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School of Electrical and Computer Engineering

**Linear Induction Motor Vector Control System Based on
Fuzzy Logic Controller**

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Thesis submitted to Addis Ababa Institute of Technology in Partial Fulfillment of the requirements for the degree of Master of Science in Electrical and Computer Engineering (Control Engineering)

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Fuzzy Logic Controller**

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Declaration

I, the understand, declared that this MSC thesis is my original work, has not been presented for fulfillment of a degree in this or other university and all sources and materials used for the work have been fully acknowledged.

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Abstract

Linear induction motors (LIM) are special developments of conventional induction motors. Conceptual construction principle of a motor is, made by cut out and laid flat rotational induction motors (RIM). The motor is used for a variety of demanding applications, including high speed ground transportation and specific industrial applications. The aim of this thesis is to present modeling of LIM including end effect using MATLAB Simulink and applied vector control system to control the proposed motor, to achieve accurate operation to required applications. In order to check accuracy of vector controlled system, simulation of the developed system is performed using MATLAB software with added Fuzzy Logic Controller on proposed control mechanisms. This controller performance is compared with conventional proportional plus integral (PI) controller. Their validity, again implemented on MATLAB. Both types of vector controller techniques are tested at different dynamic conditions, which are no-load and load condition, variation of primary resistance condition and, sudden command speed change and tracking, are presented. In addition to mentioned conditions tested, end effect existence factor on vector control systems are performed using simulation. From overall simulations results, we noticed that, FLC gives good relative responses over conventional PI controller in all conditions. For instance, change variation error occurred on PI controller from varies between (0 to 0.047) to zero steady state error and also minimize maximum peak overshoot exist on PI controller from 0.069 to 0.016. Hence, fuzzy logic controller is relatively a robust controller.

Key words: End effect, Fuzzy logic controller, Linear induction motor (LIM), MATLAB, PI controller, and Vector control.

Table of Contents

Acknowledgment	i
Abstract	ii
List of figures	v
List of tables.....	vii
List of abbreviations and symbols	viii
Chapter one	1
1. Introduction.....	1
1.1. Statement of the Problem.....	3
1.2. Objective of the Study.....	4
1.2.1. General objectives.....	4
1.2.2. Specific objectives	4
1.3. Methodology	4
1.4. Scope of the work	5
1.5. Literature review.....	5
1.6. Thesis organization	7
Chapter two.....	8
2. Construction and operation principles of linear induction motors.....	8
2.1. Construction of linear induction motors	8
2.2. Working principles of linear induction motor.....	11
2.3. Dynamic D-Q, modeling of linear induction motor(LIM).....	12
2.4. Reference frame Transformation (3- Φ to 2- Φ Transformations)	13
2.5. D-Q equivalent circuit.....	17
Chapter three.....	25
3. Vector control or field oriented control for linear induction motor	25
3.1. Direct field oriented control (DFOC) and indirect field oriented control(IFO)C	26

3.2.	Control of LIM Drives	32
3.2.1.	Inverter and their control.....	32
3.2.2.	Power semiconductor devices	33
3.3.	Pulse width modulation.....	36
3.3.1.	Sinusoidal pulse width modulation (SPWM).....	36
Chapter four	.....	39
4.	Controller Design.....	39
4.1.	Fuzzy logic principle and applications.....	39
4.1.1.	Introduction to Fuzzy-Logic	39
4.2.	Fuzzy logic controllers.....	44
4.2.1.	Design fuzzy logic controllers	46
4.3.	Conventional controller.....	49
4.3.1.	PI controller	49
Chapter five	.....	51
5.	Simulation Results and Discussions	51
Chapter six	.....	64
6.	Conclusion and Recommendation future works	64
6.1.	Conclusion	64
6.2.	Recommendation future works	64
References	.....	66
Appendix	.....	70

List of figures

Figure 2.1 Ordinary induction motor	8
Figure 2.2 Imaginary split out stator of ordinary motor for primary LIM	9
Figure 2.3 Single side linear induction motor (SLIM).....	9
Figure 2.4 Double sided linear induction motor (DLIM)	9
Figure 2.5 Short primary type LIM.....	10
Figure 2.6 Short secondary type LIM	11
Figure 2.7 Pole pitch indication between two poles	11
Figure 2.8 Stationary frame a-b-c to D-Q axis transformation	14
Figure 2.9 Side view of LIM to reaction plate	17
Figure 2.10 (a) Polarity and decaying of the entry and exit eddy currents (b) air gap magnetic flux.....	18
Figure 2.11 (a) d-axis equivalent circuit and (b) q-axis equivalent circuit of LIM	19
Figure 2.12 Over all model of linear induction motor	21
Figure 2.13 Internal structure of linear induction motor model blocks	22
Figure 2.14 Primary and secondary current formula block on MATLAB Simulink	23
Figure 2.15 End effect formula on Simulink blocks.....	23
Figure 2.16 Internal blocks of dq to abc transformations	24
Figure 2.17 Internal structure of three phase to two transformation block	24
Figure 3.1 Separately excited dc motor from	25
Figure 3.2 Phasor diagram indirect vector control	27
Figure 3.3 Current controller block diagram	31
Figure 3.4 Proposed vector control for linear induction motor general block diagram	32
Figure 3.5 Three phase inverter	35
Figure 3.6 SPWM model using MATLAB Simulink.	37
Figure 3.7 Single phase inverter	38
Figure 3.8 (a) the control sinusoidal and triangular signal ,	38
Figure 4.1 Union of fuzzy sets A and B.....	40
Figure 4.2 Intersection of fuzzy sets A and B	41
Figure 4.3 Complement of fuzzy sets B.....	41
Figure 4.4 Representation of , temperature using (a) fuzzy set and (b) crisp set	42

Figure 4.5 The two most common used membership functions: (a) triangular, and (b) trapezoidal -shaped	43
Figure 4.6 Structure of fuzzy logic controllers	44
Figure 4.7 Connection diagram of fuzzy logic controller	45
Figure 4.8 Membership function of input (E)	48
Figure 4.9 Membership function of input(CE)	48
Figure 4.10 Membership function of output (FE).....	48
Figure 4.11 PI controller block diagram with vector control.....	50
Figure 5.1 Inverter output voltage connected to LIM model without any controller.....	51
Figure 5.2 Speed output without controller	52
Figure 5.3 Force/thrust output without applying any controller	52
Figure 5.4 Three phase output currents without applying controllers.....	53
Figure 5.5 Over all content vector controlled linear induction motor derive.....	53
Figure 5.6 PI controller speed output.....	54
Figure 5.7 Fuzzy controller speed output.....	54
Figure 5.8 Force/thrust response from PI controller	55
Figure 5.9 Force/thrust response from fuzzy controller.....	55
Figure 5.10 PI controller three phase current output.....	56
Figure 5.11 Fuzzy controller three phase current output	56
Figure 5.12 PI controller speed output when load applied at 0.2sec.....	57
Figure 5.13 Fuzzy controller speed output when load applied at 0.2sec	57
Figure 5.14 PI controller thrust or force response when load applied at 0.2sec	58
Figure 5.15 Fuzzy controller thrust or force response when load applied at 0.2sec	58
Figure 5.16 Shows PI controller three phase current output when system is loaded.....	59
Figure 5.17 Shows fuzzy controller three phase current output when system is loaded.....	59
Figure 5.18 PI controller speed output when primary resistance varies by 50%	60
Figure 5.19 Fuzzy controller speed output when primary resistance varies by 50%.....	60
Figure 5.20 PI controller actual speed tracking applied reference speed.....	61
Figure 5.21 Fuzzy controller actual speed tracking applied reference speed.....	61
Figure 5.22 Uncompensated end effect PI controller actual speed tracking reference	62
Figure 5.23 Uncompensated end effect fuzzy controller actual speed tracking reference	62

List of tables

Table 3-1 Power semiconductor device and their switching capability	33
Table 3-2 Switching states of inverter phase leg a	36
Table 4-1 Rule matrix for fuzzy speed control	49

List of abbreviations and symbols

AC /ac	Alternative current
ω_r	Angular velocity of secondary (rad/sec)
θ_e	Angle of synchronously rotating frame
Ψ_{dp}, Ψ_{qp}	D-Q axis primary flux linkage
Ψ_{ds}, Ψ_{qs}	D-Q axis secondary flux linkage
DFOC	Direct field oriented control
F_e, F_f and FL	Developed ,frictional, and load force
DC /dc	Direct current
d-axis	Direct axis
DTFC	Direct torque field control
DFC	Direct force control
DLIM	Double side linear induction motor
ELS	Electromagnetic launcher system
$f(Q)$	End effect factor modeled
E	Error
FLC	Fuzzy logic controller
Q	Factor associated with length of primary
IFOC	Indirect field oriented control
D	Length of the primary (m)
LIM	Linear induction motor
L_m	Magnetizing or mutual inductance (H)

mmf	Magneto motive force
M	Mover motor mass
MF	Membership function
μ	Membership value(0 to 1 on vertical axis)
P	Number of poles
V_{dp}, V_{qp}	Primary voltage in the d-q axis (volt)
i_{dp}, i_{qp}	Primary current in the d-q axis (amp)
R_p, R_s	Primary and secondary resistance (Ω)
L_p, L_s	Primary and secondary inductance
L_{lp}, L_{ls}	Primary and secondary leakage inductance
PFOC	Primary flux oriented control
Φ	Phase
i_a, i_b, i_c	Phase a, phase b, and phase c currents
V_a, V_b, V_c	Phase a, phase b, and phase c voltages
τ	Pole pitch
PI	Proportional integral
PID	Proportional integral derivative
KP, KI	Proportional and integral gain for PI
PWM	Pulse width modulation
q-axis	Quadrature axis
RIM	Rotor induction motor

V_{ref}^*	Reference speed
Ψ_{ref}^*	Reference flux
θ_r	Rotor angle
$V_{\text{ds}}, V_{\text{qs}}$	Secondary voltage in the d-q axis (volt)
$i_{\text{ds}}, i_{\text{qs}}$	Secondary current in the d-q axis (Ampere)
ω_{sl}	Slip frequency (rad/sec)
θ_{sl}	Slip angle
ω_e	Synchronous speed of reference frame (rad/sec)
SPWM	Sinusoidal pulse width modulation
SFOC	Secondary flux oriented control
SLIM	Single side linear induction motor
V	Velocity in (m/s)
VSI	Voltage source inverter

Chapter one

1. Introduction

Linear electric motors have many categories, among of them a linear induction motor (LIM) is the one and most popularly known linear electric motors. This motor is an alternating current (AC), asynchronous motor that works by the same general principles as ordinary induction motors. But, is typically designed to directly produce linear motion without the need of gears for rotary to linear conversion. As induction motor have stator and rotor parts, linear induction motors also have primary and secondary parts, which the primary winding corresponds to the stator winding of a rotary induction motor (RIM), while the secondary corresponds to the rotor.

Normally, the secondary part is similar to the RIM rotor, that consists a sheet of conductors, such as; copper or aluminum, with a solid back iron acting as the return path for the magnetic flux.

The way of linear induction motor construction depend on the length of primary and secondary. Based on these relative primary and secondary length, linear induction motors are categorized into two types: long secondary, short primary and short secondary, long primary. With a short secondary, the behavior is almost identical to a rotary machine, provided it is at least two poles long, but with a short primary reduction in thrust that occurs very low slip, until it is eight poles or longer[1].

In the conceptual description of the LIM operation one can notice the similarity with ordinary induction motor. However, contrary to induction motor, the LIM has the "leading edge" and an end (trailing edge). This specific characteristics of LIM produce the so called "end effect". These end effects include losses in performance and efficiency that are believed to be caused by magnetic energy being carried away and lost at the end of the primary by the relative movement of the primary and secondary. Because of this problem, linear induction motors can't run normal induction motors are able to run the motor with a near synchronous field under low load conditions. Beyond to end effect, other problem affects LIM operational system is the air gap between primary and secondary parts of the motors, which additional cause's to reduce the ability of the motors.

As a result of these, the efficiency of the linear induction motor is not as good as a conventional rotary induction motor[2]. While, as comparison with conventional motor LIM have many advantageous, due to its high-starting thrust force, high-speed operation, simple mechanical construction, no need for a gear between motor and motion devices, reduction of mechanical losses and size of motion devices, silence operation, easy maintenance, no backlash, low friction, and suitability for both low and high speed applications [3].

Thus, the LIMs are now widely used in many industrial applications with satisfactory performance including transportation, conveyor systems, actuators, material handling, pumping of liquid metals, sliding door closers, robot base movers, office automation, drop towers, and elevators [4]. In most of these applications, a short primary is on the moving part and a long secondary is on the stationary part.

Furthermore, similarities between ordinary induction motor and linear induction motors, on their driving principle, for instance field oriented controlling mechanisms.

Field Oriented Control (FOC) allows performing a fast and fully decoupled control of thrust force and secondary flux in linear induction motor (LIM) drives. However, the complexities introduced by the end effects present is a challenge for efficient control. In order to obtain such a decoupled control, FOC requires the secondary flux angular position to correctly align the primary current vector. The aim of the field-oriented control is to maintain constant the direct or d-axis secondary flux and making null the quadrature or q-axis secondary flux.

In fact, the above controlling mechanisms works with different controllers, to control parameter variations occurred during different operational conditions. Among of them, conventionally known controllers are PI and PID types. However such types of controllers are highly dependent on exact mathematical model of a motor, but it is often difficult to develop accurate mathematical model, due to unknown load variation and unavoidable parameter variations occurred by end effect, saturation, temperature variations and system disturbance. Therefore, to overcome the above problems, Fuzzy logic controller (FLC) is being used for motor control purpose. There are some advantage of fuzzy logic controller as compared to conventional PI, PID and adaptive controller such as it does not require any mathematical model, it is based on linguistic rules within if, then general structure, which is the basic of the human logic [5]. To verify the performance of the proposed controller type, modeling of a motor is must. Actually the dynamic model of the

linear induction motor is analyzed by using the dq model, as abases of the equivalent electrical circuit with end effects included, which expressed by a speed inverse of the motor and put in the magnetization branch of the equivalent electrical circuit [6], [7].

1.1. Statement of the Problem

The ordinary three phase induction motor is the most widely used electrical motor. Almost 80% of the mechanical power used by industries is provided by three phase induction motors, because of its simple and rugged construction, low cost, good operating characteristics, absence of commutator and good speed regulation. However, the one drawback of this motor for any application need additional material like gears to converts rotary to linear motions, which went additional costs and add complexity on the system usage. As using in most places, it also have some limitations to use in different applications, like in high speed transportations, application needs high thrust and direct linear motions. For this reason and additional futures model and designed of LIM as substitute ordinary induction motor is crucial.

Using such type of motor has numerus advantages, such as; high-starting thrust force, high-speed operation, simple mechanical construction, no need for a gear between motor and motion devices, reduction of mechanical losses and size of motion devices, silence operation, easy maintenance, no backlash, low friction, and suitability for both low and high speed applications. Not only these the target mitting like missal shooting is difficult when we use induction motors. However, linear induction motors can easily substitute this difficulty of ordinary motor by using appropriate controlling mechanisms [8].

As compared to the above advantageous, this motor has also a series problems in relation to parameter variation at a time of usage, and an avoidable end effect. To overcome and reduce its effect using a best relative controller is required. Hence, to control vector and speed of the motor establish modern controlling method relative to human thinking and make reliable decision fuzzy logic controller is the primary objective of this work.

1.2. Objective of the Study

1.2.1. General objectives

The main objective of this work is, modelling and simulate linear induction motor Vector Control system based on fuzzy logic Controller.

1.2.2. Specific objectives

The specific objectives of this study are outlined as follow:

1. To study different speed controlling mechanisms of linear induction motors
2. To modeling linear induction motors and simulate on MATLAB Simulink
3. Designing fuzzy logic controller vector control system
4. Compare and contrast the performance of the proposed controller with conventional PI controller

1.3. Methodology

The methodology of this thesis involved the following tasks for each specific objective. The first task is the literature reviews, where all the theoretical information regarding to linear induction motors with the controlling mechanisms taken and it's a comparison of the previous similar research studied. The second task followed to this is modeling and simulating linear induction motors, within applying sinusoidal input without using any controlling mechanisms.

Then after, designing field oriented vector control mechanisms, depending on the previous modeled motors. Following to this interlinking the vector control already developed to sinusoidal pulse width modulation for switching inverter to deriving the motors. After these developing PI controller to control the speed of the motor running in different condition and put the result of the output graphical from a MATLAB.

The fifth, main task is designing and developing fuzzy logic controller rule based to control the motor in different conditions. Lastly comparing and contrasting the above controller's performances following the reference signal tracking and abilities of minimizing steady state errors.

1.4. Scope of the work

Realize the characteristics of the proposed motor with relating ordinary induction motors based on their similarity and differences. Then build a model representing motors and simulate the modeled on the mat lab software to check the performance of the motors. After checking the capacity of the motor model and design vector control for controlling the parameters of the motor and simulate this also to check the ability of the control applied with speed controller PI. After all, using fuzzy logic toolbox in the Mat lab/Simulink environment a fuzzy logic controller suitable for the application understudy is build and embedded in the control system circuit of the above mentioned model instead of the PI model. The performance of the proposed FLC will compared with an established conventional PI controller. Furthermore, a comparison with a very well-known work was carried out.

1.5. Literature review

Since linear induction motor is a very well known, some researchers are interested on designed and developed different controlling mechanisms to control many parametric variations occurred at a time of operation. Among of them a few are presented as review in this thesis.

H. Shadabi and A. Rahnama Sadat [9] in this paper the speed control method of LIM, which lead to optimal control characteristic of motor such as thrust, flux and current, is proposed. The performance of the proposed DTFC method is analyzed with considering end-effect. DTFC is one of the improved control methods which employ several PI controllers. Proper adjustment of coefficients of the PI controller plays an important role in the satisfactory performance of control system that are determined using MATLAB optimization functions. In this paper tedious works are presented, which are keeping of parameter variation and adjusting of controllers' coefficients.

Hou Yunhai and Wang Yuhua [10] proposed to apply the neuron net control method into the slip frequency vector control system of the Linear Induction Motor. In this thesis, the neuron adaptive controller is used as speed controller, and conventional PI controller as current controller. The neuron net has ability to self-learning and adaptation, so its application into control does not depends on mathematic model of control object, and the neuron net controller can overcome the defect of less robustness of the conventional PI controller while changing of motor parameters. The simulation experiment has been made under the condition of starting and loading of motor. The paper only compares the speed response of the proposed controller and PI controller with only

considering loading and unloading conditions, but not taken consideration of parameter variation and load variation.

F. Korkmaz, I. Topaloglu and R. Gurbuz [8], this paper describes Simulink model of direct thrust controlled linear induction motor with end effect for electromagnetic launcher system and presents a simple and effective scheme for direct thrust control of a linear induction motor for this the paper deals with modeling of an improved DTC scheme for ELS. The Simulink model of single sided linear induction motor with end effect developed to realize the direct thrust control. To show the effectiveness of the improved system, simulation results are presented using commercially available software package MATLAB/Simulink. In this paper the simulation of the motor controlling capability is focused only on single application, as well as to give a brief explanation of controller ability the paper is not take a comparison of proposed controller with relative controller types.

Mohammad sarvi and Hassan zamani [11], this paper presents a sensor less system drive on primary flux oriented control (PFOC) and secondary flux oriented control (SFOC) for the linear induction motor (LIM) with taking into account end effect. Extended kalman filter (EKF) is applied to estimate LIM speed by measuring motor voltages and currents. In order to achieve desirable dynamic and robustness motor performance instead of traditional PI controller, a fuzzy PI controller is used for speed regulation in LIM vector control. Transient and steady state responses of proposed controller under load thrust variations and speed command are studied. Also characteristics and performances of primary flux oriented control (PFOC) and secondary flux oriented control (SFOC) for the linear induction motor are compared with each other. In order to evaluate the proposed method, simulations are performed in MATLAB/SIMULIN. In this paper the comparison between two controllers is established in well manner including different operational problems, however the work was not under taken on compensation of an end effect problem. To overcoming almost all the above mentioned research gaps, in thesis a well-organized, fuzzy-logic-based speed control of vector Controlled linear induction Motor end effect compensated can be designed to replaces the traditional PI controller. Under the work robustness of proposed control over replacing traditional PI controller is checked using different motor operational conditions. During the checkup time variation of parameters of motors and controller gain adjacent are not series problems, when using the fuzzy logic controller (FLC) in places of

conventional. These advantages and additional futures of FLC discussed under introduction makes it more robust and, hence, found to be a suitable replacement of the PI controller for the high performance drive systems.

1.6. Thesis organization

Having familiarized the objectives of this thesis, the part of this study assured to implement the proposed goals and tasks. To achieving it this thesis, comprised of six chapters, is organized as follows.

chapter 2, deals about the basic construction system and basic principle of operation of the SLIM is discussed by analogy with the conventional rotary induction motor are discussed. Then modeling a motor using approximated equivalent circuit of primary and secondary of a machine and develop what expressed in a mathematical form on a MATLAB packaged Simulink software and also discussed in a detail away of modeling and problem exit on a motor as compare to within ordinary induction motors.

In Chapter 3, developed a vector controlling mechanisms for a motor and also presented voltage and current transformations from three phase to two phase and the reverse is included. In addition to this, under this chapter discussions about semiconductor devices and their switching capability present in detailed, then after three phase inverter and switching pulse using PWM are presented.

Chapter 4, in this chapter designing and description of PI and fuzzy logic controllers are presented, furthermore the process of fuzzy logic controller is discussed in detailed. This part includes the introduction of fuzzy sets, fuzzy operators, fuzzy rules, fuzzification, fuzzy inference, and defuzzification.

Chapter 5, in this chapter result and discussions of a developed system using different conditions are presented, not only this comparison controller ability regarding handling changing conditions are conducted and put in different format.

Finally, in Chapter 6, a set of conclusion's and future work related to this research are clarified.

Chapter two

2. Construction and operation principles of linear induction motors

2.1. Construction of linear induction motors

Linear Induction motor(LIM) is normally referred to as a special purpose motor that is in use to achieve rectilinear motion rather than rotational motion as in the case of conventional motors. This is quite an engineering transitive, to convert a general motor for a special purpose with more or less similar working principle, thus enhancing its versatility of operation. Like ordinary induction motors LIM also have two parts stator as primary and rotor as secondary.

For understanding the construction of this motor, we will first take a look at the construction of Induction Motor as shown in figure (2-1) below.

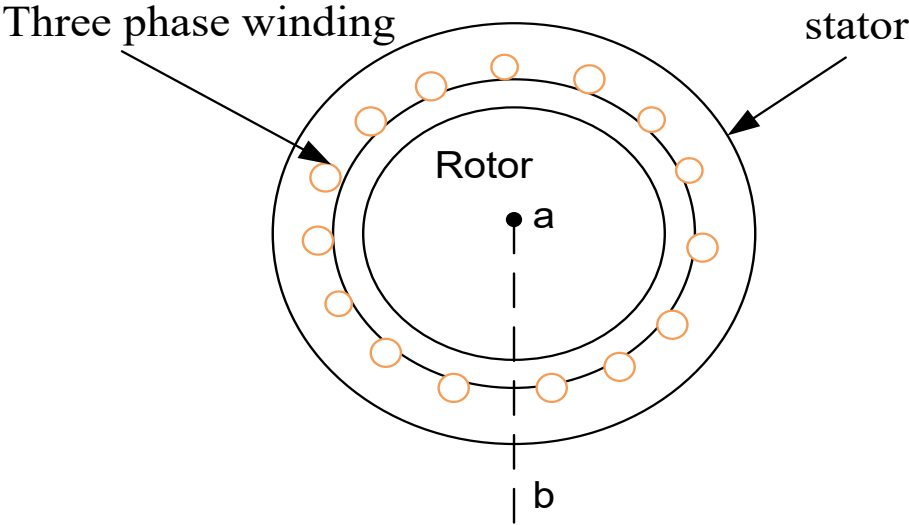


Figure 2.1 Ordinary induction motor [12]

If we stator cut across the line ab, and make it laid flat then the stator be like as shown in the figure below.

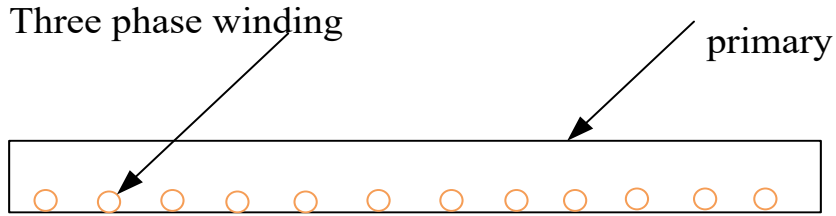


Figure 2.2 Imaginary split out stator of ordinary motor for primary LIM [12]

This is which makes the Primary of a Linear Induction Motor. So, Primary of Linear Induction Motor is flat and three phase winding is wound on it. Then, if we make the rotor of Induction Motor flat it will be nothing but a sheet of flat Aluminum, which is called the secondary of Linear Induction Motor (LIM) as shown on figure (2-3).

