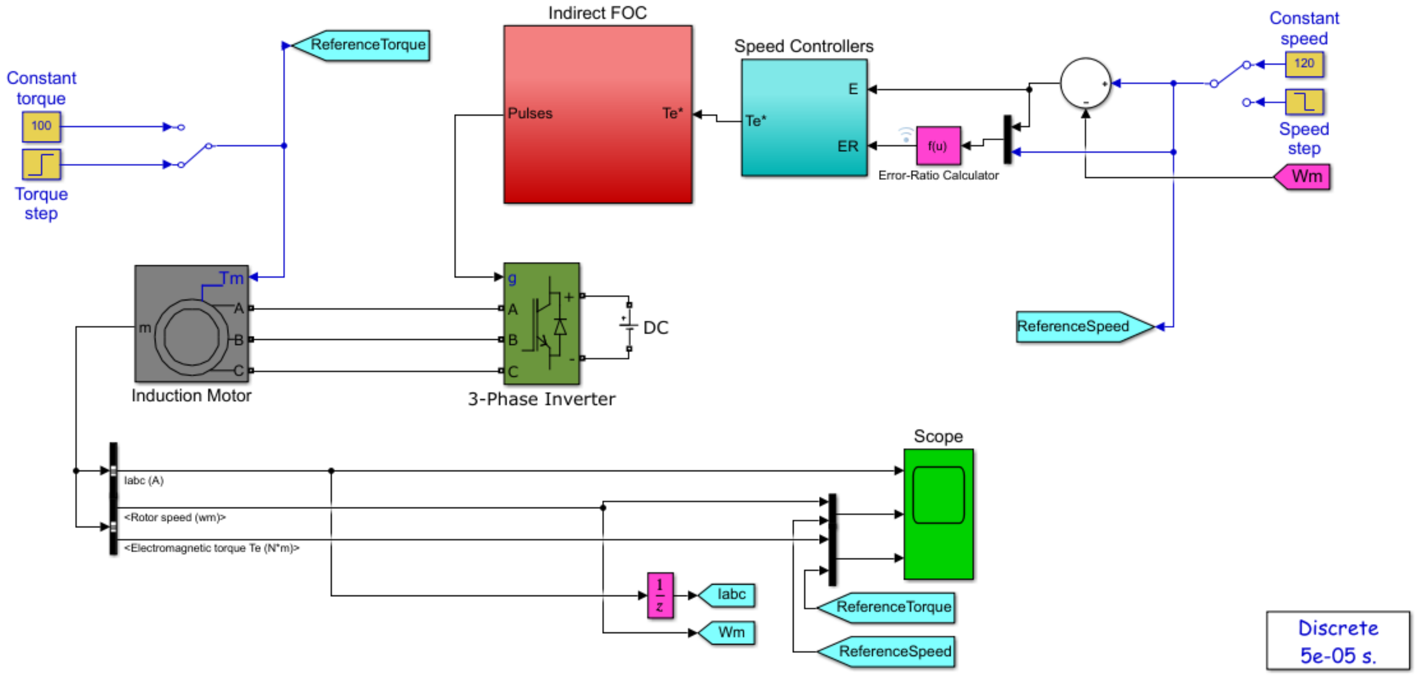

Figure A.2: Overall system.

Appendix B: Table of Parameters of Induction Motor

Parameter	**Symbol**	**Value**	**Unit**
Nominapower	Pn	50*746	VA
Voltage (line-line)	Vn	400	Vrms
Frequency	fn	50	Hz
Stator Resistance	Rs	0.087	ohm
Stator Inductance	Lls	0.8e-3	H
Rotor Resistance	Rr	0.228	ohm
Rotor Inductance	Llr	0.8e-3	H
Mutual Inductance	Lm	34.7e-3	H
Inertia	J	1.662	kg.m^2
Friction Fractor	F	0.01	N.m.s
Pole Pairs	P	2	-