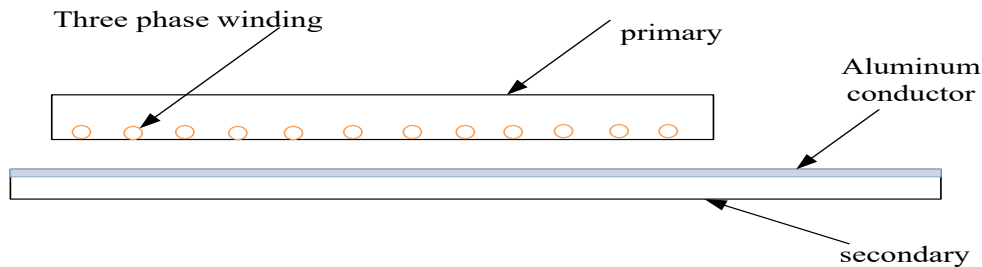


Figure 2.3 Single side linear induction motor (SLIM) [12]

Likewise, if the circular stator is cut into two sections and flattened, the motor becomes a double-sided linear induction motor (DLIM). The DLIM and SLIM both require a two or three-phase stator (primary) winding and a flat metallic or conductive plate-type armature (secondary).

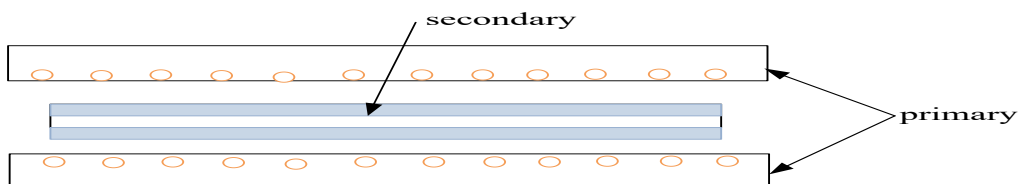


Figure 2.4 Double sided linear induction motor (DLIM) [12]

In practice, the primary or stator of a LIM consists of rectangular slotted structure formed by a stack of steel laminations. Within the slots of the primary stack are laid the poly- phase windings to produce the linearly traveling magnetic field, just like the rotating magnetic field in rotary induction motor, produced by the poly- phase stator windings. The secondary of the LIM, or rotor

which is an aluminum sheet (copper), with or without a solid back iron plate, completes the magnetic circuit and creates the magnetic flux linkage across the air gap. The secondary back iron plate within secondary sheet plays an important role in performance of SLIMS. This material used as provides a return path for the primary of the motor and employed as a mechanical support for the secondary sheet.

Depending upon the use, the linear induction machine can be one of the following two types:

➤ **Short Primary**

The primary of the motor is short and the secondary long shown on figure (2-5). This type is useful when the total distance to be travelled is large. In such type over heating of secondary is eliminated because of the continuous movement of the primary over cold part of the secondary, leaving behind the heated part. In this case primary is a mover and the secondary is stationary.

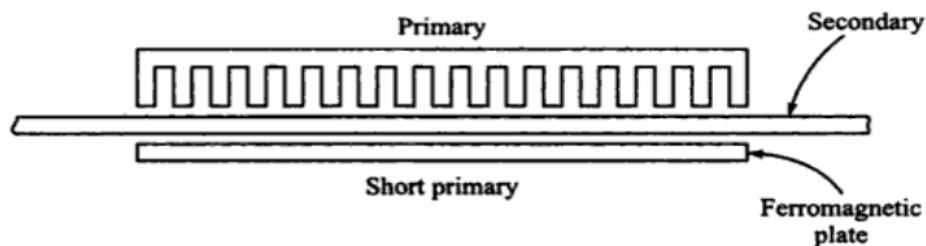


Figure 2.5 Short primary type LIM

➤ **Short Secondary**

The secondary is short in comparison with primary as shown on the figure (2-6). This type is useful when the travel is limited. The long primary and short secondary has the following drawbacks:

- ✓ Long primary is uneconomical as it requires a long three phase primary windings to be wound.
- ✓ Only that part of the primary windings which are adjacent the secondary are effective at any one time.



Figure 2.6 Short secondary type LIM

2.2. Working principles of linear induction motor

Operational principle of linear induction motor is the same as ordinary induction motor operation. As obviously known, for correct operational system input supply is directly given to stator parts of squirrel cage induction motors. Likewise, in LIM this supply is apply to the primary parts of the motors, for induced travelling flux across the coil, instead of rotating 3phase flux on conventional motor. Traveling speed of this field can be express using the following equation:

$$V_s = 2 * f_s * \tau_p \text{ m/sec} \quad (2.1)$$

Where:

V_s is the velocity of the linear traveling field in m/sec ,

τ_p is pole pitch in meter, f_s is supply frequency(Hz)

It is important to note that, the linear speed does not depend upon the number of poles, but as we have seen in above equation (2.1) it is dependent only on the pole pitch. The pole pitch used in this equation, is defined as the distance found between neighboring pole and expressed as the ratio of primary side length to number of poles a motor have.

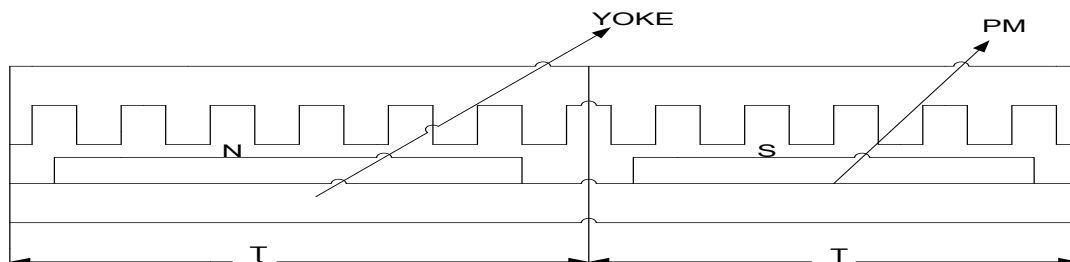


Figure 2.7 Pole pitch indication between two poles

Due to the relative motion between traveling flux of primary and secondary conductor, magnetic field is induced a voltage on this parts, which is a causes of induced currents on the secondary parts of motors, used for produces a second traveling magnetic field. The interaction of these two magnetic field produces a force, which tends to move primary along of the secondary.

Because of open ended construction of linear induction motor, it display unfamiliar effect known as end effect. This effect can be grouped into static end effect and dynamic end effect. In static end effect the mutual inductance of the phase windings are not equal to one another. This leads to asymmetric flux distribution in the air gap and gives rise to unequal induced voltages in the phase winding. The dynamic end effect occurs due to the relative motion between primary and secondary.

As the primary moves over the secondary at every instant, a new secondary conductor is coming under the leading edge of the primary, while one old secondary conductor is leaving the trailing edge of the primary. The conductor coming under the leading edge opposes the magnetic flux in the air gap, while the conductor leaving the trailing edge tries to maintain the flux. Therefore the flux distribution in the air gap is distorted. The flux weaker in the leading edge region as compared to the trailing edge. It also leads to braking action especially at lower values of slip. Thus linear induction motor working efficiency is lower than rotary induction motors. The factor reduces the efficiency of LIM as comparing with induction motor is an existence an avoidable factor i.e. end effect, but this factor can be reduced with an increase in the number of poles, in the LIM. This is because more poles tend to share the constant end-effect a loss between them, resulting in a better performing machine. Thus, it would be advantageous to have a machine with a large number of pole.

2.3. Dynamic D-Q, modeling of linear induction motor(LIM)

Dynamic model describes the transient as well as the steady state behavior of the linear induction motors. The model can be used to simulate the linear induction motor drives and evaluate their transient performances including that of using scalar control, vector control, sliding mode control, adaptive control and direct force control(DFC) techniques.

Beyond to the transient performance evaluation, the main task for modeling and simulating linear induction motor is check the existence of the following problems and minimize if it present. Which are:

- Draws of large current
- Produce voltage dips
- Oscillatory of force
- Injection of harmonics on the supply side

To resolve of these problems various models have been developed, among of them the q-d axis model for the study of transient behavior has been well tested and proven to be reliable and accurate.

From the three commonly used induction motor (D,Q) modeling reference frame, i.e. the stationary reference frame, rotating reference frame and synchronously reference frames. Synchronous reference frame is preferable, due to the steady state variables constant, do not vary sinusoidal with time and advantageous for studying multi-machine system. While to starting modeling and analyzing of motor using this reference frame, some initial requirement should be satisfied, for instance transformation of three phase conventional power supply to two phase or D,Q power supply. Why because in dynamic modeling of the machine three phase machine is represented by two phase equivalent machine[13].

2.4. Reference frame Transformation (3- Φ to 2- Φ Transformations)

As I point above for induction motor the dynamic model of linear induction motor can be derived, if the equivalence between three-phase and two phase machine is studied and their transformation is satisfied. The equivalence is based on the quantity of magneto motive force produced in two-phase and three phase windings along with equal current magnitudes. Assuming that each of the three-phase winding has N_s turns per phase and equal currents magnitudes, the two-phase winding will have $\frac{3 \cdot N_s}{2}$, turns per phase for MMF equality. The d and q axes MMF are found by resolving MMF of the three-phase to two axes. The common term, the number of turns is cancelled on both sides of equations leaving behind the current equalities. The q axis assumed to be lagging a -axis by θ . The relationship between dqo and , abc currents and voltages are as follows.

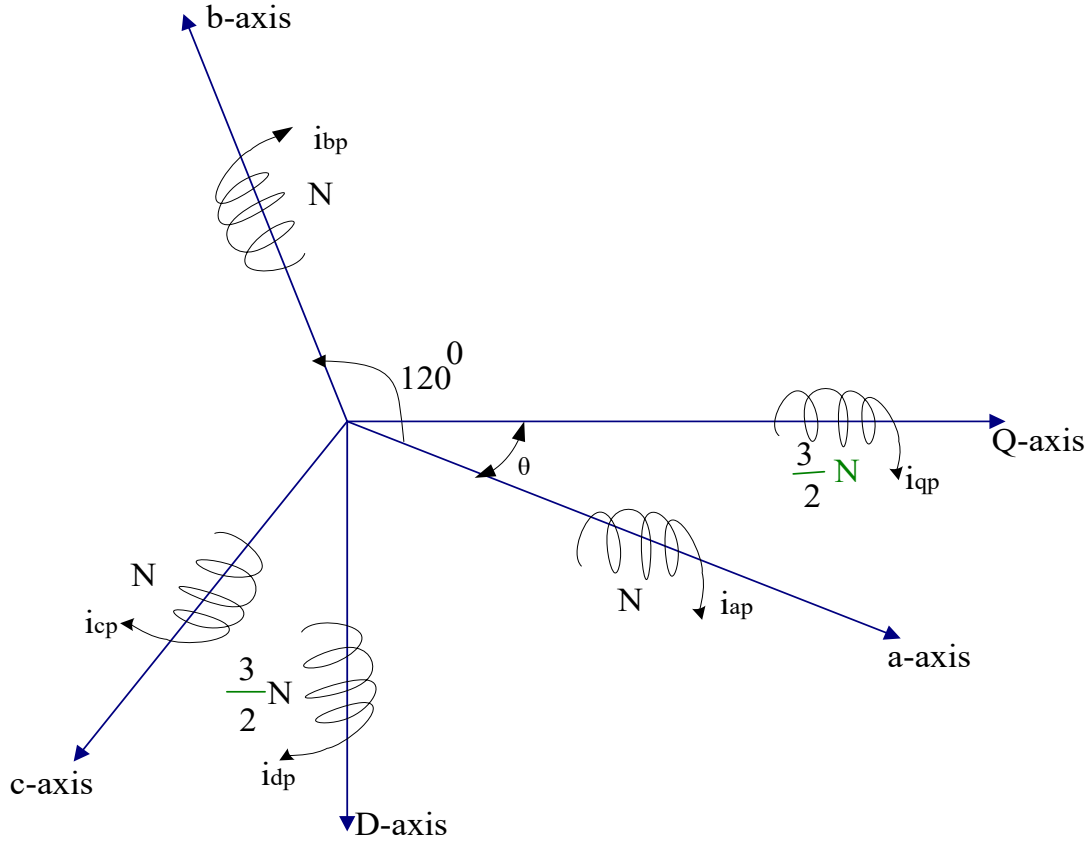


Figure 2.8 Stationary frame a-b-c to D-Q axis transformation [13]

Let the magneto motive force mmf = $f = NI$

This gives us:

$$f_q = \frac{3 \cdot i_q}{2} N = Ni_a \cos(\theta) + Ni_b \cos(\theta - \frac{2\pi}{3}) + Ni_c \cos(\theta + \frac{2\pi}{3}) \quad (2.2)$$

$$f_d = \frac{3 \cdot i_d}{2} N = Ni_a \sin(\theta) + Ni_b \sin(\theta - \frac{2\pi}{3}) + Ni_c \sin(\theta + \frac{2\pi}{3}) \quad (2.3)$$

When we removing N from both sides of the above equation we obtain the following relationship:

$$i_q = \frac{2}{3} (\cos(\theta) i_a + \cos(\theta - \frac{2\pi}{3}) i_b + \cos(\theta + \frac{2\pi}{3}) i_c) \quad (2.4)$$

$$i_d = \frac{2}{3} (\sin(\theta) i_a + \sin(\theta - \frac{2\pi}{3}) i_b + \sin(\theta + \frac{2\pi}{3}) i_c) \quad (2.5)$$

The above equations (2.4) and (2.5) can be rewritten in a matrix form, like as follows:

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2.6)$$

Equation (2.6) will be expressed in a compact form by

$$i_{qd} = [T_{abc}] i_{abc} \quad (2.7)$$

Where:

$$i_{qd} = [i_q \quad i_d]^t \quad (2.8)$$

$$i_{abc} = [i_a \quad i_b \quad i_c]^t \quad (2.9)$$

And transformation from dq to abc or inverse can be expressed as :

$$[T_{abc}] = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \quad (2.10)$$

The compact inverse transformation of the above equation in matrix form as:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} \quad (2.11)$$

Like of the above three phase to two phase compact form two phase to three phase written as:

$$i_{abc} = [T_{abc}]^{-1} i_{qd} \quad (2.12)$$

Where:

$$[T_{abc}]^{-1} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \quad (2.13)$$

When q – axis is aligning on a – axis, the phase difference between the two axis are equal to zero, i.e. $\theta = 0^0$, due to this condition the relationship between dq and abc is changed to equation (2.14). In short this transformation is called stationary reference frame or (α, β) transformation or Clark transform.

$$\begin{bmatrix} i_q^s \\ i_d^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2.14)$$

Where:

$$[T_{abc}] = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \quad (2.15)$$

Inverse transformation from two phase to three phase looks like as follows:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_q^s \\ i_d^s \end{bmatrix} \quad (2.16)$$

Where :

$$[T_{abc}]^{-1} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \quad (2.17)$$

The above transformation is not used for only current transformation, while it can also use for voltage transformation, in similar manner with current transformation equations as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} v_q \\ v_d \end{bmatrix} \quad (2.18)$$

In addition to this, three phase to two phase voltage transformation like current transformation looks like:

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2.19)$$

2.5. D-Q equivalent circuit

The second and most important requirement for analyzing the dynamic model of LIM are D-Q equivalent circuits with considering end effect as a general. The end effect problem included on the circuit is a cause created due to relative motion between a primary of finite length and an infinite long secondary [14]. While, when the primary of a LIM does not move, there is no difference in the equivalent circuits of LIM and RIM, therefore we do not consider the existence of an end effect. However, if the primary coil of LIM moves, the equivalent circuit of RIM does not better, and the failure is usually attributed to the end effect. Since the primary coil set of the LIM moves, a new field penetrates into the reaction rail in the entry area, whereas the existing field disappears at the exit area of the primary core. Both generation and disappearance of the fields create the eddy current in the secondary. The eddy current in the entry grows very rapidly to mirror the primary current, nullifying the primary MMF and reducing the flux to nearly zero at entry [7]. This conceptual description is shown on the following figure.

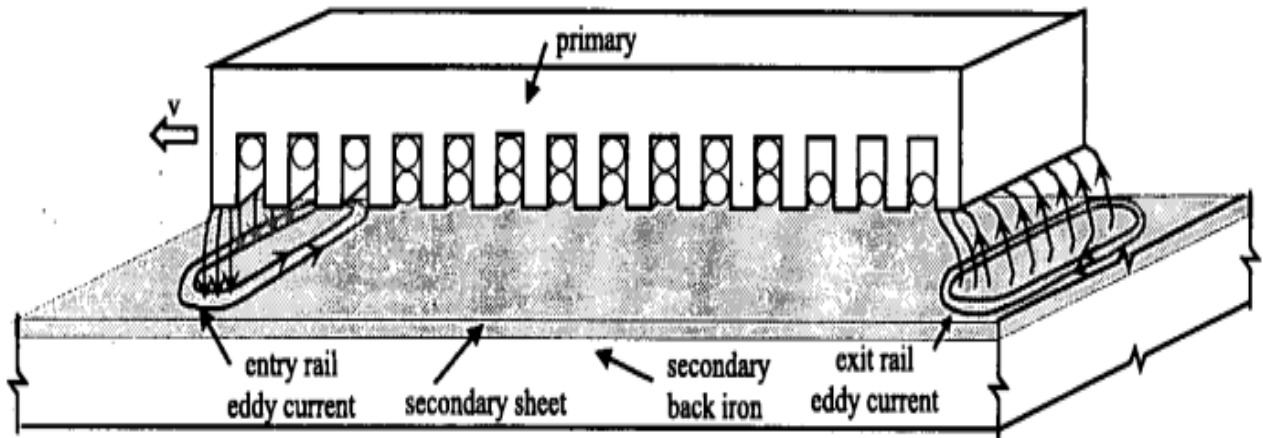


Figure 2.9 Side view of LIM to reaction plate [8]

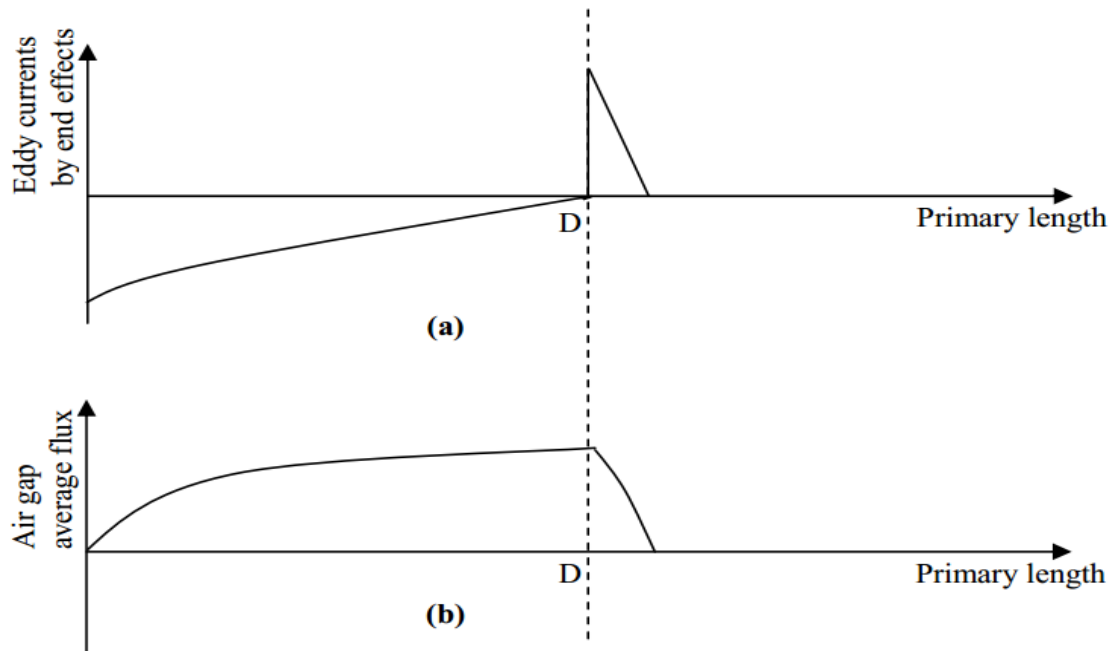
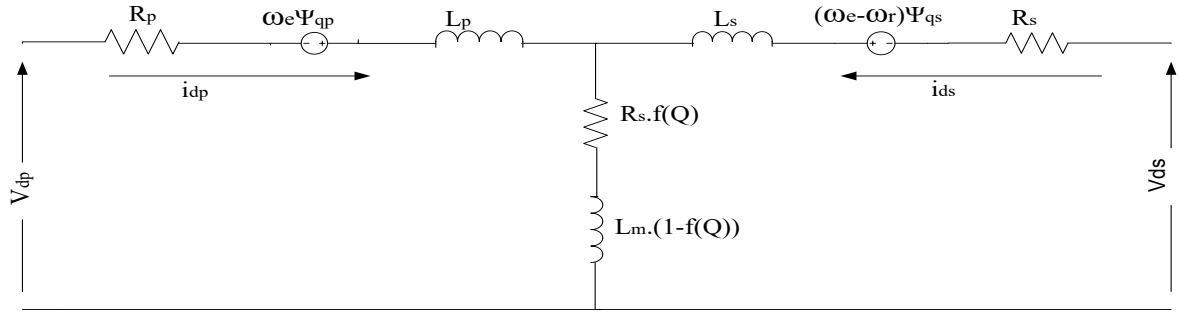


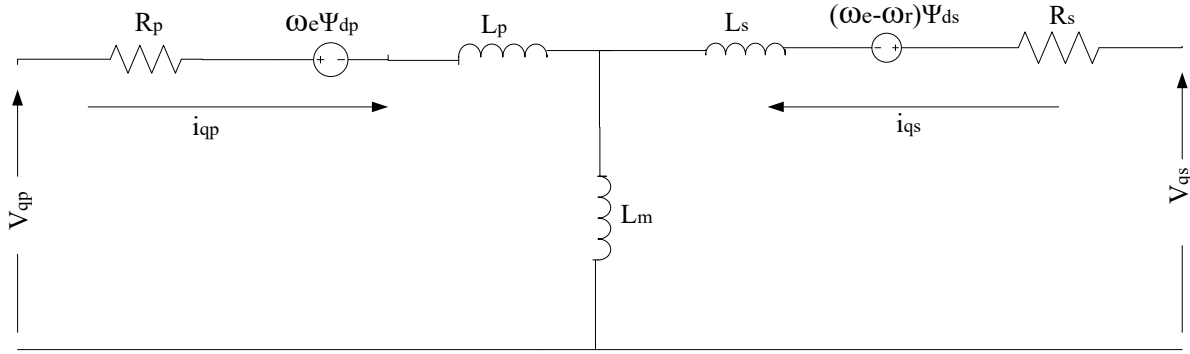
Figure 2.10 (a) Polarity and decaying of the entry and exit eddy currents
(b) air gap magnetic flux [7]

With the above intention the q-axis equivalent circuit of the linear induction motor is identical to the q-axis equivalent circuit of the traditional induction motor, i.e. the parameters do not vary with the end effects. However, the d-axis entry eddy currents affect the air gap flux by decreasing, Ψ_{ds} . Therefore, the d-axis equivalent circuit of the traditional induction motor cannot be used in the linear induction motor analysis when the end effects are considered.

Figure (2-11 (a)) shows the d-axis equivalent, wherein the magnetization branch differs from that of the traditional induction motor. In figure (2-11 (b)), the equivalent circuit is the same as that we will use in the traditional induction motor. From both dq equivalent circuit of the LIM, shown on figure (2-11), the primary and secondary voltage equations in a synchronous reference system aligned with the secondary flux are given by [8].



(a)



(b)

Figure 2.11 (a) d-axis equivalent circuit and (b) q-axis equivalent circuit of LIM [15]

Using the above equivalent circuits, the primary and secondary voltage equations in the synchronous reference frame are given as:

$$V_{qp} = R_p i_{qp} + \frac{d}{dt} \Psi_{qp} + \omega_e \Psi_{dp} \quad (2.20)$$

$$V_{dp} = R_p i_{dp} + R_s f(Q) (i_{dp} + i_{ds}) + \frac{d}{dt} \Psi_{dp} - \omega_e \Psi_{qp} \quad (2.21)$$

$$V_{ds} = 0 = R_s i_{ds} + R_s f(Q) (i_{dp} + i_{ds}) + \frac{d}{dt} \Psi_{ds} - (\omega_e - \omega_r) \Psi_{qs} \quad (2.22)$$

$$V_{qs} = 0 = R_s i_{qs} + \frac{d}{dt} \Psi_{qs} + (\omega_e - \omega_r) \Psi_{ds} \quad (2.23)$$

The variable $f(Q)$ in the above equations is expressed as:

$$f(Q) = \frac{1-e^{-Q}}{Q} \quad (2.24)$$

Q , in above equations is expressed by Duncan, which is a factor related to primary length and speed for evaluating end-effect. According to factor, in low speed condition, end effect can be neglected. Therefore, in low speed there are no any change in flux and magnetization inductance. On the contrary, with increasing speed, end-effect will be stronger more and will reduce flux and magnetization inductance of the LIM. Its equation relates like below:

$$Q = \frac{DR_s}{(L_{ls}+L_m)V} \quad (2.25)$$

Where the relation between linear speed and rotor angular speed in LIM can be written as follow:

$$\omega_r = \frac{\pi}{\tau} V \quad (2.26)$$

The primary and the secondary flux linkages in the d-q axes are given by:

$$\Psi_{dp} = [L_p - L_m f(Q)] i_{dp} + L_m [1 - f(Q)] i_{ds} \quad (2.27)$$

$$\Psi_{qp} = L_p i_{qp} + L_m i_{qs} \quad (2.28)$$

$$\Psi_{ds} = L_m [1 - f(Q)] i_{dp} + [L_s - L_m f(Q)] i_{ds} \quad (2.29)$$

$$\Psi_{qs} = L_s i_{qs} + L_m i_{qp} \quad (2.30)$$

From the above equations (2.20-2.23), the flux linkage relationships with d-q axis voltages is drive as follow:

$$\Psi_{dp} = \int (V_{dp} - R_p i_{dp} - R_s f(Q)(i_{dp} + i_{ds}) + \omega_e \Psi_{qp}) dt \quad (2.31)$$

$$\Psi_{qp} = \int (V_{qp} - R_p i_{qp} - \omega_e \Psi_{dp}) dt \quad (2.32)$$

$$\Psi_{ds} = \int (V_{ds} - R_s i_{ds} - R_s f(Q)(i_{dp} + i_{ds}) + (\omega_e - \omega_r) \Psi_{qs}) dt \quad (2.33)$$

$$\Psi_{qs} = \int (V_{qs} - R_s i_{qs} - (\omega_e - \omega_r) \Psi_{ds}) dt \quad (2.34)$$

Recall equations (2.27-2.30), the primary and secondary currents are given by:

$$i_{dp} = \frac{\{L_s - L_m f(Q)\} \Psi_{dp} - L_m \{1 - f(Q)\} \Psi_{ds}}{\{L_s - L_m f(Q)\} \{L_s - L_m f(Q)\} - L_m^2 \{1 - f(Q)\}^2} \quad (2.35)$$

$$i_{qp} = \frac{\Psi_{qp}L_s - L_m\Psi_{qs}}{L_sL_p - L_m^2} \quad (2.36)$$

$$i_{ds} = \frac{\{L_p - L_m f(Q)\}\Psi_{ds} - L_m\{1 - f(Q)\}\Psi_{dp}}{\{L_p - L_m f(Q)\}\{L_s - L_m f(Q)\} - L_m^2\{1 - f(Q)\}^2} \quad (2.37)$$

$$i_{qs} = \frac{L_p\Psi_{qs} - L_m\Psi_{qp}}{L_sL_p - L_m^2} \quad (2.38)$$

The thrust force and motion equation are expressed in the following equations

$$F_e = \left(\frac{3}{2}\right) \left(\frac{n_p}{2\pi}\right) (\Psi_{dp} i_{qp} - \Psi_{qp} i_{dp}) \quad (2.39)$$

In other way:

$$F_e = M \frac{dv}{dt} + F_f + F_L \quad (2.40)$$

From the above, motion equation can be rearranged as:

$$V = \frac{1}{M} \int (F_e - F_f - F_L) dt \quad (2.41)$$

Using the above mentioned equations, the MATLAB modeling of the linear induction motor as a general is the following:

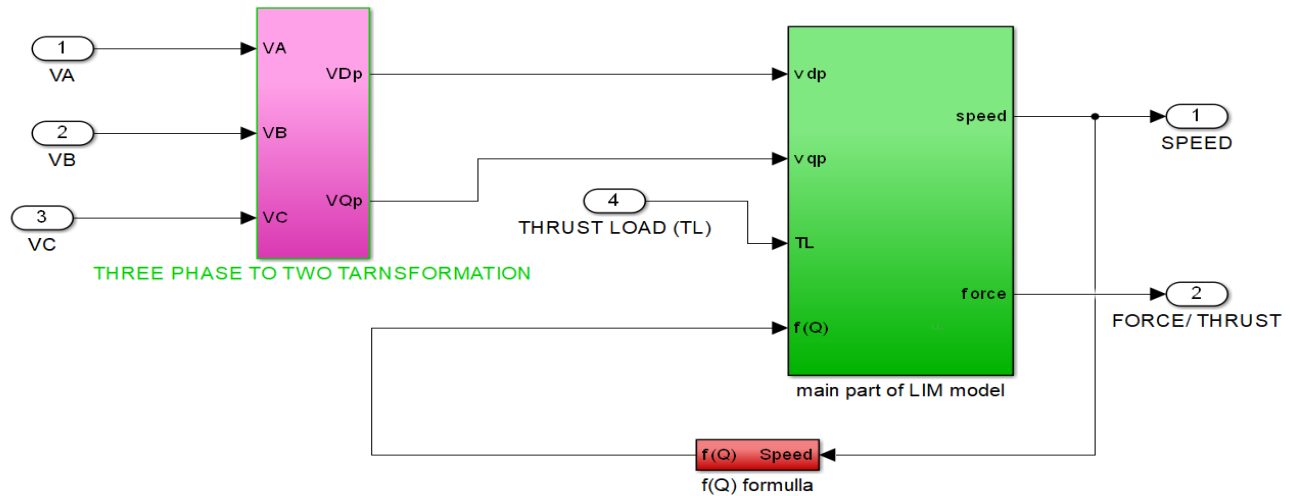


Figure 2.12 Over all model of linear induction motor

Internal structure of linear induction motor model is as shown in the figure below.

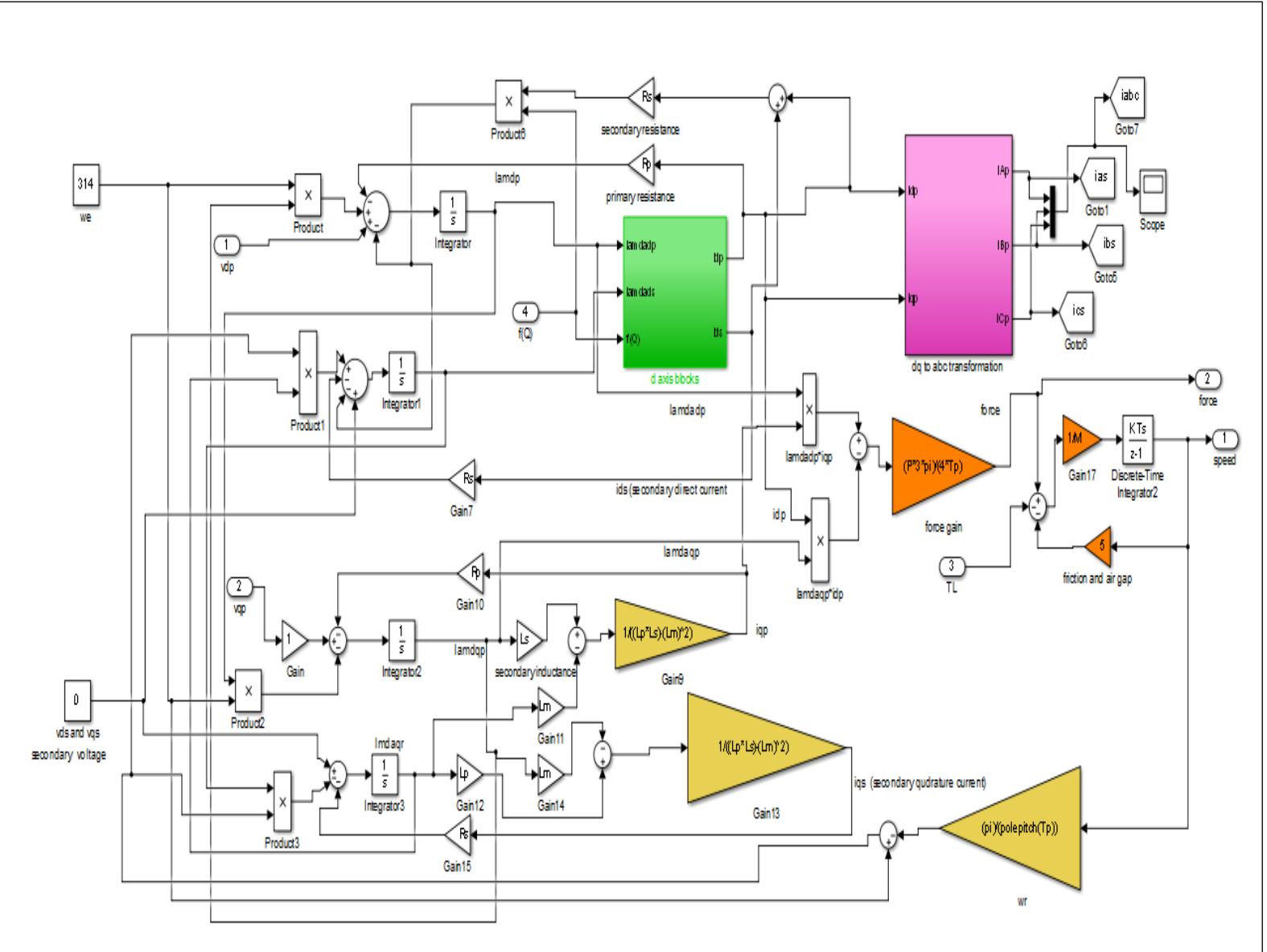


Figure 2.13 Internal structure of linear induction motor model blocks

The d- axis blocks for the internal structure of figure (2-13), is as shown in the figure below.

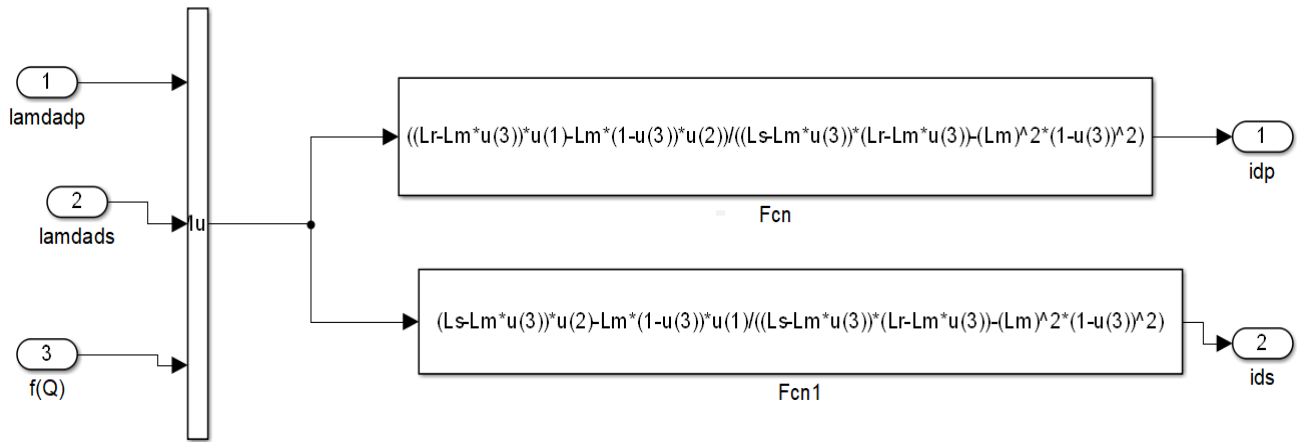


Figure 2.14 Primary and secondary current formula block on MATLAB Simulink

End effect, $f(Q)$ formula internal structure from figure(2-12) is as shown below:

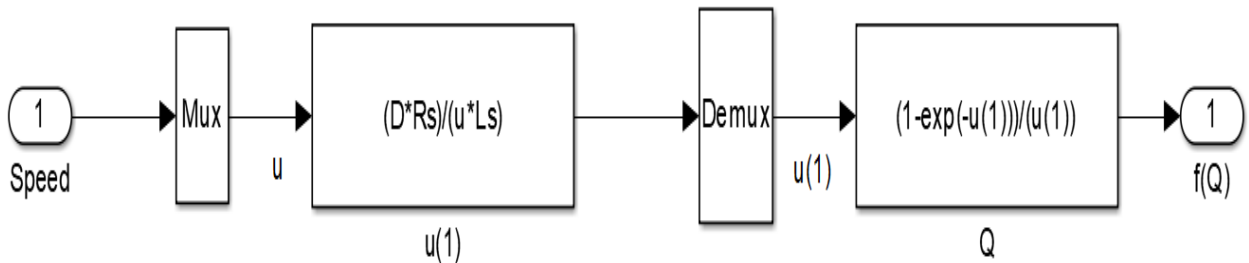


Figure 2.15 End effect formula on Simulink blocks

Internal blocks of three phase to two phase transformation block from figure(2-12) and dq transformation to abc block from figure (2-13) are shown on the following figures.

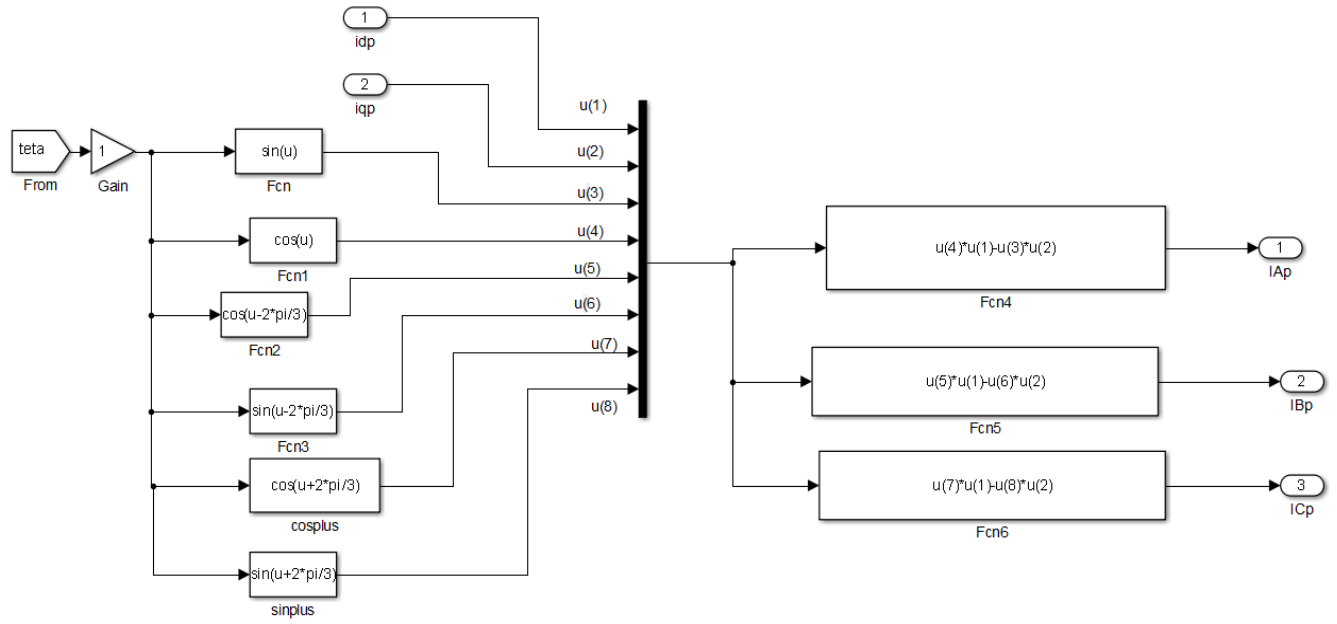


Figure 2.16 Internal blocks of dq to abc transformations

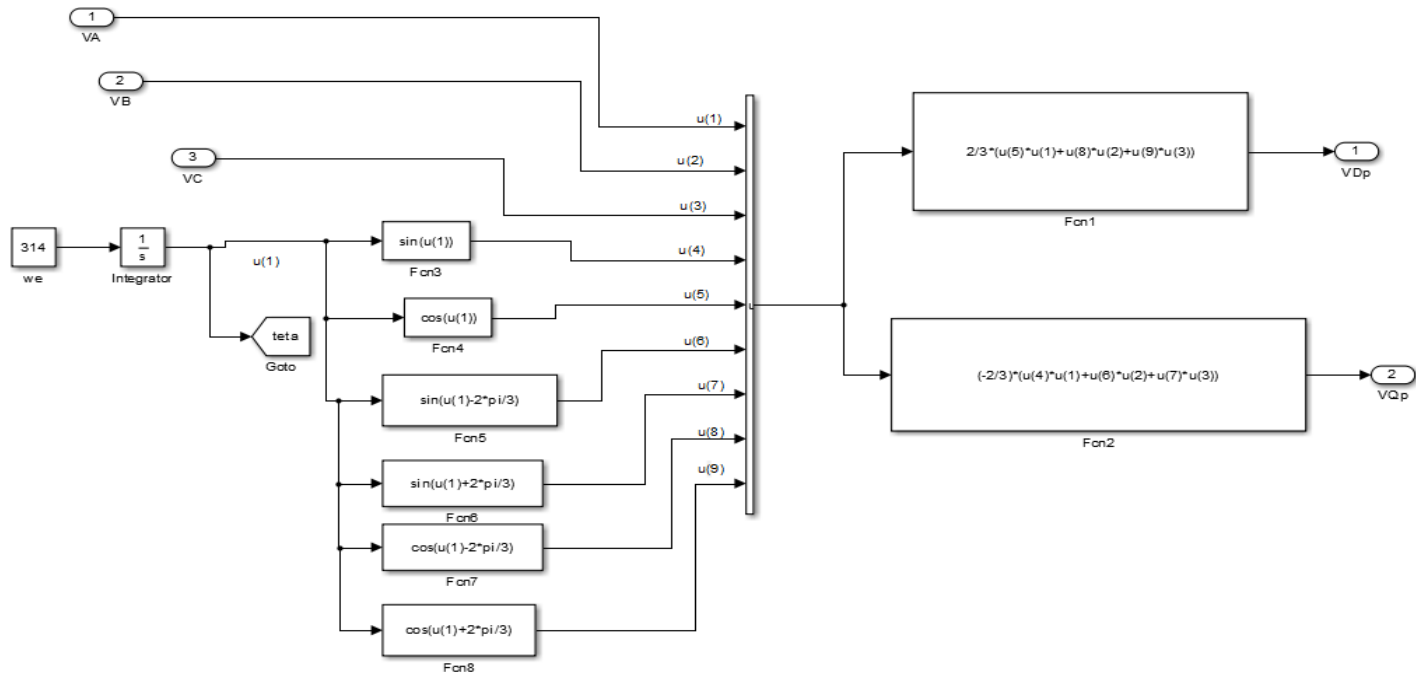


Figure 2.17 Internal structure of three phase to two transformation block

Chapter three

3. Vector control or field oriented control for linear induction motor

The concept of field orientation control, proposed by Hasse in 1969 and Blaschke in 1972, constitutes, arguably, the most important paradigm in the theory and practice of control of induction motors [16]. Now days the controlling mechanisms get the most performing and accepted control strategy in a real world for driving RIM, with offers a number of benefits including speed control over a wide range, precise speed regulation, fast dynamic response and operation of above base speed. For this reason it has been here directly adopted for LIM drives within similar driving principles to RIMs, but its control characteristics are more complicated than the RIM , due to the existence of end effect on a motor [17]. Likewise to induction motor, principal operation of the field oriented control scheme enables to control linear induction motor in the same way as separately excitation DC motors.

In DC machine 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 [18, 19].

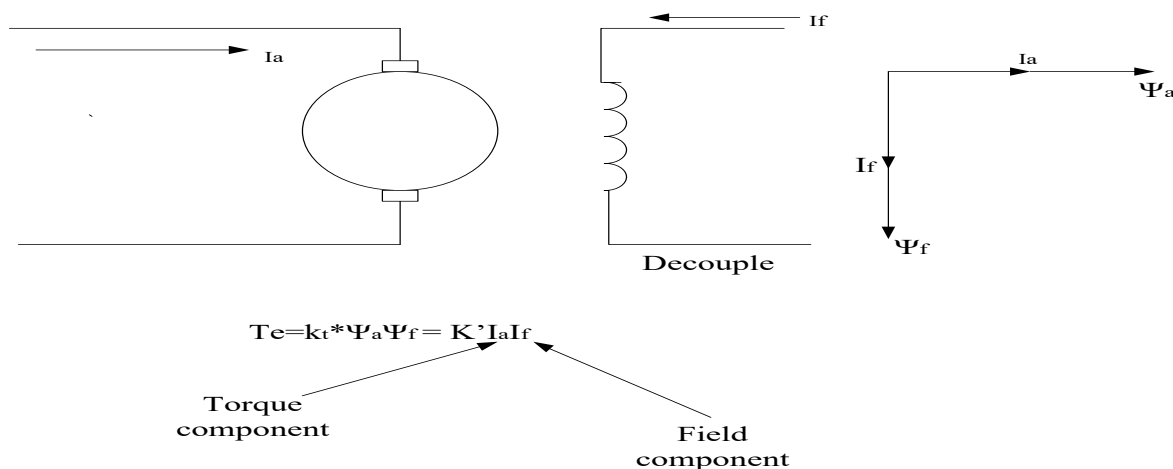


Figure 3.1 Separately excited dc motor from [20]

However an AC machine is not simple as DC machine, because due to the existence interaction between stator and the rotor fields, orientation found in the two field is not held 90 degree appears, which is varying with the operating conditions [21]. But we can obtain DC machine-like performance in holding a fixed and orthogonal orientation between the stator field and rotor or secondary fields in an AC machine. Which is achieved by orienting the stator current with respect to the rotor flux so as to attain independently controlled flux and torque. Such, a control scheme is called flux-oriented control or vector control.

Like ways the ordinary induction motor orthogonal making between the two fields, for LIM also applicable in which, thrust control of linear induction motor is achieved by controlling the thrust current component and flux current component control secondary flux independently. These controlling mechanism is only satisfied when thrust and flux are properly decouple, however due to speed dependent parameters i.e. new resistance and inductance included in the magnetizing branch decoupling thrust and flux purely is difficult [22]. However, to applying similar controlling principle of ordinary induction motor to LIM, decoupling of these currents will be apply by constant the d-axis secondary flux and makes zero the q-axis secondary flux initially. Where, this performance is done by using a d-q rotating reference frame synchronously with the rotor flux space vector.

As a general there are two types of vector controlling mechanisms for deriving AC motors:

- ❖ Indirect vector control (indirect field oriented control) and
- ❖ Direct vector control (direct field oriented control).

3.1. Direct field oriented control (DFOC) and indirect field oriented control(IFOC)

In DFOC strategy secondary flux vector is either measured by means of a flux sensor mounted in the air gap or by using the voltage equations starting from the electrical machine parameters. But in case of IFOC secondary flux vector is estimated using the field oriented equations (current mode) requiring a secondary speed measurement. Among both schemes, IFOC is more commonly used, because in closed loop mode it can easily operate thought the speed range from zero speed to high speed field -waking. For high performance drive the indirect method of vector control is preferred [18]. The indirect vector control method is essentially same as the direct

vector control except the unit vector signals θ_e is generated in an indirect manner using the measured speed ω_r and the slip speed ω_{sl} . To implement the indirect vector control strategy, it necessary to take the following dynamic equations into consideration with respect to phasor diagram, which is shown in figure(3-2). This figure explains the fundamental principles of indirect vector control with the help of a phaser diagram. Synchronously rotating axes $d^e - q^e$ are rotating ahead of the $d^s - q^s$ axes by the positive slip angle θ_{sl} corresponding to slip frequency ω_{sl} .

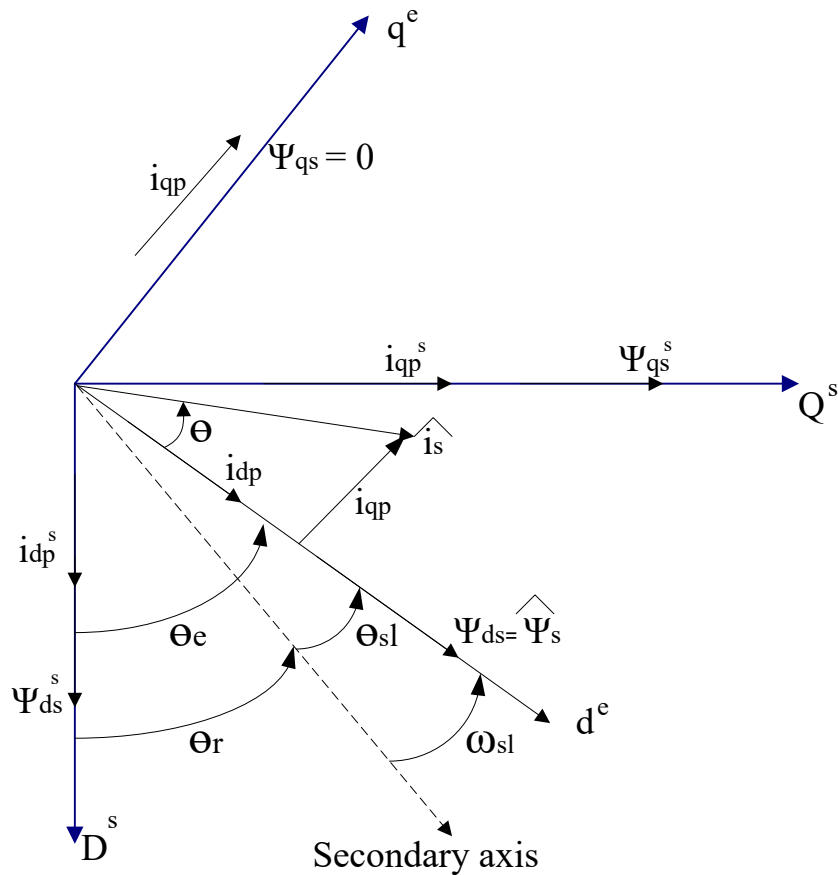


Figure 3.2 Phasor diagram indirect vector control [23]

Where:

The apostrophe , s and e, on above diagram represents stationary and synchronous reference frame respectively.

$$\theta_e = \sqrt{\omega_e dt} = \sqrt{(\omega_r + \omega_{sl})dt} = \theta_r + \theta_{sl} \quad (3.1)$$

For decoupling control, the primary flux component of current i_{dp} , should be aligned on the d^e axis, and the thrust component of current i_{qp} should be on q^e axis, that leads to

$$\Psi_{qs} = 0 \quad (3.2)$$

and

$$\Psi_{ds} = \widehat{\Psi}_s = \text{constant} \quad (3.3)$$

These equation(3.2) and (3.3), are basic descriptions of indirect vector control. Using this description we can get equation (3.1), which used for transformations of three phase to two phase and a reverse, following the steps shown below.

Measure the stator phase currents i_a, i_b and i_c . These currents are feed to Clark transformation module that gives two components, i_{dp}^s and i_{qp}^s in stationary reference frame.

1. To aligned on d^e axis and q^e axis, the above stationary reference frame i_{dp}^s and i_{qp}^s transform in to synchronous reference frame i_{dp} and i_{qp} . This transformation is called park transformation, i.e. for these transformation firstly we use equation(2.14), to Clark transformations, and for park transformation we would use the following relationship:

$$i_{dp} = i_{qp}^s \cos\theta_e - i_{dp}^s \sin\theta_e \quad (3.4)$$

$$i_{qp} = i_{qp}^s \sin\theta_e + i_{dp}^s \cos\theta_e \quad (3.5)$$

In compact matrix form:

$$\begin{bmatrix} i_{dp} \\ i_{qp} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{qp}^s \\ i_{dp}^s \end{bmatrix} \quad (3.6)$$

2. The second term used for IFOC deriving system is estimation of Ψ_{ds} . For estimation of this parameter firstly we used the above transformation as a basic. From this transformation necessary parameter is i_{dp} , because the target of the controlling system is making Ψ_{ds} only dependent on primary currents. For deriving the equation now start from equation (2.29), however, as we have seen this equation it also depend on secondary current i_{ds} , to satisfy the controlling target apply basic IFOC description on equation (2.22), from this we get

$$i_{ds} = -\frac{\frac{d\Psi_{ds}}{dt} - R_s * f(Q) i_{dp}}{R_s + R_s * f(Q)} \quad (3.7)$$

Then add the above equation in to equation (2.29) to make Ψ_{ds} only dependent on primary current as follows:

$$\Psi_{ds} = \frac{-\frac{d\Psi_{ds}}{dt} * (L_s - L_m * f(Q)) - R_s * f(Q) (L_s - L_m * f(Q)) * i_{dp} + L_m (1 - f(Q)) * (R_s + R_s * f(Q)) * i_{dp}}{R_s + R_s * f(Q)} \quad (3.8)$$

After applying few step manipulation this equation is reduced to:

$$\Psi_{ds} = \frac{R_s (L_m - L_s * f(Q)) * i_{dp}}{\frac{d}{dt} (L_s - L_m * f(Q)) + R_s (1 + f(Q))} \quad (3.9)$$

3. Including the above two steps the slip of the motor from equation (2.23), after applying IFOC basic description, it becomes:

$$\omega_{sl} = -\frac{R_s}{\Psi_{ds}} i_{qs} \quad (3.10)$$

To make equation (3.10) dependent on primary current, we can take the equivalence relation from equation (2.30) after applying equation (3.1), the relation becomes:

$$i_{qs} = \frac{-L_m * i_{qp}}{L_s} \quad (3.11)$$

Then substitute this equation on equation (3.10) and becomes the following

$$\omega_{sl} = \frac{R_s * L_m}{L_s * \Psi_{ds}} i_{qp} \quad (3.12)$$

Since $\omega_{sl} = \omega_e - \omega_r$, the slip frequency equation found on equation (3.12) is used in equation (3.1) for secondary angle, Θ_e finding, which required for coordinate transformation.

Note: $\omega_r = \frac{\pi}{\tau} * V$

4. The remaining criterial included in, indirect field oriented control which used as a base for obtaining the deriving voltage to the inverter are, i_{dp}^* and i_{qp}^* can be determining using IFOC basic description.

Using equation (3.9) as a base and making as difference from the coordinate transformation on step 1, make the star on i_{dp} and for differing Ψ_{ds} from the estimation we can also star on it, after this the relation between the two can be put as follows:

$$i_{dp}^* = \frac{\left(\frac{d}{dt} (L_s - L_m * f(Q)) + R_s (1 + f(Q))\right) * \Psi_{ds}^*}{R_s (L_m - L_s * f(Q))} \quad (3.13)$$

For considering the system steady state error is zero, $\frac{d}{dt}(L_s - L_m * f(Q)) = 0$ equation (3.13) becomes

$$i_{dp}^* = \frac{(1+f(Q))\Psi_{ds}^*}{(L_m - L_s * f(Q))} \quad (3.14)$$

5. The motor speed, v is compared with the reference speed, v_{ref}^* and the error produced is fed to the speed controller. The output of the speed controller is thrust force, from this we can derive i_{qp}^* , to get it we will depend on equation (2.39). But, as we have seen this equation contains of different terms i.e. Ψ_{qp} , Ψ_{dp} and i_{dp} . To make a direct relationship between thrust force and i_{qp} , with a constant parameters these terms should be removed, to do this applying IFOC basic principle on equation(2.30) which gives us equation (3.11), then after add this equation in to equation (2.28 and it becomes :

$$\Psi_{qp} = \frac{L_s * L_p * i_{qp} - L_m^2 * i_{qp}}{L_s} \quad (3.15)$$

Another variable need to substitute by relative variable from equation (2.39) is Ψ_{dp} , which need changed to secondary estimated flux, to get it we can start from equation (2.27), and equation (2.29).

From equation (2.29)

$$i_{ds} = \frac{\Psi_{ds} - L_m(1-f(Q)) * i_{ds}}{L_s - L_m f(Q)} \quad (3.16)$$

Then add this in to equation (2.27) and it becomes the following

$$\Psi_{dp} = \frac{(L_p - L_m * f(Q))(L_s - L_m f(Q)) * i_{dp} + L_m(1-f(Q))\Psi_{ds} - (L_m(1-f(Q)))^2 i_{dp}}{L_s - L_m * f(Q)} \quad (3.17)$$

Now using equation (3.15) and equation (3.17) in to equation (2.39), and after applying very long manipulation this equation becomes:

$$F_e = \frac{3}{2} * \frac{\pi}{\tau_p} * \frac{P}{2} * \frac{L_m(1-f(Q))}{L_{ls} + L_m(1-f(Q))} (\Psi_{ds} * i_{qp}^* - \frac{L_{ls}^2}{L_s} * \frac{f(Q)}{1-f(Q)} * i_{qp} * i_{dp}) \quad (3.18)$$

Due to the existence of end effect on the model, the second term on equation (3.18), which forbidden to decouple quadrature and direct current is called dynamic breaking force [24]. To overcome this problems compensation of the system is necessary, to do this we can simply add forward compensator on equation (3.15), on the left side, as value of:

$$F_{e,com} = -L_{ls}^2 * \frac{f(Q)}{1-f(Q)} * \frac{i_{qp} * i_{dp}}{\Psi_{ds}} \quad (3.19)$$

Where:

$F_{e,com}$ is thrust or compensation developed force

Then after adding the compensation the quadrature reference current becomes the following:

$$i_{qp}^* = \frac{4*\tau_p*F_e}{3*\pi*P} \frac{L_{ls}+L_m(1-f(Q))}{L_m(1-f(Q))*\Psi_{ds}} \quad (3.20)$$

To summarize discussion of vector control block shown on figure (3-4), the left sub blocks are introducing about current controllers. To introduce it we can start by pointing coming signals i_{dp} and i_{qp} , which are compared with their reference counterparts, i_{dp}^* and i_{qp}^* , can be gives i_{dp} and i_{qp} error signals respectively. These change or error currents are applied to their respective controllers integral (PI) type as shown on figure (3-3), to produce components V_d and V_q of the reference voltage vector, V , for the pulse width modulator. Which generates the switching variables, a, a' , b, b' and c, c' for the inverter. In this thesis work a PWM technique used is, the SPWM modulator.

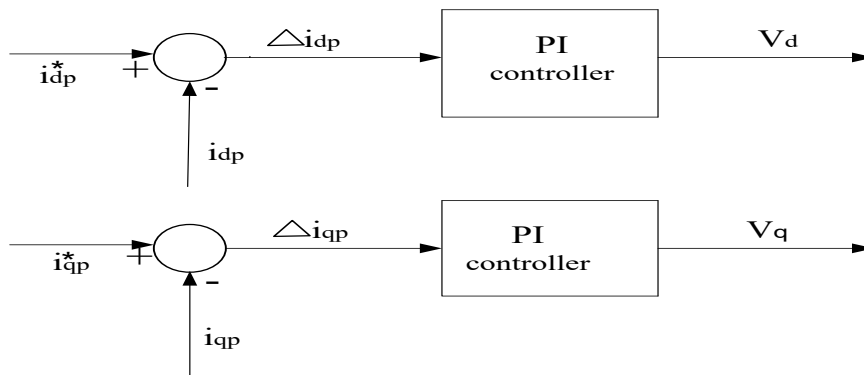


Figure 3.3 Current controller block diagram

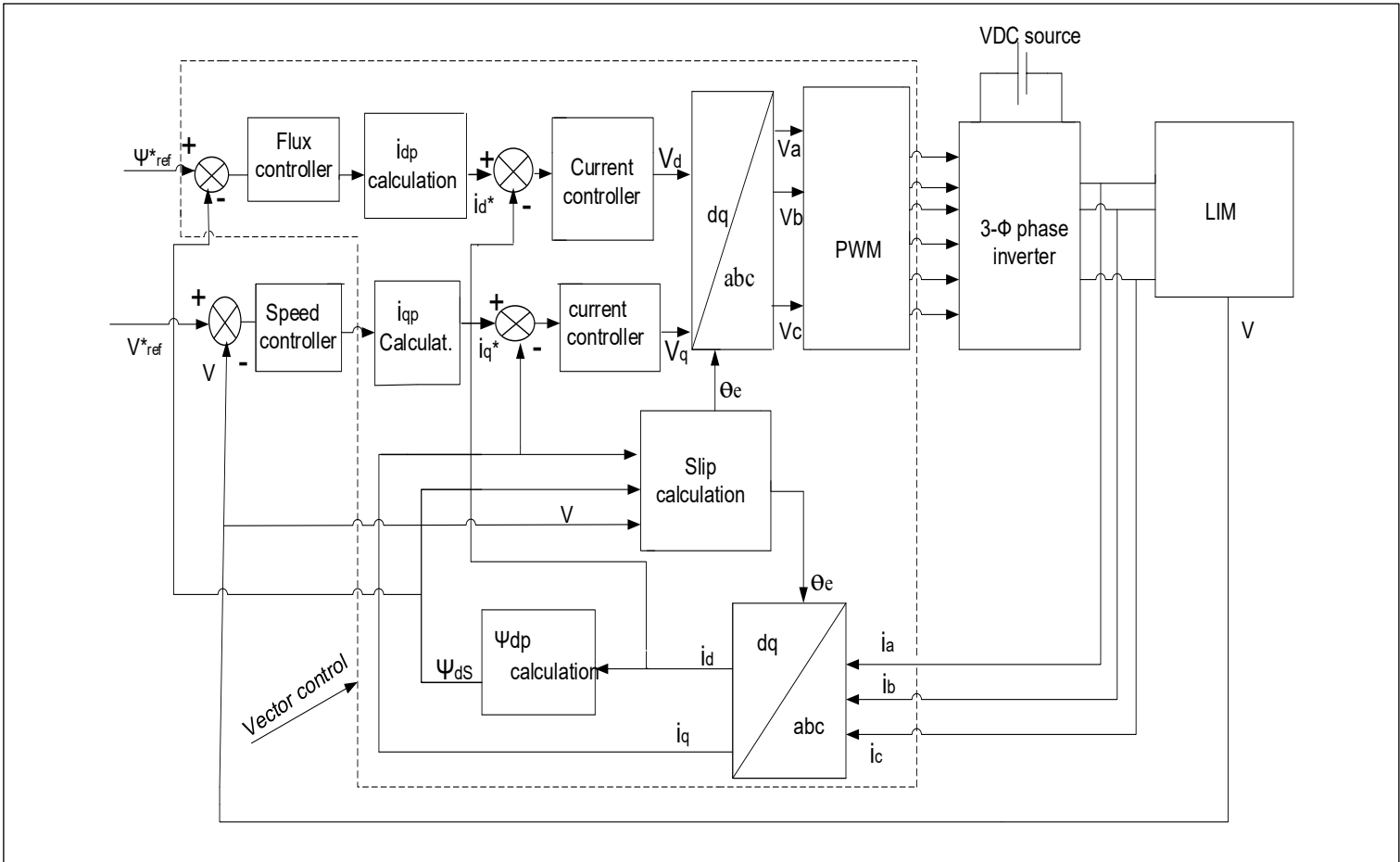


Figure 3.4 Proposed vector control for linear induction motor general block diagram

3.2. Control of LIM Drives

3.2.1. Inverter and their control

The sub system blocks used for drive linear induction motor is the standard power electronic converter module. To get variable speed in the machine, variable frequency of the primary currents is required, which is achieved with an inverter. The inverter requires a dc voltage input, which, in a majority of the cases, is obtained from an AC supply by rectification with a diode bridge semiconductor devices, and a pulsating signals get from pulse width modulation (PWM) for making on and off inverter switches.

3.2.2. Power semiconductor devices

Power semiconductor devices constitute the heart of modern power electronic apparatus. They are used in power electronic converters in the form of on-off switches. And help to convert power from ac-to-dc (rectifier), dc-to-dc (chopper), ac-to-ac at the same (ac controller) or different frequencies and dc-to-ac (inverter). For these applications the most commonly available switching semiconductor devices are diodes, bipolar junction transistors (BJTs), metal oxide semiconductor field-effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs) and get turn off thyristors (GTOs). The devices list with their respective power switching capabilities are shown in table(3.1). From these power devices MOSFET is considered a universal power device for low power and control advantages, while IGBT has a wide acceptance for inverters to derive ac and dc motors in variable frequency, and other application in the low and medium power range [25].

Table 3-1 Power semiconductor device and their switching capability [25]

Device	Power capability	Switching speed
BJT	Medium	Medium
GTO	High	Low
IGBT	Medium	Medium
MOSFET	Low	High
THYRISTOR	High	Low

3.2.2.1. DC Input Source

Dc and ac motor drives require variable voltage or current input at variable frequency to give a variable speed operation. The single - phase or three - phase power source we get from utility, has constant frequency and voltage, it cannot be directly used in these machines to get a desired one. To obtain these the power conversion from one condition to the other is must. This power conversion process starts firstly by converting of a utility AC to variable or fixed DC conversion (rectification) and then a DC to variable voltage or current, variable frequency AC conversion (inversion). The rectifier convert ac to dc utility power may be controlled or uncontrolled type. The uncontrolled rectifier with diodes only provides a constant DC voltage. The controlled rectifier with self-commutating devices(i.e. BJT,MOSFET,IGBT and GTO) provides a variable DC

voltage. Despite of its higher cost and complexity in control, this is upcoming in a few applications where its operational flexibility in providing variable voltage, AC input current shaping, and output ripple reduction are highly required.

3.2.2.2. Voltage Source Three-Phase Inverter

Inverters are devices which convert a DC voltage to AC voltage/current of variable frequency and magnitude, this indicates to us both voltage source and current source inverters can be used for drives electric machines, to a required speed. While, the majority of inverters used in motor drives are voltage source inverters (VSI), in which the output voltage to the motor is controlled to appropriate the operating conditions of the motor [20, 26].

To obtain appropriate operations the output voltage could be fixed or variable, at a fixed or variable frequency. A variable output voltage is get by varying AC voltage and making the gain of the inverter constant, or the DC voltage is fixed and a varying output voltage. This is obtained by varying the gain of the inverter, which is accomplished by pulse width modulation (PWM) control within the inverter. The inverter gain can be defined as the ratio of AC output to DC input voltage. The AC output voltage wave form we get from an inverters which give varying gain are, sinusoidal for ideal inverters and non-sinusoidal or contain certain harmonics for practical. But, with the availability of high-speed power semiconductor devices, practical inverter output AC voltage harmonic contain can be minimized, hence among the mentioned power devices in table (3-1). The average one is IGBT to accomplish this task and extensively applied in DC/AC derives and power supply system [20]. For these applications three phase inverters consist of six power IGBTs (Insulated Gates) switches in parallel with freewheeling diode that protect a device from over voltages caused by an inductive (motor) load, and connected to a DC voltage source as depicted in figure (3-5).

The IGBT is a transistors denoted as Q_1 to Q_6 , which can conduct or blocks current in the direction of the arrow in the figure (3-5) (in the other direction it always blocks). These conduct or blocks of currents are controlled by a, a', b, b', c and c' signals comes from PWM. For AC motor control, when an upper transistor is switched on, i.e., when a, b or c is 1, the corresponding lower transistor is switched off, i.e., the corresponding a', b' or c' is 0. That means, turning the upper line switch on requires turning off the lower line switch and vice versa. Therefore, the on and off states of the upper transistors Q_1, Q_3 and Q_5 , or equivalently, the states of a, b and c , determine the output AC

voltage. These voltages are, voltages which directly connected to primary side or phase of motors can be described using the subscribed letters a, b, and c, respectively as V_a , V_b and V_c , shown on the following figure.

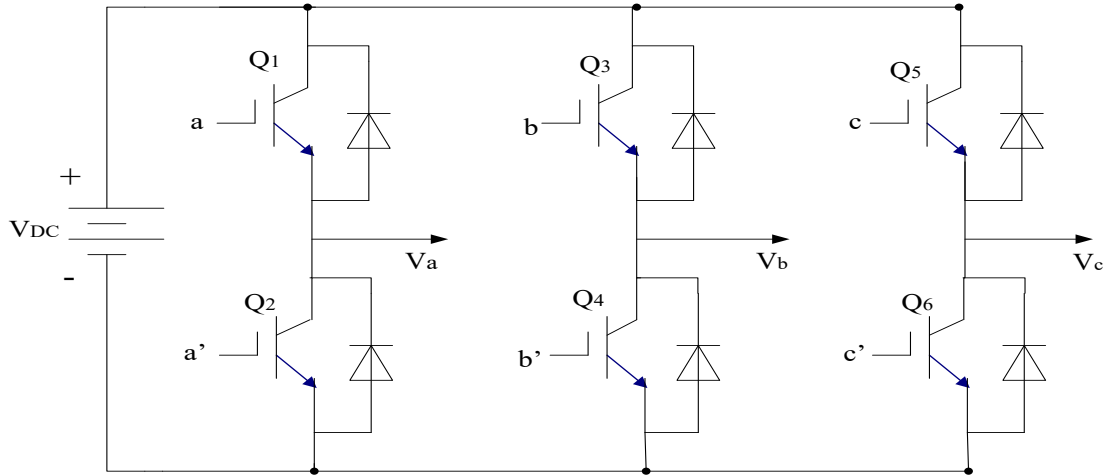


Figure 3.5 Three phase inverter

To understand its basic operation, let assume the DC link voltage is constant in the three phase inverter circuit and the line voltage can be constructed from phase voltages as follows.

$$V_{ab} = V_{a0} - V_{b0} \quad (3.21)$$

$$V_{bc} = V_{b0} - V_{c0} \quad (3.22)$$

$$V_{ca} = V_{c0} - V_{a0} \quad (3.23)$$

Where:

V_{ab} , V_{bc} and V_{ca} are line voltage, while V_{a0} , V_{b0} and V_{c0} are phase voltages. From these equations, the phase voltages are derived assuming that the system is balanced, and the phase-shift found between them is $\frac{2\pi}{3}$, as well as the summing of the three phase currents and voltages are equal to zero. The phase voltages in terms of the line voltages are given as:

$$V_{a0} = \frac{V_{ab} - V_{ca}}{3} \quad (3.24)$$

$$V_{bo} = \frac{V_{bc} - V_{ab}}{3} \quad (3.25)$$

$$V_{co} = \frac{V_{ca} - V_{bc}}{3} \quad (3.26)$$

As we saw figure (3-5), the inverter is a six-switched power device, consisting of three legs, one for each phase. Since these legs are works independently, let see the operational principles of one leg depending on switching condition on and off, i.e. phase a, V_a , with respect to ground (o) and is determined by a set of switches (Q_1) and (Q_2), whose taking a coming signal, a and a', for making on and off the transistors.

Table 3-2 Switching states of inverter phase leg a [27].

switching states of inverter phase leg a				
A	a'	Q_1	Q_2	V_{a_o}
On	Off	1	0	V_{dc}
Off	On	0	1	0

3.3. Pulse width modulation

The main challenge faced by the power electronic design engineers are about the reduction of harmonic content in inverter circuits [28]. The classical square wave inverter used in low or medium power applications suffers from a series disadvantages to minimizing this harmonic content from an output voltage. One of the solution to overcome this problem is using of PWM control methods. The main objective of using PWM technique was to fabricate highly approximate waves of AC output voltage to a sinusoidal wave form, in which there magnitude and frequency can be controllable. For obtaining this results, different types of PWM techniques are available i.e. sinusoidal pulse width modulation is the one and most commonly used type of PWM in modern power electronics drive [29].

3.3.1. Sinusoidal pulse width modulation (SPWM)

Sinusoidal PWM techniques is a commonly known method of controlling the output of inverters, which used for derives ac motor, by managing both frequency and magnitude of the voltage and current applied to a motor. To model and implement this method for control purpose is easy, and it is also compatible with almost all the modern digital applications [30].

The general modeling of sinusoidal pulse width modulation modeled on MATLAB Simulink is shown on figure(4-6). In this figure the coming signal represented by V_a , V_b , and V_c are controlled or reference voltages.

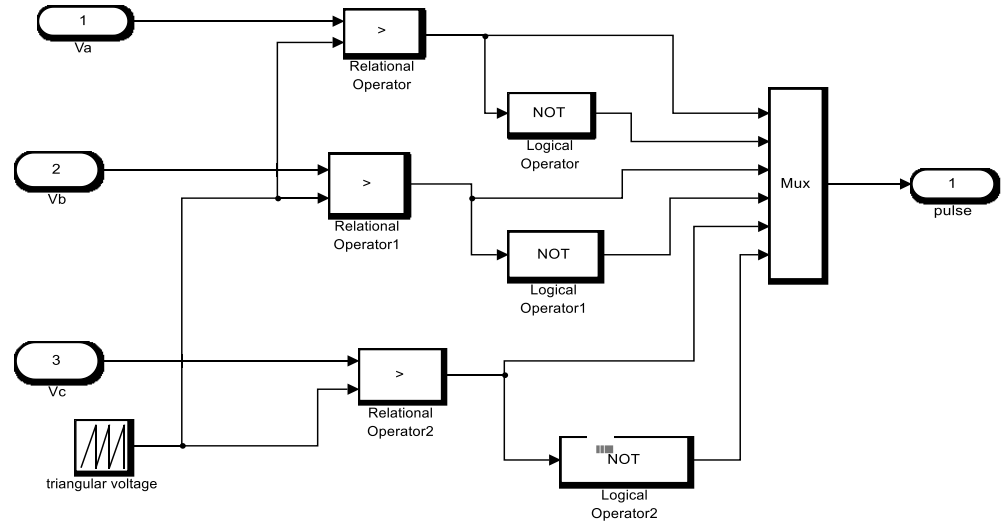


Figure 3.6 SPWM model using MATLAB Simulink.

In single and multiple PWM techniques the width of all pulses are same, however in sinusoidal pulse width modulation the width of each pulse is varied in proportion to the amplitude of coming waves, for reduced distortion factor(DF) and for significantly reduced lowest order harmonic (LOH) [31]. The way of generating this signal is requires a triangular wave form and a controlled sinusoidal reference wave. When the value of the reference signal is more than the modulation wave form (a triangular wave), the PWM signal comparator output is in the high state, otherwise it is the low state. Using these states as an input the inverter output is determined in the following relationships.

- When $V_{\text{control}} > V_{\text{tri}}$, $V_{\text{ao}} = \frac{V_{\text{dc}}}{2}$
- When $V_{\text{control}} < V_{\text{tri}}$, $V_{\text{ao}} = -\frac{V_{\text{dc}}}{2}$

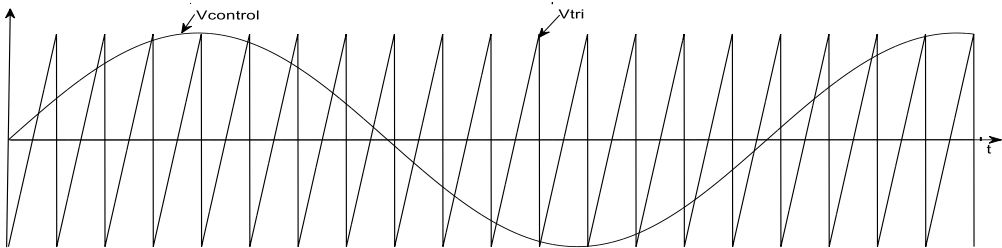
Where:

V_{control} , is control voltage and V_{tri} , is triangular voltage

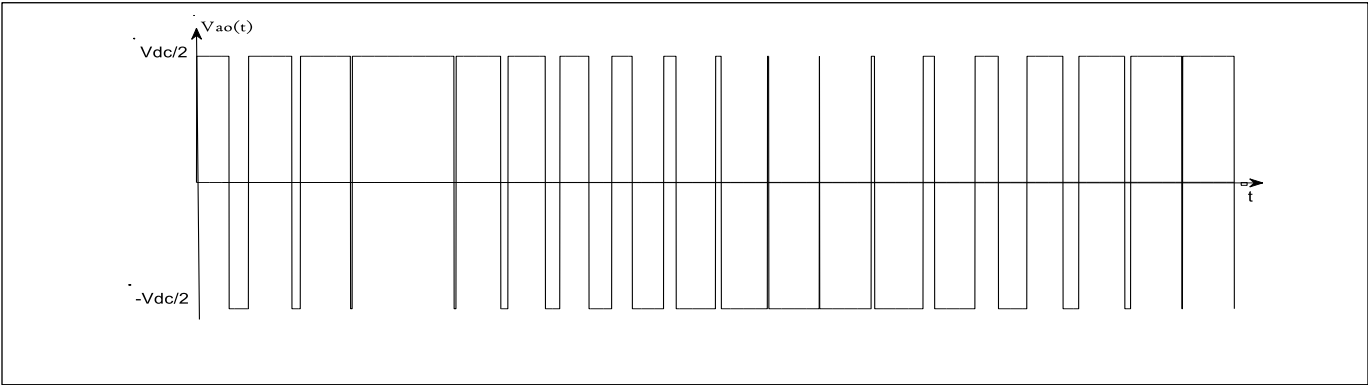
These results and description of SPWM are illustrated using single phase inverter switch on the following sample diagrams as follows:



Figure 3.7 Single phase inverter



(a)



(b)

Figure 3.8 (a) the control sinusoidal and triangular signal ,
 (b) single phase inverter (SPWM) output signal

Chapter four

4. Controller Design

4.1. Fuzzy logic principle and applications

4.1.1. Introduction to Fuzzy-Logic

The fuzzy logic is a part of artificial intelligence with a recent history and applications. The concept of fuzzy logic was first proposed by professor Lotfi A.Zadeh, a computer scientist, at the university of California at Berkeley in 1965 [32]. At that time not presented as a control methodology, but as a way of processing data by allowing partial set membership rather than crisp set membership or non-membership.

Human thinking is often fuzzy, vague, uncertain, qualitative, or imprecise in nature, and, therefore cannot be represented by yes (1) or no (0) type precision used in expert system (ES) [20]. By the same token fuzzy rule acts like human knowledge to analysis of complex system, can be defined as a conditional statement in the form if, then rules, in interval $[1, 0]$, rather than representation as yes or no. To reach at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information, fuzzy logic allows the programmer to deal with natural, “linguistic sets” of states, such as very fast, fast, medium, slow, etc.

Fuzzy logic creates a control surface by combining rules and fuzzy sets, which allows the designer to build controllers even though their knowledge of the mathematical model of the system is incomplete [33].

4.1.1.1. Fuzzy sets

The classical set theory is based on Boolean logic, where a particular object or variable is either a member of a given set (logic 1), or it is (logic 0). On the other hand, in fuzzy set theory based on fuzzy logic, a particular object has a degree of membership function in a given set that may be anywhere in the range of $[0, 1]$. For this reason, fuzzy logic is most often defined as multi-valued logic (0 to 1), compared to bi-valued Boolean logic. A membership function value of zero implies that the corresponding element is definitely not an element of the fuzzy set, while a value of unity means that the element fully belongs to the set. A grade of membership in between corresponds to

the fuzzy membership to set. If an element in the universe, say x , is a member of fuzzy set F , then this mapping is given by, $\mu_F(x) \in [0,1]$

4.1.1.2. Operations on fuzzy sets

The basic operational properties of Boolean logics are also valid for fuzzy logics, for this valuation, let A and B be two fuzzy sets in the universe (U) with membership functions, μ_A and, μ_B , respectively. The operations which fuzzy sets defined like of Boolean sets via their membership function defined are union, intersection, and complement etc. More specifically, see the following:

Union: Given two fuzzy sets A and B , defined in the universe discourse X denoted ($x \in X$), the union ($A \cup B$), with the membership function are given as :

$$\begin{aligned} \mu_{A \cup B} &= \max[\mu_A(x), \mu_B(x)] \\ &\equiv \mu_A(x) \vee \mu_B(x) \end{aligned} \tag{4.1}$$

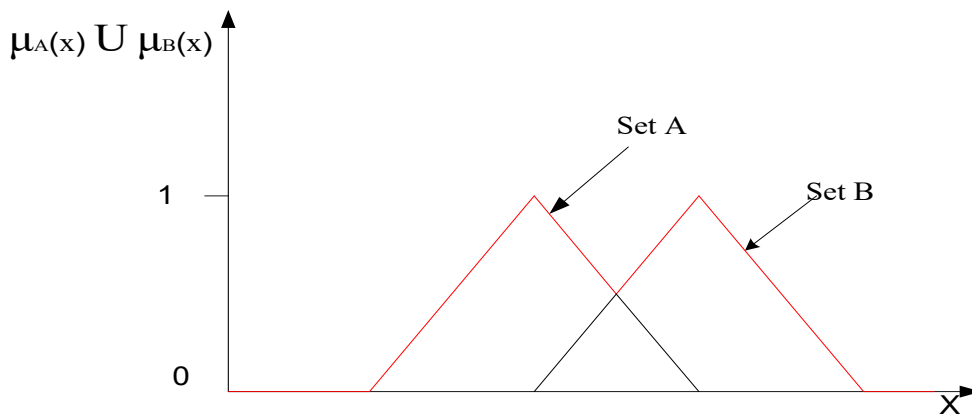


Figure 4.1 Union of fuzzy sets A and B[20]

Intersection : The intersection of two fuzzy sets A and B in the universe of discourse X , denoted by $A \cap B$, has the membership function given by:

$$\begin{aligned} \mu_{A \cap B} &= \min[\mu_A(x), \mu_B(x)] \\ &\equiv \mu_A(x) \wedge \mu_B(x) \end{aligned} \tag{4.2}$$

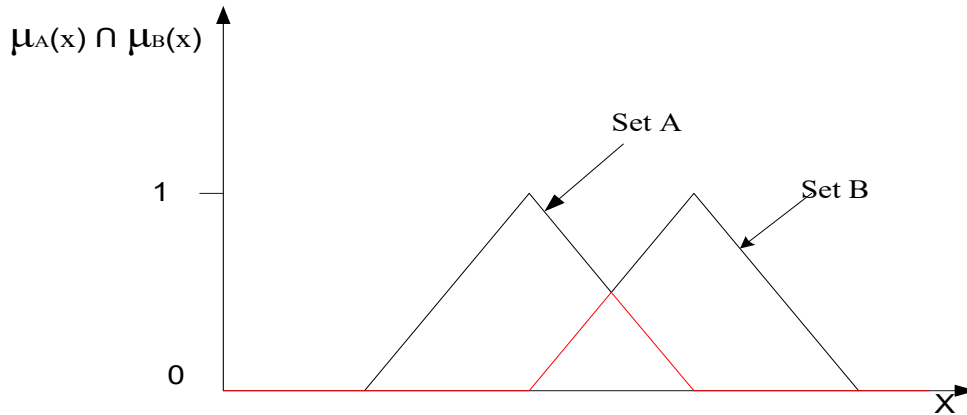


Figure 4.2 Intersection of fuzzy sets A and B [33]

Complement or Negation: The complement of a given set B, in the universe of discourse X, is denoted by \bar{B} , and a membership function.

$$\mu_{\bar{B}}(x) = 1 - \mu_B \quad (4.3)$$

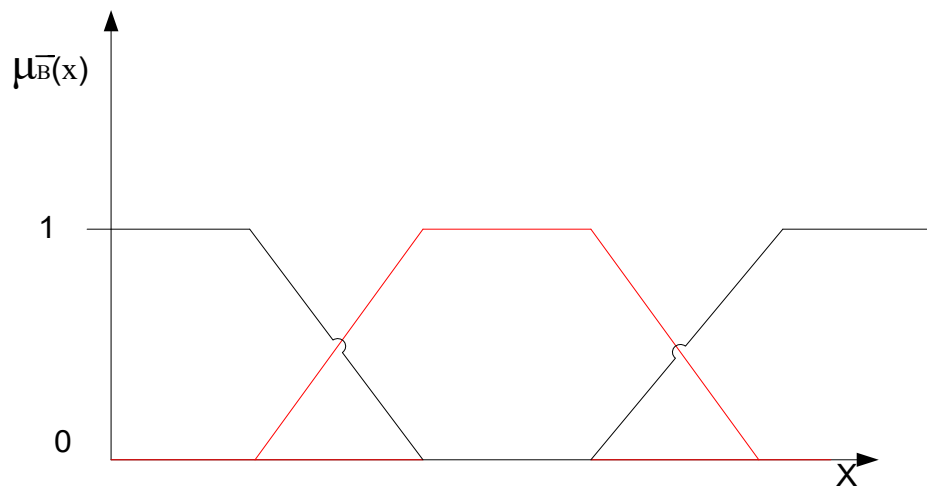


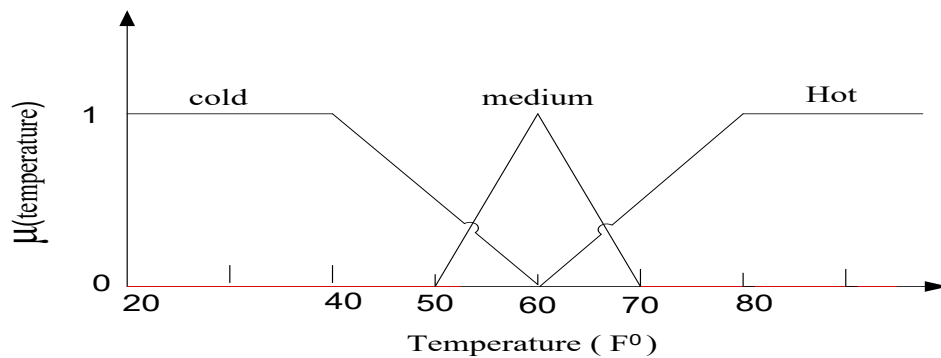
Figure 4.3 Complement of fuzzy sets B [33]

✓ Linguistic Variables

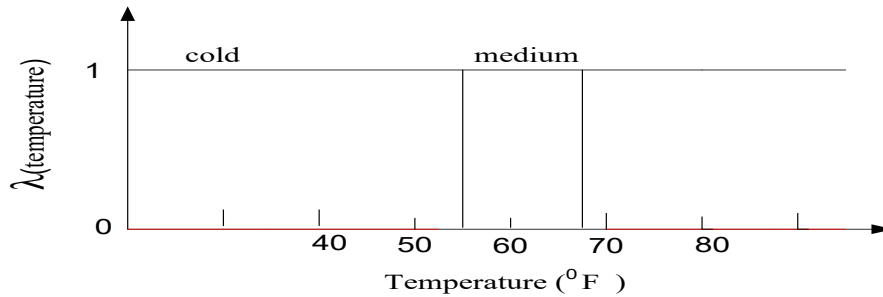
Cognitive scientists tell us that humans base their thinking primarily on conceptual patterns and mental images rather than on any numerical quantities. Furthermore, humans communicate with their own natural language by referring to previous mental images with rather vague but simple

terms. Whereas, the use of fuzzy sets provides a basis for a systematic way for the manipulation of vague and imprecise concepts. In particular, we can employ fuzzy sets to represent linguistic variables [33].

A linguistic variable can be regarded as a variable whose values are defined in linguistic terms. A linguistic variable associates words or sentences with a measure of belief functions, also called membership function. The set of values that it can take is called term set. Each value in the set is a fuzzy variable defined over a base variable. The base variable defines the Universe of discourse for all the fuzzy variables in the term set [34].



(a)



(b)

Figure 4.4 Representation of , temperature using (a) fuzzy set and (b) crisp set[35]

Using the above temperature representation figure (4-4 a) of fuzzy sets, let clarify the linguistic explanation of vague concepts.

As shown on the figure, temperature of the motor is taken as fuzzy variable, and its values are defined by the qualifying linguistic variables (fuzzy sets or subsets) Cold, Medium, or Hot, where

each set is represented by a triangular or straight line segment membership function(MF). The fuzzy sets can have additional subdivisions such as Zero, Very Cold, Medium Cold, Medium Hot, and Very Hot, for more precise descriptions of temperature. On this figure, if the temperature is below 40°F, it belongs completely to the set Cold, i.e. ,MF=1,

✓ **Membership Function (MF)**

Membership function is a function which changes the crisp variables (classical sets) in to fuzzy sets. All information contained in a fuzzy set is explained by its membership function. MFs describe the degree of confidence of all elements in the universe of discourse (dynamic range) to each fuzzy set spans a region of input or output value mapped with the membership.

Any particular input is interpreted from this fuzzy set and a degree of membership also interpreted. For these interpretation we can use different forms of membership functions, such as, triangular MFs, trapezoidal MFs, gaussian MFs, generalized bell MFs, π - Shaped Membership Function and S-Shaped Membership function. Among of the listed, triangular and trapezoidal shaped membership functions are the most common usage, because of they are easier to represent in embedded controllers and have simple formulas and simple computational [35].

However other shapes may be able to reflect natural phenomena, but may require complex equations to model, that can affect drastically increase the size and complexity of the fuzzy system [36].

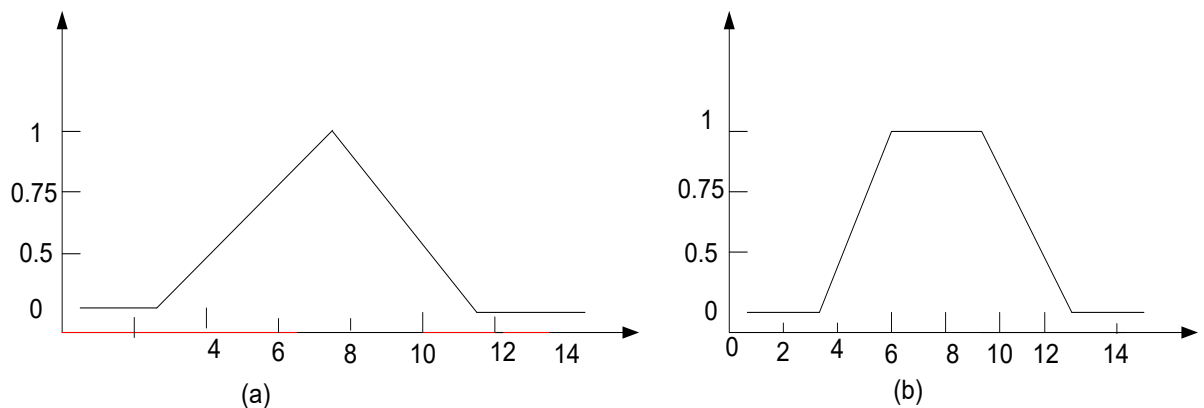


Figure 4.5 The two most common used membership functions: (a) triangular, and (b) trapezoidal -shaped [20]

4.2. Fuzzy logic controllers

The fuzzy set theory first introduced by Zadeh has found many application in variety of fields. As an illustration fuzzy logic control is a successful application of this theory. The basic idea behind fuzzy logic control is to incorporate the experience of a human operator in the design of a controller in controlling. A process whose, input-output relationship is described by a collection of fuzzy control rules (e.g. IF-THEN rules) involving linguistic variables. Figure (4-6) shows the structure of fuzzy logic controllers.

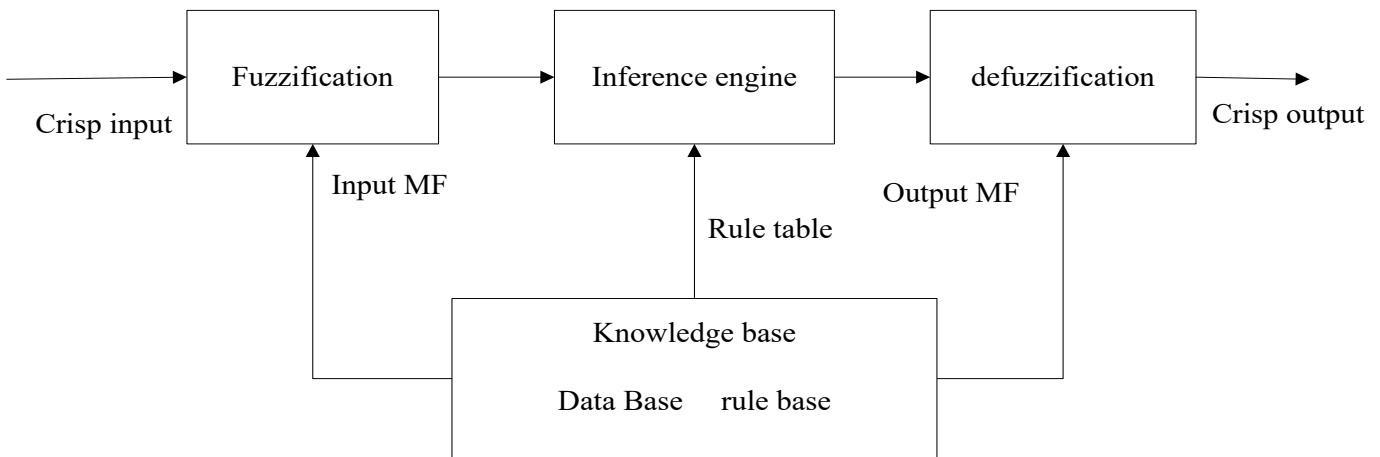


Figure 4.6 Structure of fuzzy logic controllers [37]

As we saw in above figure, it consists of four major process blocks that mentioned as follows:

1. Fuzzification
2. Knowledge base
3. Inference engine (decision generation logic)
4. Defuzzification

The input variables go through the fuzzification inference that information to linguistic variables. The rule base holding the decision making logic used to infer the fuzzy output, a defuzzification converts fuzzy output in to fuzzy signal.

✓ Fuzzification

A fuzzification inference, the fuzzy control initially converts the crisp error and its rate change of error in to fuzzy variables. Then, they are mapped in to linguistic labels membership functions are defined within the normalized range and associate with each label NB(NEGATIVE BIG), NM(NEGATIVE MIDUM), NS(NEGATIVE SMALL), Z(ZERO), PS (POSITVE SMALL), PM (POSITIVE MIDUM), PB(POSITIVE BIG). Seven MFs are chosen for $E(pu)$ and $CE(pu)$ and seven for output. Thus maximum $7 \times 7 = 49$ rules can be formed as tabulated in table(4-1). In this table top and left column of the matrix indicates, the fuzzy sets variables E AND CE, respectively, and the MFs of the output variable U are shown in body of the matrix.

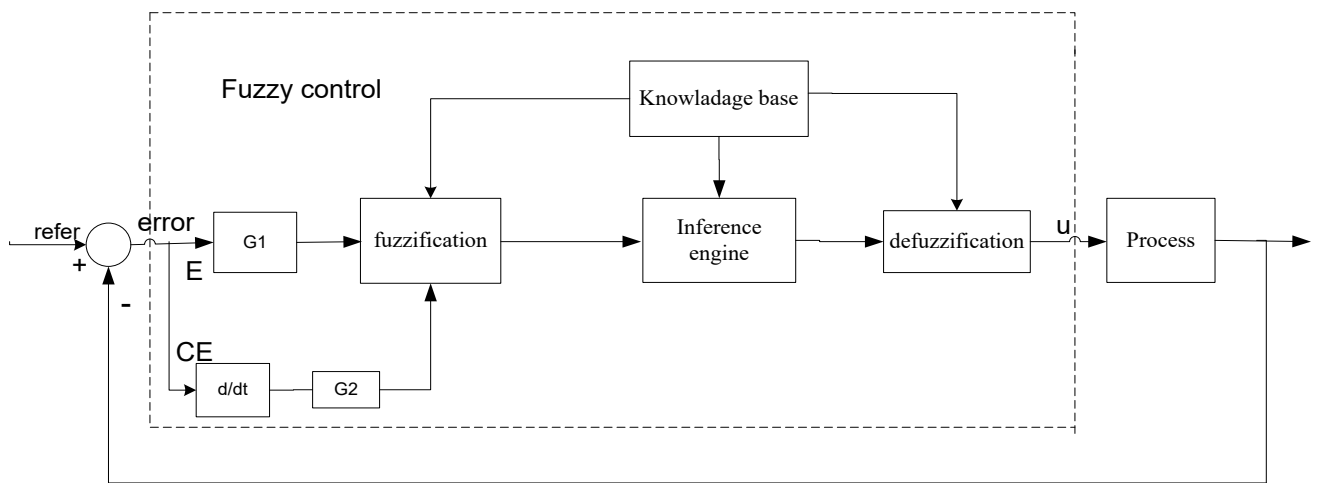


Figure 4.7 Connection diagram of fuzzy logic controller [37]

✓ Knowledge

A knowledge base consists of rule base and data base. The basic function of the data base is to provide the necessary information for the proper functioning of the fuzzification, whereas the function of the rule base is to represent the expert knowledge in the form IF-THEN rule structure.

The number of rule base depends on the number of membership in the fuzzy set of the inputs. For example if the system contains one input with fuzzy set contains 5 membership then there are 5 base results. If the system has two inputs and one of them is contains 7 member ship in its fuzzy set, and the other contains 5 membership then the total rule base is equal to $7 \times 5 = 35$ rule base. The efficiency of the system is depend on the proportional number of membership functions.

✓ Inference engine

An inference mechanism (also called engine or fuzzy inference module), which is heart of fuzzy control. This part is pose the capacity to the human decisions and emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant. For inference mechanisms we can use either Mamdani method, or Surgeon methods. While, Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology and suitable for DC machine or induction machine [37]. The function of this method is converts fuzzy output value in to the crisp value of the output variable. The center of Area (COA) defuzzification method is generally used.

✓ Defuzzification

A defuzzification inference is an inverse process of fuzzification, which convert the conclusions of inference mechanisms or output of an inference in to actual inputs for the process. In this works; center of Area (COA) is used as a defuzzification method, which it's discretization universe of discourse is written as:

$$Z_O = \frac{\sum_{i=1}^n Z_i \mu_{out}(z_i)}{\sum_{i=1}^n \mu_{out}(z_i)} \quad (4.4)$$

Where :

z_o =is the crisp output

n =number of discrete

Z_i = The value of discrete

μ_{out} = the corresponding MF value at the point z_i

4.2.1. Design fuzzy logic controllers

To design fuzzy logic controller for speed control of linear induction motors, we can use the following methodology.

- ❖ Determine the input and output of fuzzy variables
- ❖ Define the universe of discourse of variables i.e. for this work use for the input [-1,1] range and output range is considered [-3500,3500].

- ❖ Fuzzified the input
- ❖ Formulate the fuzzy sets and select the corresponding MFs shape of each sets
- ❖ Formulate the rule table and atypical rule read format
- ❖ Choose inference mechanism engine
- ❖ Choose the defuzzification methods

The following portion presented what taken in this thesis works for designing fuzzy logic controller depend on the above methodology. As we discussed above the input signals are two, which represented as abbreviation E and CE. Figure(4-8) & (4-9) shows the fuzzy set and corresponding triangular MF of each signal. The fuzzy sets are defined (the linguistic definition is immaterial) as follows, that recall from fuzzification portion of this works .

Z= Zero

NB= Negative big

PB = Positive big

NM= Negative medium

PM= positive medium

NS= Negative small

PS= Positive small

The universe of discourse of input variables, covering the whole region, as it is defined under design metrology expressed in $[-1,1]$ interval, while output interval is $[-3500 \ 3500]$. The membership numbers taken as input for this works are seven for E and CE, also for output (FE) signal also taken seven membership functions. All the MFs symmetrical for positive and negative values of the variables. Table(4-1) shows the corresponding rule table for speed controller. The top row and left column of the matrix indicate the fuzzy sets of the variables E and CE, respectively, and the MFs of the output variable U, are shown in the body of the matrix. There are $49(7*7)$ possible rules that we would get in this matrix. As a result, the typical rules can be read as follow:

1. IF (E is NM) and (CE is NB) then (U is NB)
2. IF (E is NS) and (CE is NB) then (U is NB)
3. IF (E is Z) and (CE is NB) then (U is NB) etc.

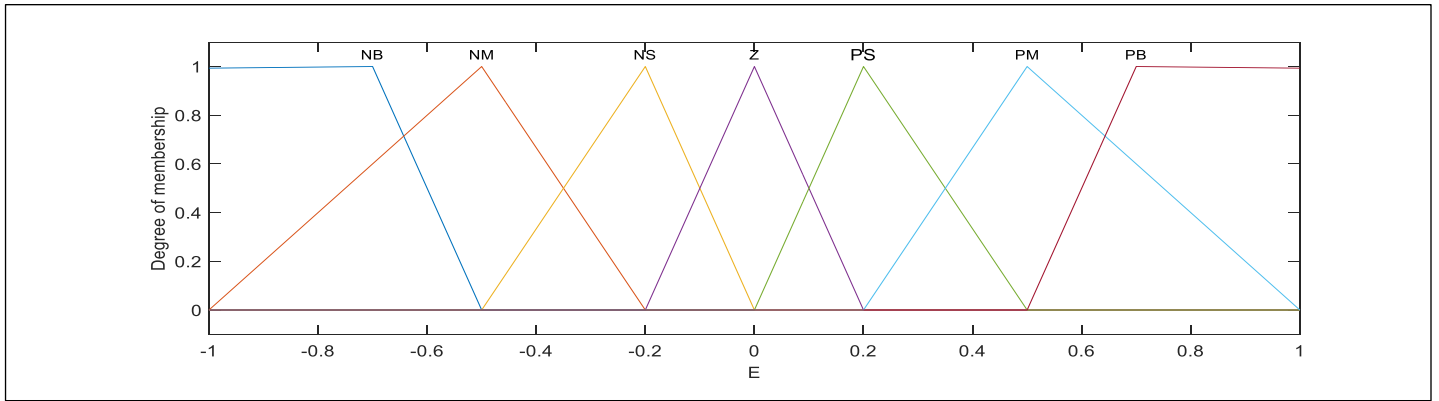


Figure 4.8 Membership function of input (E)

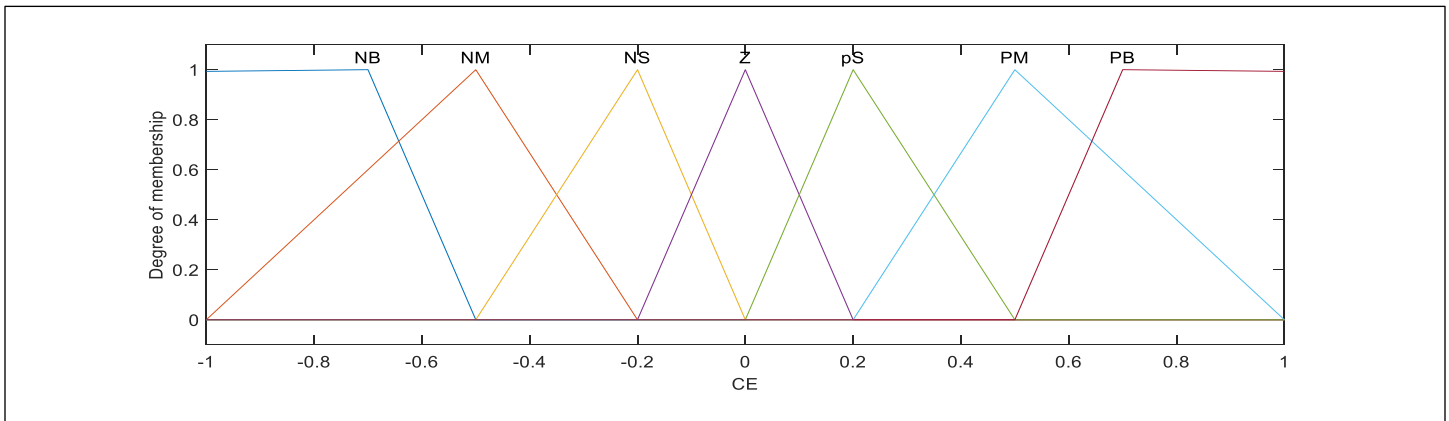


Figure 4.9 Membership function of input(CE)

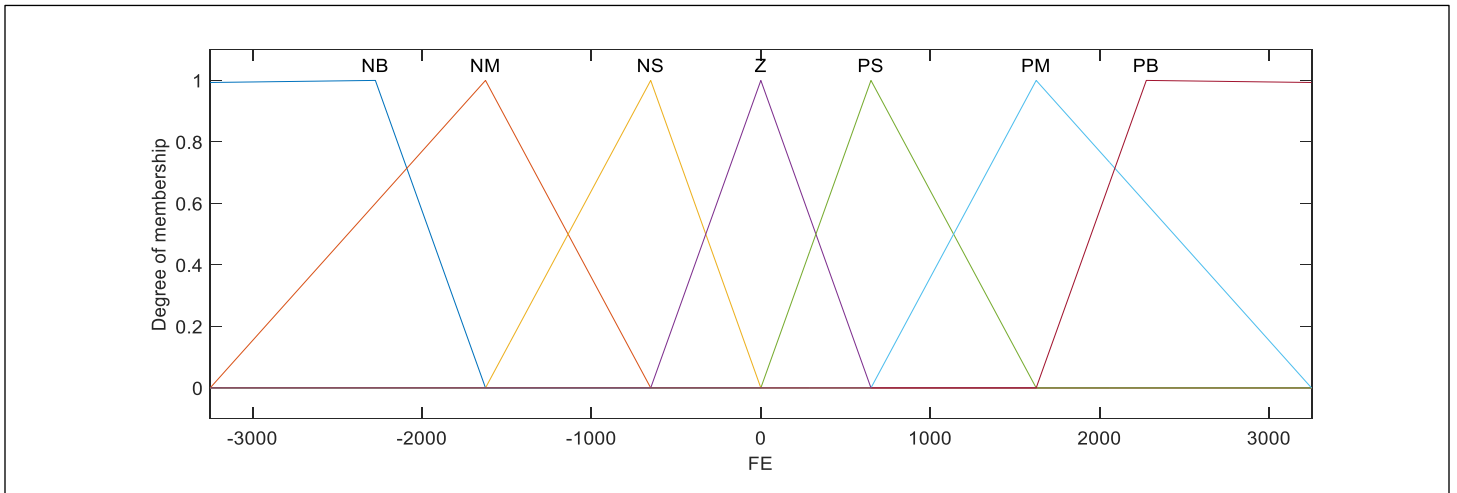


Figure 4.10 Membership function of output (FE)

Table 4-1 Rule matrix for fuzzy speed control

U

CE \ E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

4.3. Conventional controller

The dynamic model of an AC motor is complex, multivariable, and nonlinear. However, vector control or field oriented control can overcome this problem, but accurate vector control is nearly impossible. To combat this problem, classical control and fuzzy control are combined with indirect field oriented control to solve this problem [20]. A linear induction motor can be controlled with the help of conventional controllers PI, PD, and PID with the use of indirect field oriented control technique. However in this thesis work only PI type of conventional controller is designed and apply on the system developed as mathematical on the MATLAB/ Simulink with indirect vector control. The main target of this controller applying on speed control to the system is for the seek of comparation the performance of controller ability with the modern type of fuzzy controller.

4.3.1. PI controller

PI controller or proportional plus integral type of controller is a most widely adapted controller for AC motors, due to, its simple structure, easy to design and implemented as hardware and software, in addition to this, type of controller is less costly[38].

The error represents the difference between the desired motor and the actual motor speed and, it is expressed as:

$$E = V_{ref}^* - V \quad (4.5)$$

Figure(4-11), shows the block diagram of classical PI controller. The transfer function for PI controller is expressed as:

$$\frac{U(S)}{E(S)} = K_P + K_i/S \quad (4.6)$$

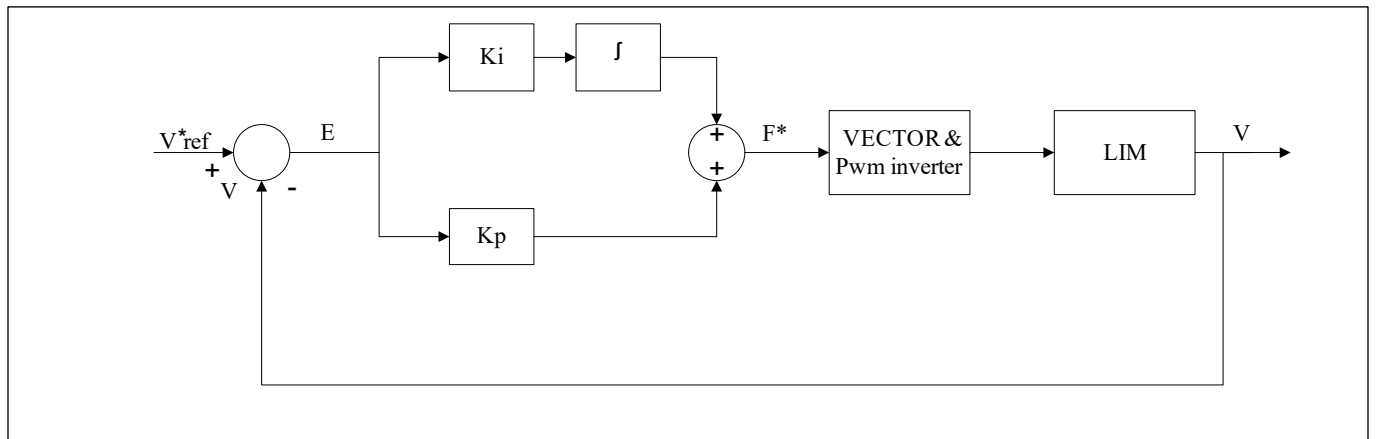


Figure 4.11 PI controller block diagram with vector control

The constant, i.e. K_p and K_i shown on figure (4.11), are the tuning knobs, are adjusted to obtain the desired output, the signals adjusted under this controller is an error (E) comes from comparators compares of actual and reference speeds signals which represented as V and v_{ref}^* respectively. However, the PI controller has some disadvantages such as, the high starting overshoot, sensitivity to controller gains and sluggish response due to sudden disturbance. So, comparatively a new intelligent controller by using MATLAB/Simulink package should be applied to the system to obtain a better responses than the traditional PI controller for the speed control. Due to this fact, in this work a type of controller applied for speed controlling is typically fuzzy logic controller.

Chapter five

5. Simulation Results and Discussions

Simulation result obtained for the develop system in this work is carried out in two phases. The first phase was, without applied any type of controller to the system i.e. the supplied source is directly connected to the system. And the second stage is performed by applied of fuzzy vector controller to derive linear induction motors with and without compensation of end effect. For both phases simulation have been done by MTLAB software.

In this section thrust/force, speed, and primary currents of the proposed motor derive without controller and with fuzzy logic controller is considered and compare with conventional type of PI controller vector controlled linear induction motor derive. The following figure shows interconnection of derived LIM without applied any controller.

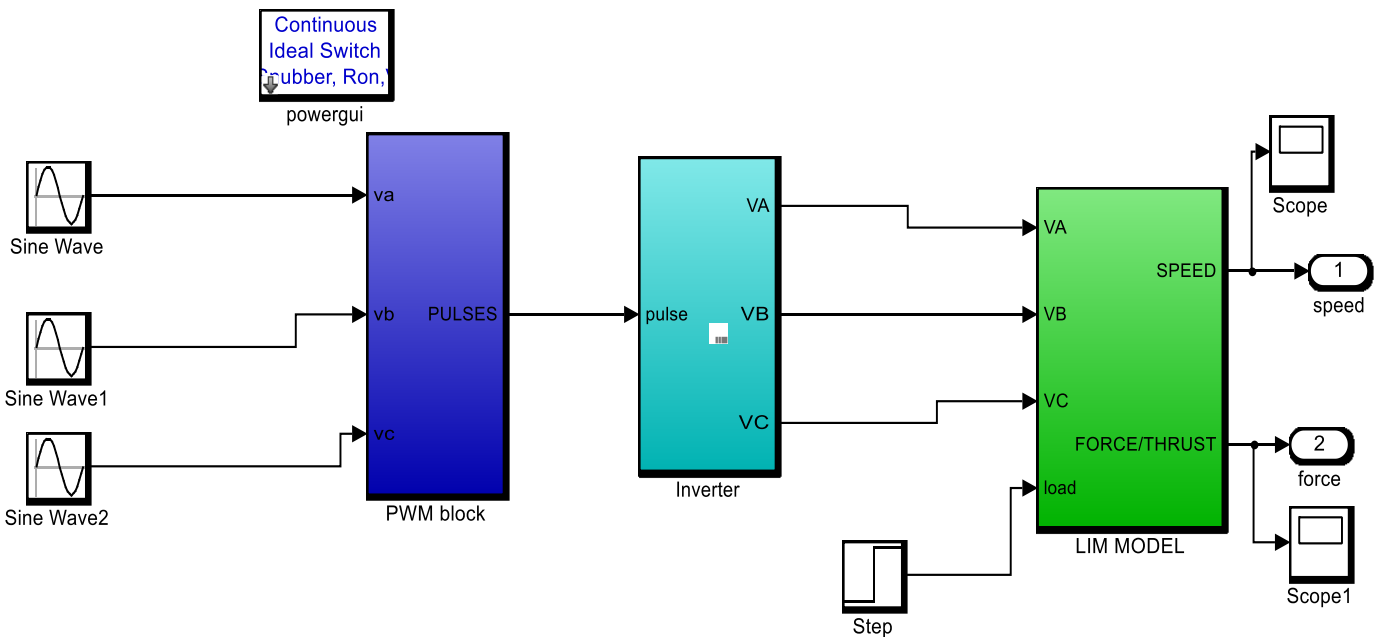


Figure 5.1 Inverter output voltage connected to LIM model without any controller

Speed output as shown in figure (5-2) is the results of an interconnection blocks shown on figure (5-1). From the result we observed peak overshoot time is occurred at a time ($t = 0.1783\text{sec}$) and again from the figure we noticed, gotten a constant settling time to be a response stay within a

constant rage is impossible. In addition to this, the thrust/force response shown on figure (5-3) is an output obtained from interconnection of figure (5-1). It points toward that, the problems of the system response without applied controllers with higher fluctuation between (-1747N to 1643N) amplitude ranges.

The third response from figure (5-1), is an output shown in figure (5-4), this figure shows the responses of three phase currents.

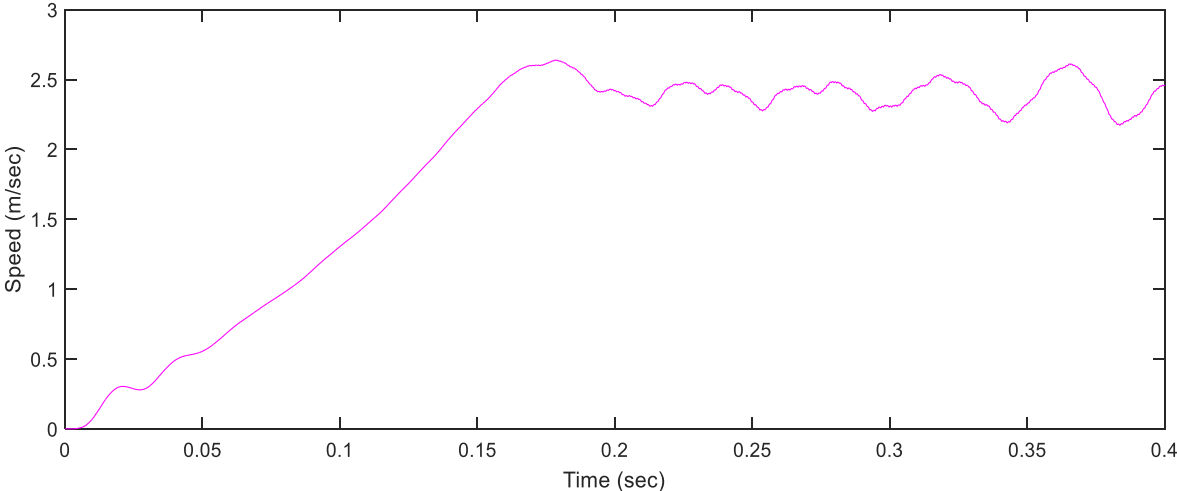


Figure 5.2 Speed output without controller

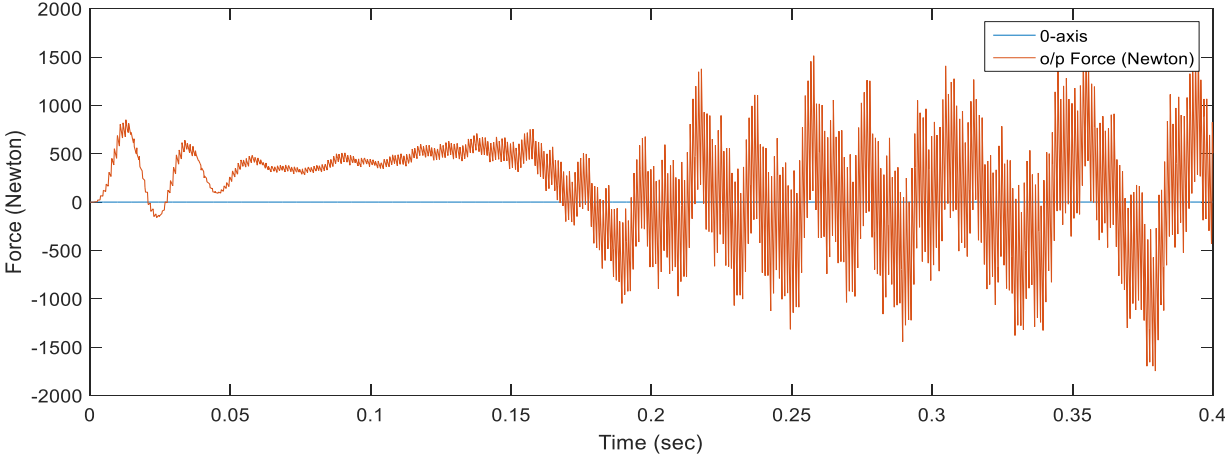


Figure 5.3 Force/thrust output without applying any controller

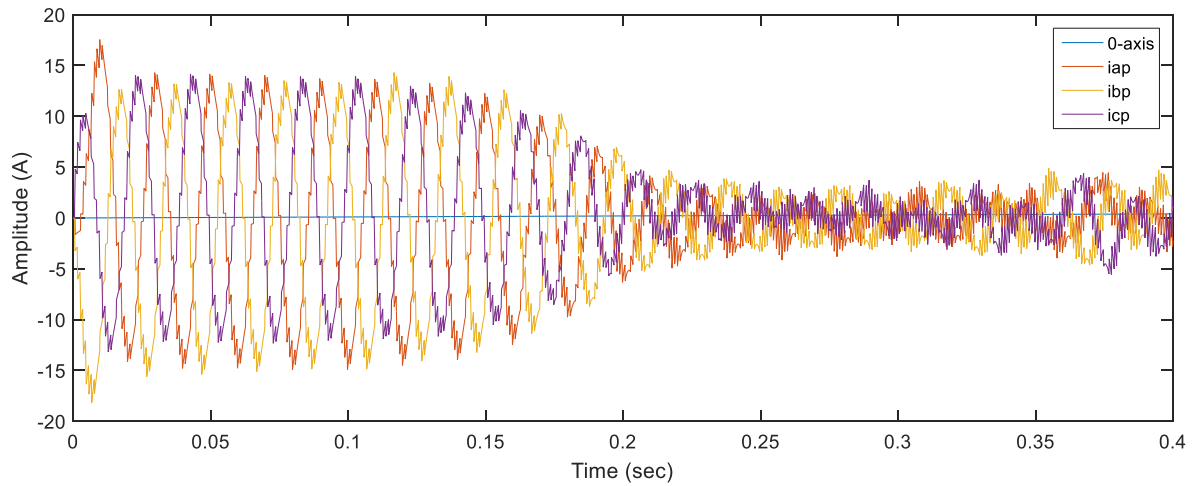


Figure 5.4 Three phase output currents without applying controllers

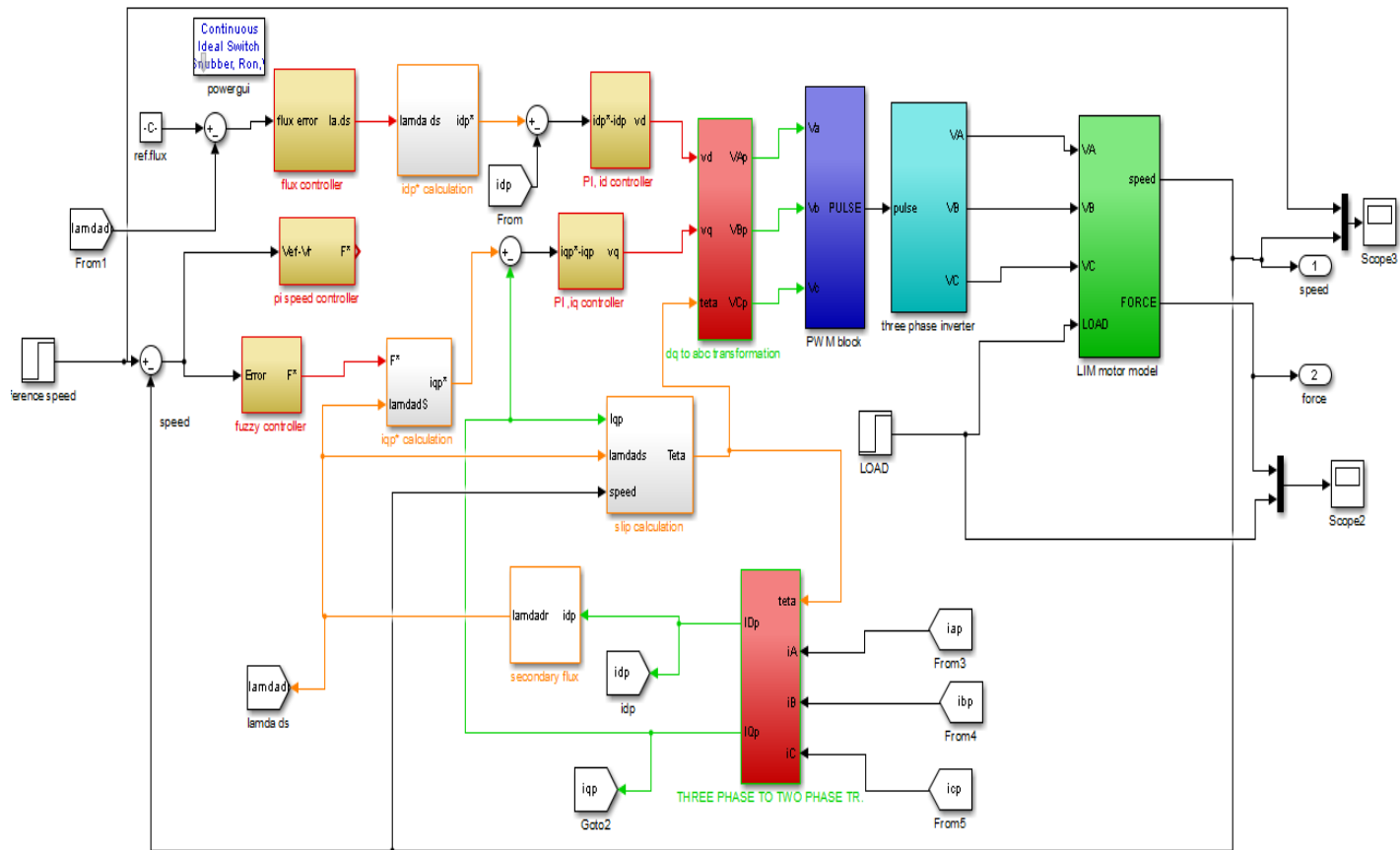


Figure 5.5 Overall content vector controlled linear induction motor drive

Figure (5-5) shows the overall interconnections, applied to derive linear induction motor using fuzzy and PI vector controlled. For such types of controllers, simulation of a system accomplished

in different condition, such as the result speed output shown in figure (5-6) & (5-7) are gets at a time of our system no loaded, with a given parameters at nominal value put on an appendix.

The time to reached steady responses of both figures achieved at time ($t = 0.0257\text{sec}$), but PI controller result in figure (5-6) slowly oscillated between (0 to 0.047) steady state error. From figure (5-7) or fuzzy controller response we realize that, the fluctuation existence on PI controller is handled with steady state error zero. Again, comparatively as we seen their maximum peak overshoot amplitude, from PI controller response we obtained 0.069, and from fuzzy logic controller we get 0.016, amplitudes from reference signals.

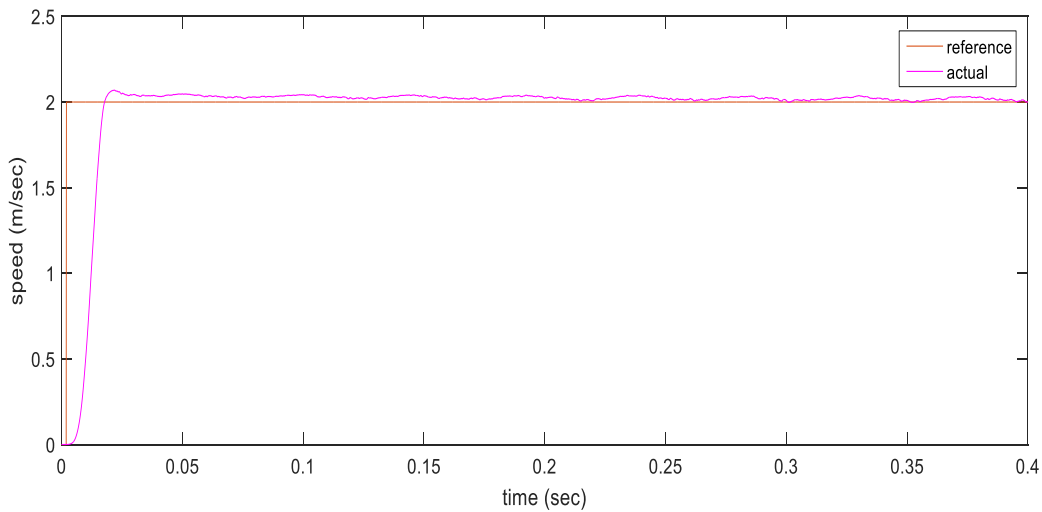


Figure 5.6 PI controller speed output

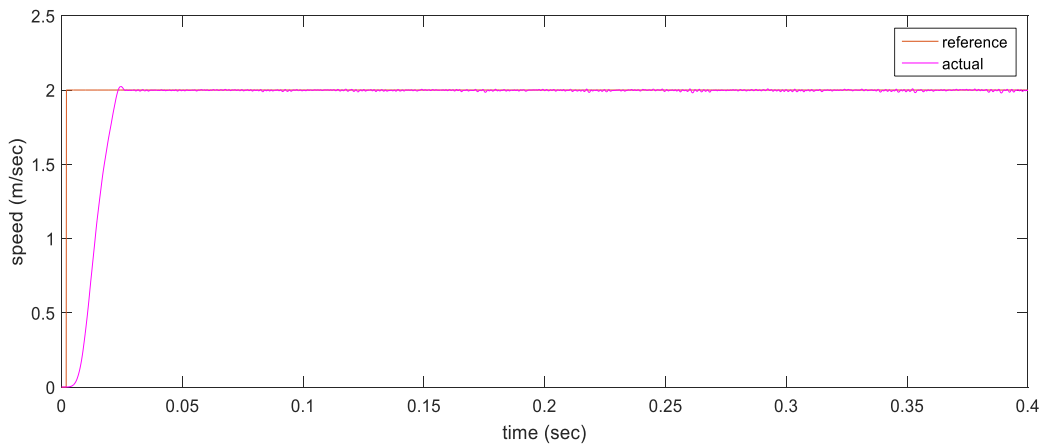


Figure 5.7 Fuzzy controller speed output

Simulation results as shown in figure (5-8) and (5-9) shows the thrust/ force response have gotten at a time the motor no loaded and normal conditions. When compared the results, the response gotten from PI controller, fluctuation amplitude is less from fuzzy controller output, while starting overshoot force is equal to (6207Newton) from PI controller output, which is very high relative to fuzzy controller output amplitude, 4309Newton. The bad effect of overshooting the thrust/force is that the motor is forced to draw a higher starting currents, which causes for heating of a motor.

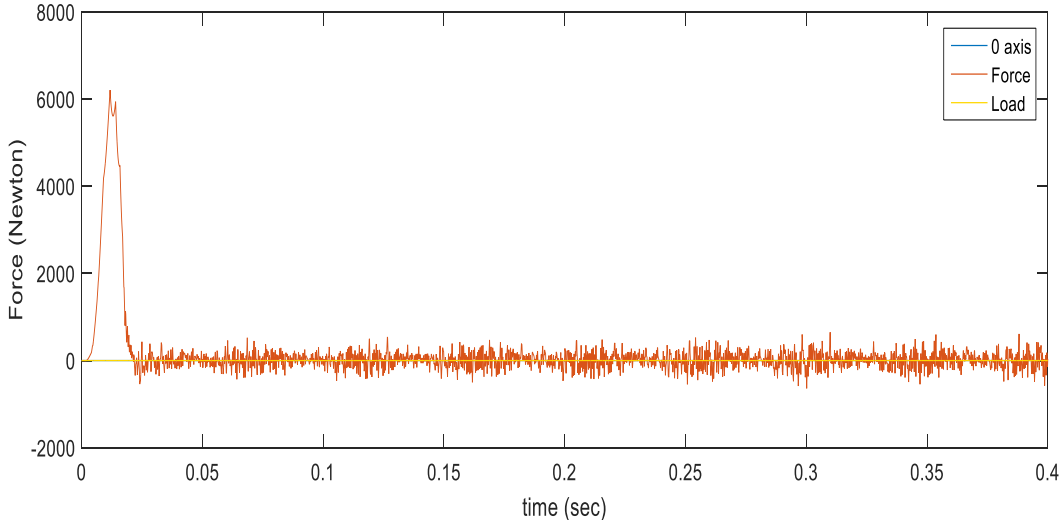


Figure 5.8 Force/thrust response from PI controller

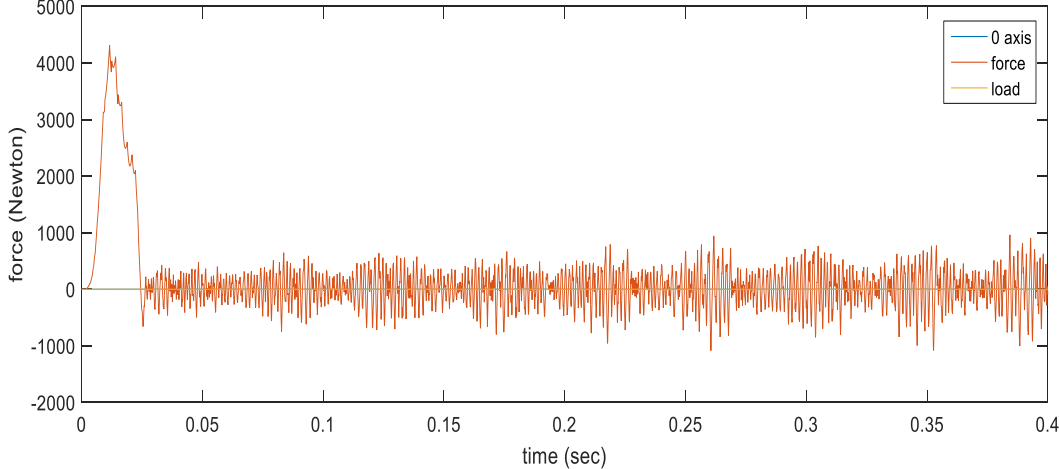


Figure 5.9 Force/thrust response from fuzzy controller

Figure (5-10) and figure (5-11) shows three phase current output of PI controller and Fuzzy controller respectively. Phase (b) starting amplitude from figure (5-10) is (49.82A) and, from figure (5-11) this phase amplitude is reduced to (42.96A). Again, from phase (c) starting amplitude from PI controller response is 47.82A and, this phase amplitude from fuzzy logic controller result reduced to 42.42A. In short, from these significances we noticed that, amplitude of three phase current on PI controller output is higher than amplitude of fuzzy logic controller at starting time.

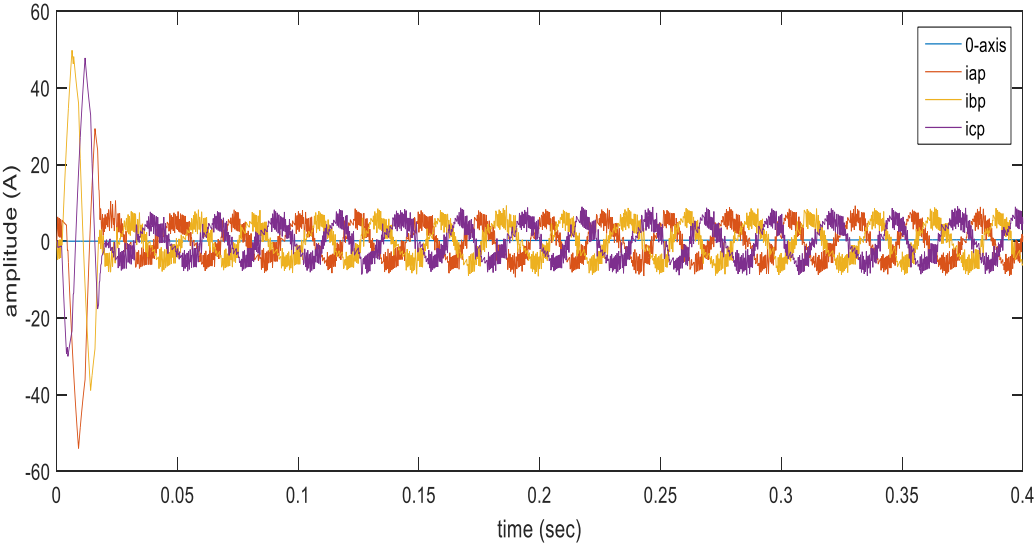


Figure 5.10 PI controller three phase current output

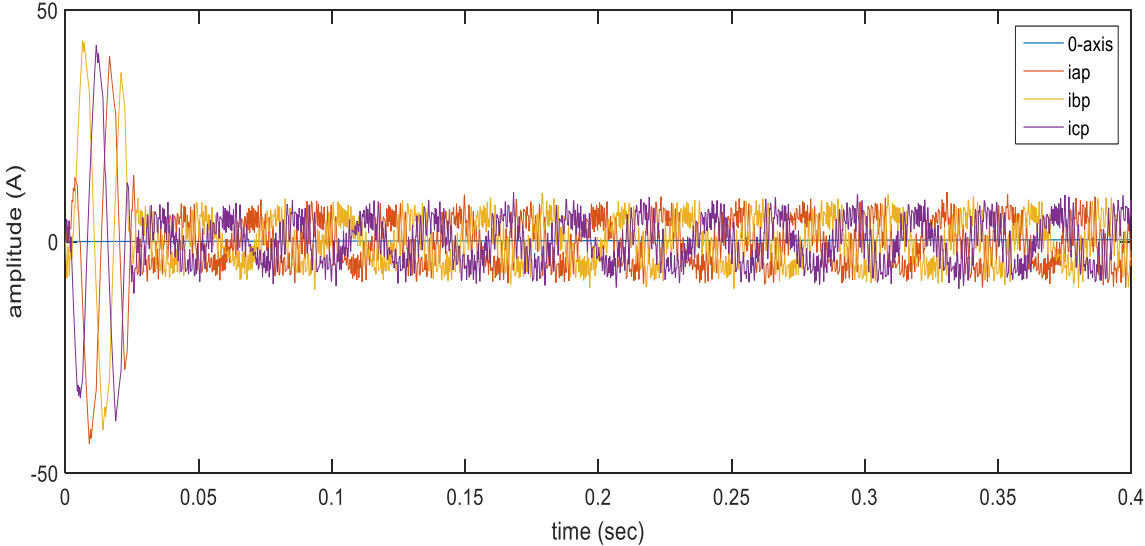


Figure 5.11 Fuzzy controller three phase current output

The second case performed under this thesis work is, loading condition. On this case the result of a simulations are shown from figure (5-12) to (5-17). Figure (5-12) and figure (5-13) shows speed response for motor having 500N, load at 0.2sec. From speed response shown in figure (5-12) we obtain an error varies between (0 to 0.177) after load is applied, while in figure (5-13), this error variation is managed by controller to try back to reference speed within a few delay time to zero error. Hence figure (5-13) shows that the proposed FLC is reliable for load disturbance as compared to PI controller.

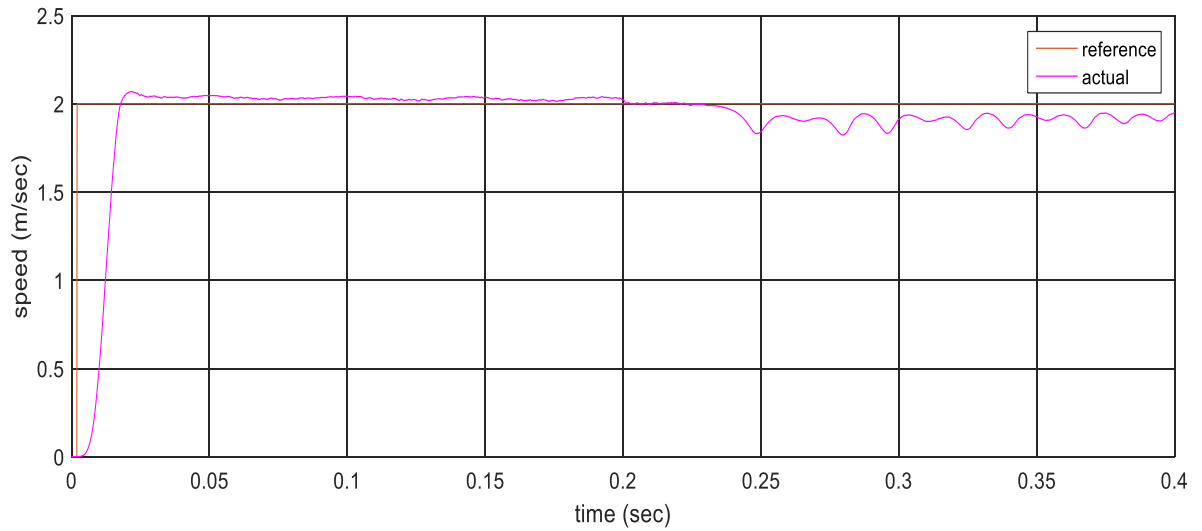


Figure 5.12 PI controller speed output when load applied at 0.2sec

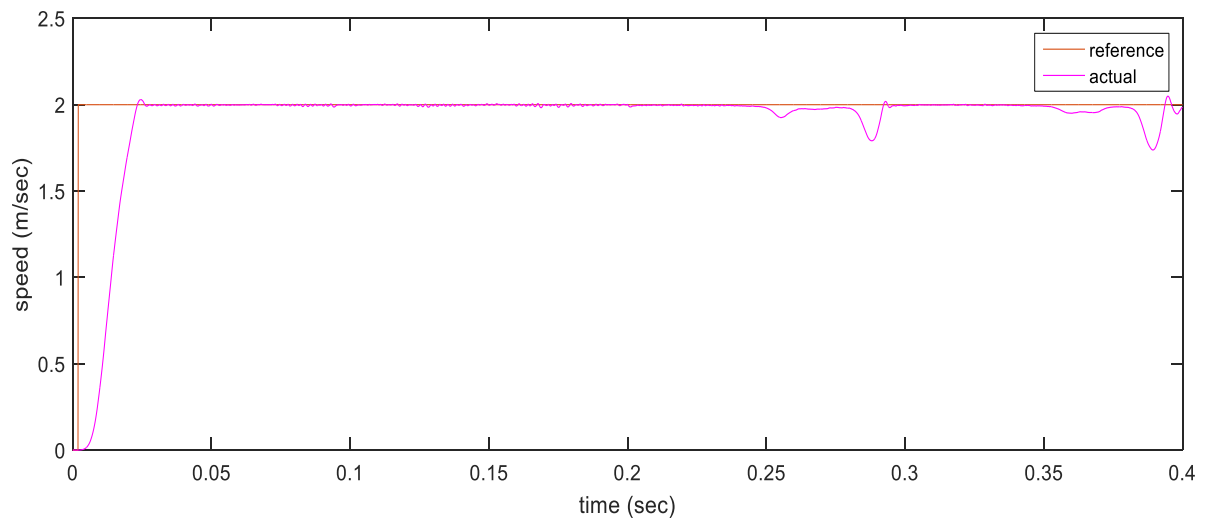


Figure 5.13 Fuzzy controller speed output when load applied at 0.2sec

Under this condition, another simulation result performed was analysis of force/thrust, which are shown on figure(5-14) and figure (5-15), for PI controller and fuzzy logic controllers respectively. As we have seen the relative controller performance, due to actual thrust or force following the loaded thrust, FLC is better than conventional type of controller PI.

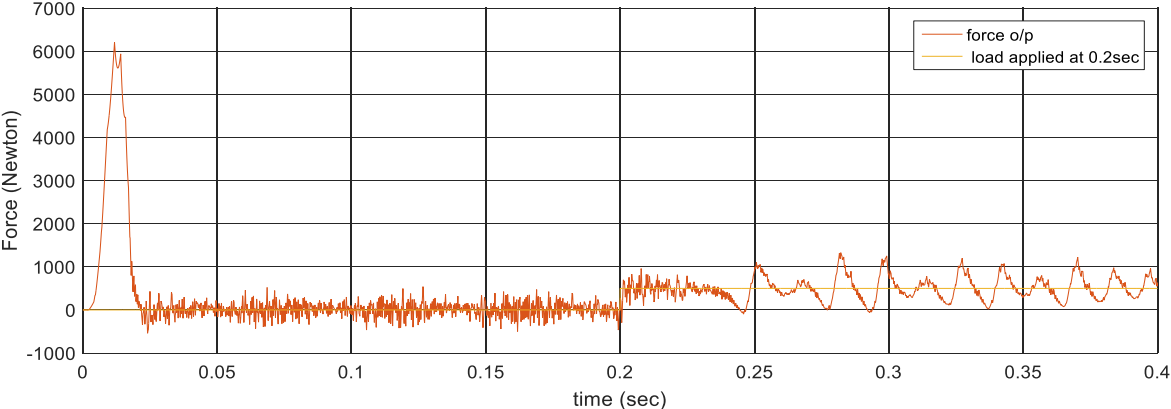


Figure 5.14 PI controller thrust or force response when load applied at 0.2sec

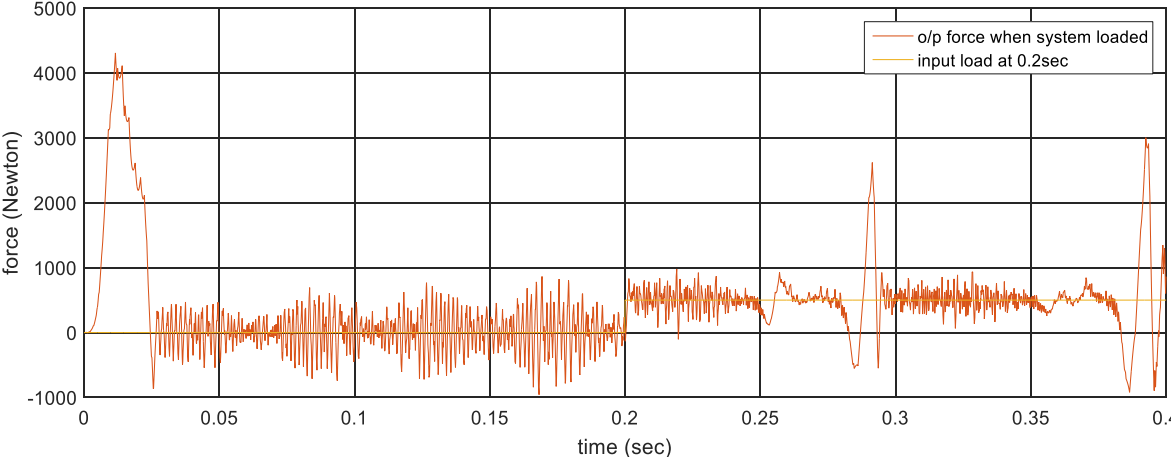


Figure 5.15 Fuzzy controller thrust or force response when load applied at 0.2sec

The third response saw with loaded condition, is three phase current output, which are shown in figure (5-15) and (5-16).

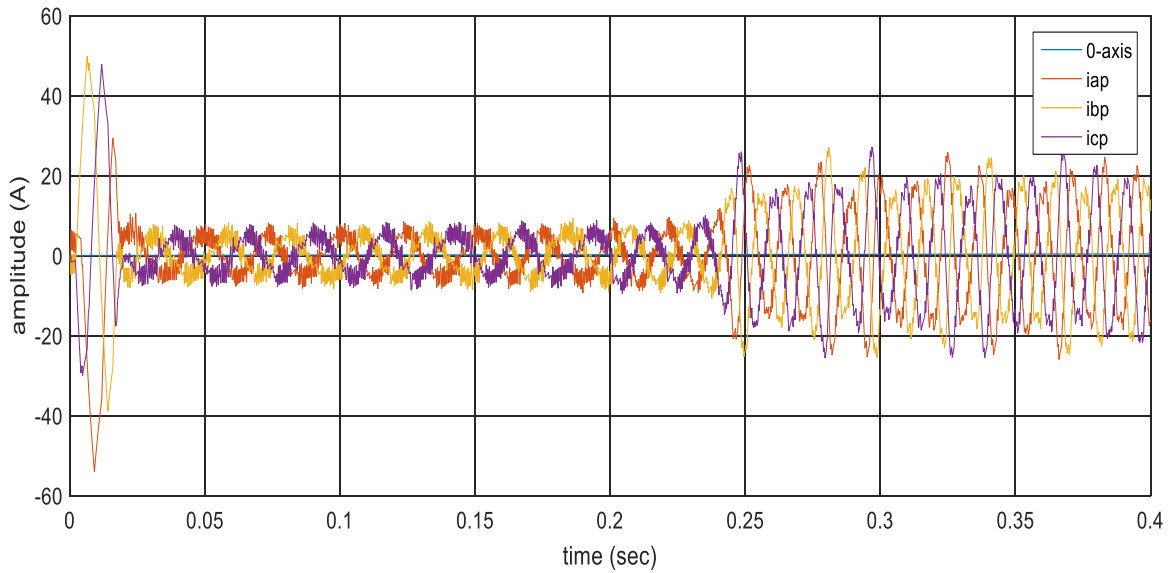


Figure 5.16 Shows PI controller three phase current output when system is loaded

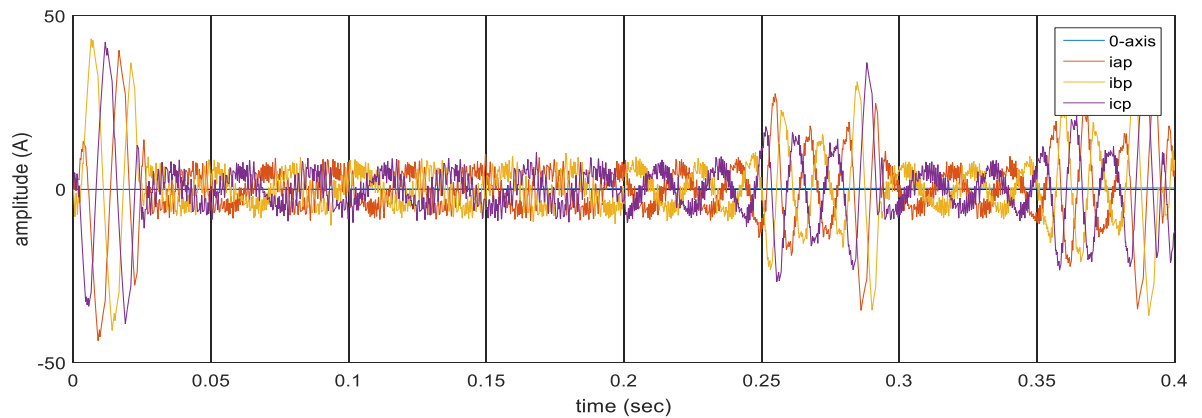


Figure 5.17 Shows fuzzy controller three phase current output when system is loaded

Third case carried out is, variation of input parameters, such as varying 50% primary resistance. For this case simulation result is shown in figure(5-18) and (5-19), using PI controller and fuzzy logic controller respectively. From result shown on figure (5-17) we have seen the steady state time variation from nominal value response ($t = 0.0257\text{sec}$) to ($t = 0.0424\text{sec}$) and peak amplitude is changed from 2.069m/sec , found on nominal response to 2m/sec . But in figure (5-19) the effect of primary resistance variation is only changed peak amplitude from, 2.016m/sec to 2.005m/sec .

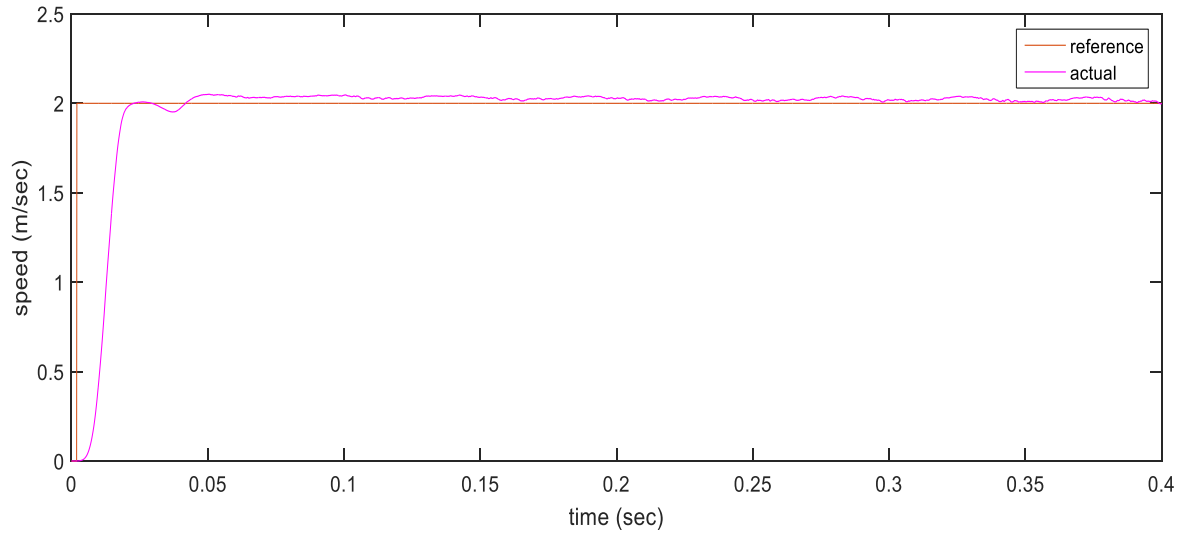


Figure 5.18 PI controller speed output when primary resistance varies by 50%

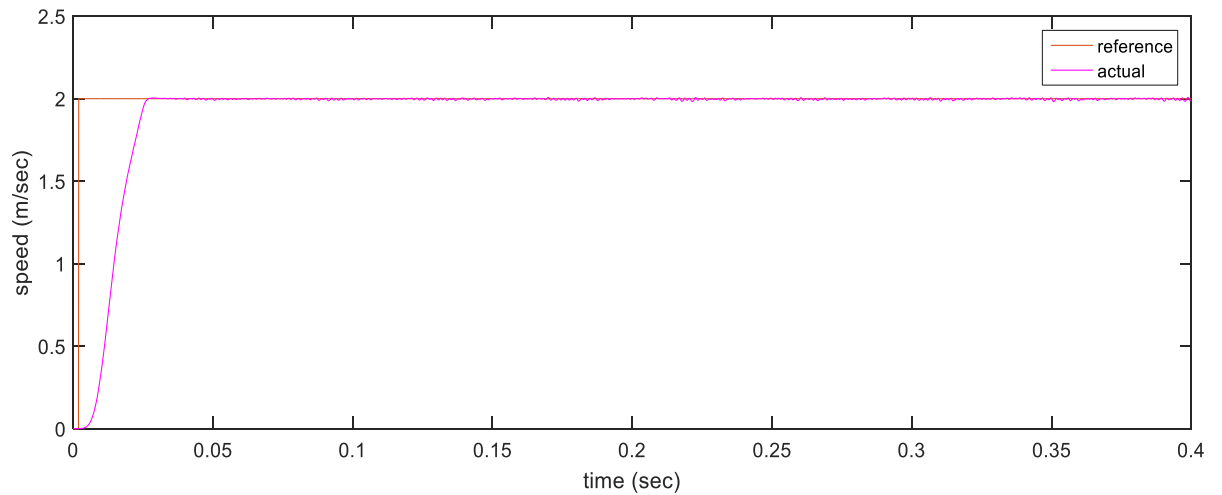


Figure 5.19 Fuzzy controller speed output when primary resistance varies by 50%

The fourth condition is, checking the performance of fuzzy logic controller over conventional type of controllers by tracking abilities of sudden change reference speed. For this, figure (5-20) shows the PI controller tracking reference signal performance. In this figure actual response following reference changed at time ($t = 0.1\text{sec}$) starts after time ($t = 0.1304\text{sec}$) with an error varies between 0.052 to 0.081, until second reference speed change its amplitude on (0.15sec). And, figure (5-21) shows fuzzy controller performance regarding tracking of applied input reference signal. In this

figure tracking reference signal starts at time ($t = 0.1295\text{sec}$) with zero error until second reference signal change its amplitude on time ($t = 0.15\text{sec}$). Again from figure (5-20) we have seen proportional integral controller abilities of actual speed following reference amplitude change occurred at time ($t = 0.15\text{sec}$). Under this condition following reference speed with changed error starts at time ($t = 0.1648\text{sec}$) and fuzzy logic controller response shown in figure (5-21) starts tracking amplitude changed at time ($t = 0.15\text{sec}$) at time ($t = 0.1601\text{sec}$) with zero error. Comparatively of figure (5-20) and figure (5-21), the fuzzy logic controller response exhibit that better speed tracking performance compared to PI controller response.

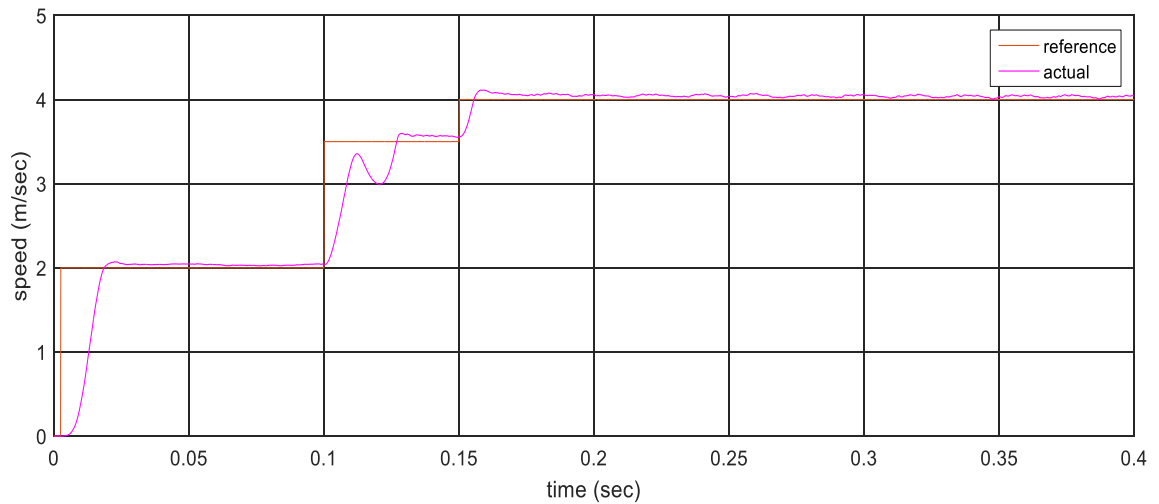


Figure 5.20 PI controller actual speed tracking applied reference speed

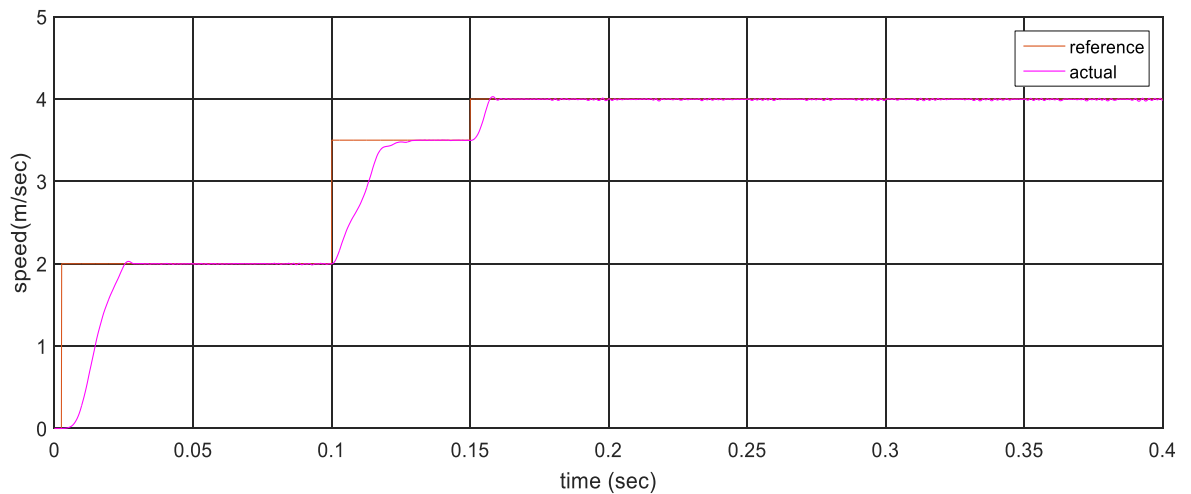


Figure 5.21 Fuzzy controller actual speed tracking applied reference speed

Finally, the event used for second stage is to recognize, observing the problem of an end effect existence on linear induction motor, means looking the uncompensated actual speed results performed using PI controller and fuzzy logic controllers.

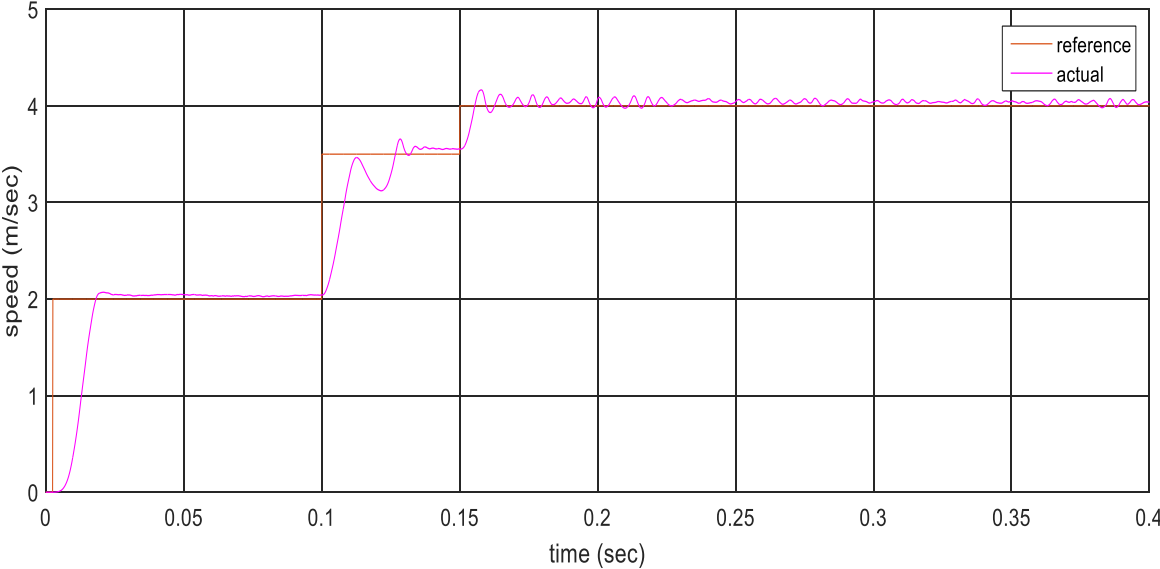


Figure 5.22 Uncompensated end effect PI controller actual speed tracking reference

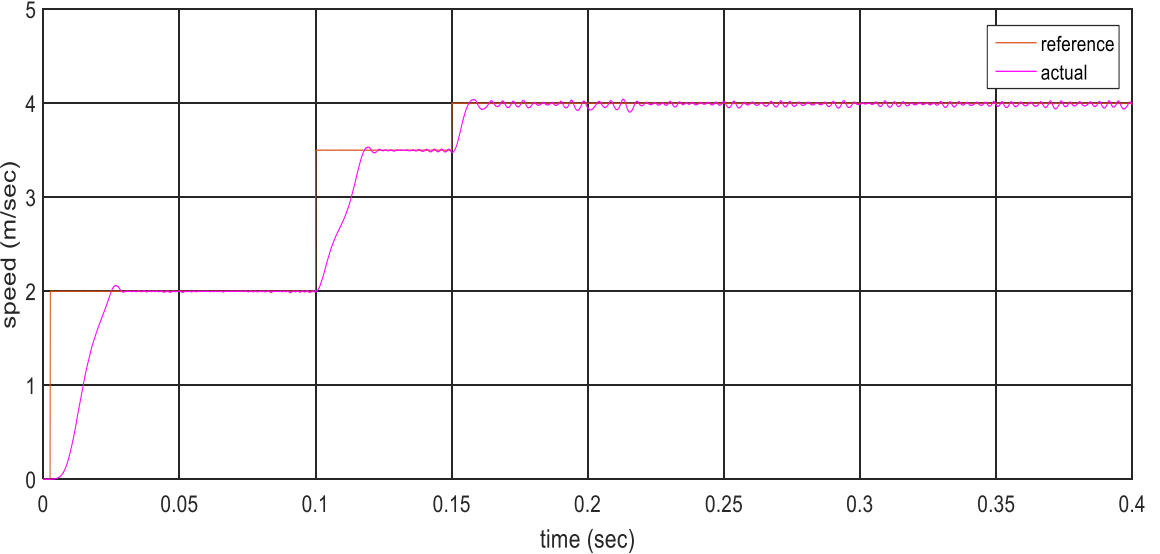


Figure 5.23 Uncompensated end effect fuzzy controller actual speed tracking reference

As we saw, compensated and uncompensated end effect problem from vector controller proposed, figure (5-20) and figure (5-22) PI controller speed tracking responses, the response noticed from uncompensated shown on figure(5-22) more fluctuation than response we get from compensated shown on figure (5-21). Just as compared to seen figure (5-20) and (5-22), figure (5-21) and figure(5-23) fuzzy logic response actual speed tracking of reference speed, the latter figure or uncompensated vector control end effect response contains fluctuation within the reference tracking, while figure (5-21) or compensated vector control response free from this problem.

Chapter six

6. Conclusion and Recommendation future works

6.1. Conclusion

Simulation conducted on first phase contains different defects, to manage and minimize the problems found on it, indirect vector controlled system is developed. This system proposed to solve the linear induction motor coupling effects problem that makes the system response undesired. Using this control system the performance and robustness of conventional and intelligent types of controllers have been evaluated under different operating conditions, such as: nominal condition, loading condition, sudden changing reference speed condition, variation parameter from nominal value condition and also challenges of end effect on a controlling systems has been performed. Those mentioned conditions and problems of end effect uncompensated from vector control are, analyzed comparatively using conventional, PI controller and intelligent, fuzzy logic controller, using MATLAB simulation in a well manner. The simulated result shows that a better dynamic performance with fuzzy Controller in relation to PI controllers in all conditions. The overshoot and large number pulsating in the force/thrust are observed with PI controller, which results in oscillated in speed between an error (0 to 0.047) and leads to take large settling time to become purely stable. Fuzzy logic controller based drive has lower starting overshoot in force/thrust, which changes (6207Newton) amplitude found on PI to 4309Newton and, also eliminate steady state error exist on PI controller responses to zero. Again fuzzy logic controller given robust performance in the presence of linear induction motor parameter variation and sudden load changes, however PI controller based drive is sensitive with parameter variation, such as; at a time of loading condition, controller response produced steady state error varies between (0 to 0.177). This result tells us PI controller highly dependent on model of the motor. Other comparative conducted condition was tracking abilities of changing to extended an operation above base speed. Due to this, fuzzy logic controller robustness tracking reference speed was highly satisfactory. In relation to the conditions mentioned above handling talent, the fuzzy logic controller can responded analogous to the expertise operator. Hence, it is known intelligent controller. The other simulation performed was problems of end effect on both types of controllers,

in this case from the results, noticed that an end effects had relatively a great influence on the speed responses.

6.2. Recommendation future works

This study investigated LIM, MATLAB modeling based on equivalent circuit including end effect and applied vector control system to analysis the performance of the modeled motor using simulation software, MAT LAB. Beyond to this study we mentioned the following tasks that are consider for future work

- ✓ Implementation of simulation for real work
- ✓ In this thesis the electronic derive pulse is SPWM, as we saw before slight harmonic content output have been collected, to overcome this defect we went to advice apply SVPWM in places of SPWM.
- ✓ Each and every task conducted in this paper is only about of SLIM but for future we recommended to work on DSLIM in similar manner.

References

- [1] E. R. Laithwaite, "Linear electric machines—A personal view," *Proceedings of the IEEE*, vol. 63, pp. 250-290, 1975.
- [2] A. P. Johnson, "High speed linear induction motor efficiency optimization," Cambridge, Massachusetts; Massachusetts Institute of Technology, 2005.
- [3] A. Loukianov, J. Rivera, A. Y. Alanis, and J. Raygoza, "Super-twisting sensorless control of linear induction motors," in *Electrical engineering, computing science and automatic control (CCE)*, 2012 9th international conference on, 2012, pp. 1-5.
- [4] Z. Zhang, T. R. Eastham, and G. E. Dawson, "Peak thrust operation of linear induction machines from parameter identification," in *Industry Applications Conference, 1995. Thirtieth IAS Annual Meeting, IAS'95., Conference Record of the 1995 IEEE*, 1995, pp. 375-379.
- [5] B. N. Kar, K. Mohanty, and M. Singh, "Indirect vector control of induction motor using fuzzy logic controller," in *Environment and Electrical Engineering (EEEIC)*, 2011 10th International Conference on, 2011, pp. 1-4.
- [6] E. F. da Silva, C. C. dos Santos, and J. Nerys, "Field oriented control of linear induction motor taking into account end-effects," in *Advanced Motion Control, 2004. AMC'04. The 8th IEEE International Workshop on*, 2004, pp. 689-694.
- [7] J.-h. Sung and K. Nam, "A new approach to vector control for a linear induction motor considering end effects," in *Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE*, 1999, pp. 2284-2289.
- [8] F. Korkmaz, I. Topaloglu, and R. Gurbuz, "Simulink model of vector controlled linear induction motor with end effect for electromagnetic launcher system," *Elektronika IR Elektrotehnika*, vol. 20, pp. 29-32, 2014.
- [9] H. Shadabi, A. R. Sadat, A. Pashaei, and M. Sharifian, "SPEED CONTROL OF LINEAR INDUCTION MOTOR USING DTFC METHOD CONSIDERING END-EFFECT PHENOMENON."
- [10] H. Yunhai and W. Yuhua, "Based on Neuron Adaptive Controller for Linear Motor Slip Frequency Vector Control system," in *Intelligent Human-Machine Systems and Cybernetics, 2009. IHMSC'09. International Conference on*, 2009, pp. 94-98.

- [11] M. Sarvi and H. Zamani, "Sensorless Vector Control of Linear Induction Motor on Primary and Secondary Flux Oriented based on Fuzzy PI Controller," *International Journal of Smart Electrical Engineering*, vol. 2, pp. 111-119, 2013.
- [12] F. Hoyos Velasco, S. Ocampo-Gutiérrez, R. Largo Taborda, and N. Toro, *Construction of Three Phase Linear Induction Motor*, 2015.
- [13] R. Krishnan, *Electric motor drives: modeling, analysis, and control* vol. 626: Prentice Hall New Jersey, 2001.
- [14] F. Benmohamed, I. Bousserhane, A. Kechich, B. Bessaih, and A. Boucheta, "New MRAS secondary time constant tuning for vector control of linear induction motor considering the end-effects," *COMPEL-The international journal for computation and mathematics in electrical and electronic engineering*, vol. 35, pp. 1685-1723, 2016.
- [15] C. Ganguly and M. Kowsalya, "Mathematical modelling of Linear Induction Motor with and without considering end effects using different reference frames," in *Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, IEEE International Conference on, 2016, pp. 1-5.
- [16] A. M. Trzynadlowski, *Control of induction motors*: Elsevier, 2000.
- [17] M. Khorshidi, S. S. Fazel, and B. Moaveni, "Speed Observer Design for Linear Induction Motor Drives," *Advances in Railway Engineering, An International Journal*, vol. 2, pp. 21-28, 2014.
- [18] A. Mishra and P. Choudhary, "Speed control of an induction motor by using indirect vector control method," *International Journal of Emerging Technology and Advanced Engineering*, vol. 2, pp. 144-150, 2012.
- [19] J. Finch, D. Atkinson, and P. Acarnley, "Scalar to vector: General principles of modern induction motor control," in *Power Electronics and Variable-Speed Drives*, 1990. Fourth International Conference on (Conf. Publ. No. 324), 1990, pp. 364-369.
- [20] K. Bimal, "Bose," *Modern power electronics and AC drives*, 2002.
- [21] L. J. Phukon and N. Baruah, "Fuzzy Logic based Speed Control of an Induction Motor Using Indirect Vector Control Method," *International Journal of Emerging Trends in Science and Technology*, vol. 2, 2015.

- [22] E. Da Silva, E. Dos Santos, P. Machado, and M. De Oliveria, "Vector control for linear induction motor," in *Industrial technology, 2003 IEEE international conference on*, 2003, pp. 518-523.
- [23] K. Bimal, *Modern power electronics and AC drives*: Prentice-Hall, 2001.
- [24] J. Zhao, Z. Yang, J. Liu, and T. Q. Zheng, "Indirect vector control scheme for linear induction motors using single neuron PI controllers with and without the end effects," in *Intelligent Control and Automation, 2008. WCICA 2008. 7th World Congress on*, 2008, pp. 5263-5267.
- [25] E. L. C. Arroyo, "Modeling and simulation of permanent magnet synchronous motor drive system," *University of puerto rico, Mayagüez Campus*, 2006.
- [26] B. K. Bose, "Power electronics and variable frequency drives-technology and application," *IEEE Press*, 1997.
- [27] B. Tolunay, "Space Vector Pulse Width Modulation for Three-Level Converters: a LabVIEW Implementation," ed, 2012.
- [28] K. V. Kumar, P. A. Michael, J. P. John, and S. S. Kumar, "Simulation and comparison of SPWM and SVPWM control for three phase inverter," *ARPJN Journal of Engineering and Applied Sciences*, vol. 5, pp. 61-74, 2010.
- [29] S. P. Awate and N. Wagh, "Sinusoidal PWM Inverter fed Induction Motor Drive," *International Journal of Engineering Trends and Technology*, vol. 31, 2016.
- [30] A. Aktaibi, M. Rahman, and A. Razali, "A critical review of modulation techniques," 2010.
- [31] R. K. Rao, P. Srinivas, and M. S. Kumar, "design and analysis of various inverters using different PWM techniques," *The International Journal of Engineering And Science (IJES)*, ISSN (e), pp. 2319-1813, 2014.
- [32] P. MacVicar-Whelan, "Fuzzy sets for man-machine interaction," *International Journal of Man-Machine Studies*, vol. 8, pp. 687-697, 1976.
- [33] S. S. Nerurkar, "Design and implementation of fuzzy logic controller for a process control application," *New Jersey Institute of Technology, Department of Electrical and Computer Engineering*, 1994.
- [34] L. Reznik, *Fuzzy controllers handbook: how to design them, how they work*: Elsevier, 1997.

- [35] O. A. M. Ali, A. Y. Ali, and B. S. Sumait, "Comparison between the effects of different types of membership functions on fuzzy logic controller performance," *International Journal*, vol. 76, pp. 76-83, 2015.
- [36] A. Karakaya and E. Karakas, "The speed control of permanent magnet synchronous motor using fuzzy logic and self tuning fuzzy PI controller," *Proc. ELECO'05*, 2005.
- [37] R. Kavitha and S. Nagaraju, "Modeling and Implementation of fuzzy vector control for Induction motor Drive," *International Journal of Engineering Research and General Science*, vol. 3, pp. 371-382, 2015.
- [38] A. H. O. Ahmed, "Speed Control of Vector Controlled Induction Motors Using Integral-Proportional Controller," 2014.

Appendix

Deriving input parameters for LIM

```
%Primary and secondary resistance in ohm
Rp=5.3685;
Rs=3.535;
% primary and secondary inductance in hennergy (H)
Lp=0.05265;
Ls=0.05265;
% mutual inductance in hennergy(H)
Lm=0.02419;
% Number of poles
P=8;
% pole pitch length of the motor in (meter)
Tp=0.027;
% mass of the motor in kilo gram (Kg)
M=25;
% length of a motor in meter
D=0.216;
% sampling time in second
Ts=0.0001;
% current controller PI gain, ''kp= proportional gain, ki= integral gain''
Kp=473;
Ki=675;
% speed controller PI gain, ''kps= proportional gain, kis=integral gain''
Kps=3250;
Kis=6350;
% fuzzy logic controller gains '' ke= error gain, kd=derivative gain''
Ke=2.4;
Kd=0.0004;
% FLUX controller gains '' kpf=proportional gain, kif=integral gain''
Kpf=7;
kif=45;
```

