

# FUZZY LOGIC BASED SOFT STARTING OF INDUCTION MOTOR WITH CURRENT CONTROL

*A Thesis Submitted in Partial Fulfillment of the Requirements for the  
Award of the Degree of Master of Technology*

*in*

*Electrical Engineering  
(Power Electronics & Drives)*

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**DEPARTMENT OF ELECTRICAL ENGINEERING  
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PIN-769008, ODISHA  
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**Under the Supervision of**

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(2012-2014)**

**To**

***God and my parents***



# **National Institute Of Technology, Rourkela**

## **Certificate**

This is to certify that the thesis entitled “**Fuzzy Logic based Soft Starting of Induction Motor with Current Control**” submitted by **Mr. Suvra Gupta** to the National Institute of Technology, Rourkela for the award of degree of **Masters of technology** in **Electrical Engineering** of specialization, **Power, Electronics and Drives**, is a bonafide record of research carried out by her under my supervision. The content of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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**Suvra Gupta**

# ABSTRACT

Induction Motors are the most commonly used machines in industries mainly because it is robust, inexpensive and easy to maintain. For an Induction Motor, the starting current is around ten times the rated current and this persists for a few cycles. This may be very much detrimental for the machine and hence there is a need for using starters to limit the starting current. During earlier times, mechanical starters like star delta, direct online and autotransformer starters were used. Thyristorized soft starters are of low cost. Their reliability is on the higher side and they are simple and occupy lesser space, and hence their use is a fruitful solution to the induction motor starting problem. The ac motor starters incorporating power semiconductors are used frequently nowadays for their controlled soft starting ability with reduced starting current.

In this study, a closed loop MATLAB SIMULINK model is developed which would reduce the current at the soft starting period. A fuzzy logic based soft start scheme for induction motor drives is used which would give optimal performance. Fuzzy logic has received higher emphasis in the field of power electronics because of its adaptive capability. The three phase stator currents are converted into two phase currents. The magnitude of current is then converted to per unit. Then it is compared with a reference value. The error is passed through a Fuzzy Logic Controller (FLC). The FLC output is used to control the amplitude of the reference sine wave. Hence by controlling the modulation index, the applied voltage to the stator is controlled and hence the starting current is limited.

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$Z_{AB}$	impedence seen along A and B,
$X_L$	inductive reactance,
$X_C$	capacitative reactance,
$R_s$	stator resistance,
$R_r'$	rotor resistance,
$X_{ls}$	stator leakage reactance,
$X_{lr}'$	rotor leakage reactance and
$Z_{Lmin}$	minimum impedance as seen from A and B.
$m_a$	amplitude modulation index
$v_{control}$	amplitude of control voltage
$v_{tri}$	amplitude of triangular voltage
$m_f$	frequency modulation ratio
$f_s$	switching frequency
$f$	supply frequency
$V_d$	dc link voltage of the inverter
$I_{2s}$	Rotor current at a slip $s$
$R_2$	Rotor resistance
$s$	Slip of the machine
$E_{20}$	Rotor induced Emf at the standstill condition
$X_{20}$	Rotor reactance at standstill condtion

$T_L$	Load Torque
$T_b$	Base Torque
$\omega_{rm}$	Maximum mechanical Rotor Speed in rad/sec
$\omega_{bm}$	Base rotor speed mechanical in rad/sec

# CHAPTER 1

---

## INTRODUCTION

1.1 Overview

1.2 Motivation

1.3 Objective of Thesis

1.4 Thesis Organisation

## 1.1 OVERVIEW

Most of the machines used in the industries are three phase induction motors. They have simple and rugged construction and their robust nature make them possible to operate in all environmental condition. Also induction machines are cheaper in cost and maintenance free. Also they are having starting torque and are widely used in domestic and industrial applications.

Inverter based induction machines are having widespread applications, especially in Hybrid Electric Vehicles, used in modern cars.

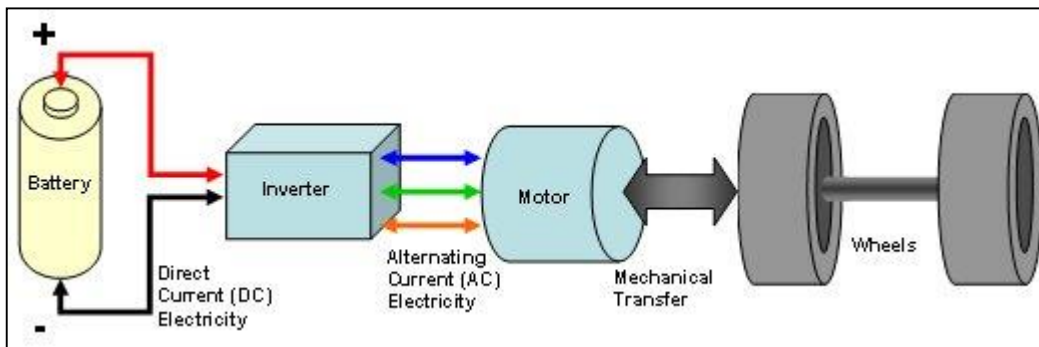


Fig 1.1 a HEV drive system

Figure 1.1 shows diagram of an electric drive system, where the inverter is fed direct current (DC) from the battery and converts it to alternating current (AC) and sends it to the motor. The electric motor uses this to create torque to power the wheels for propulsion. This shows a modern application of inverter and power electronics.

The expression for the rotor current of an induction motor at is given by  $I_{2S} = \frac{sE_{20}}{R_2 + jsX_{20}}$

At the time of starting, the value of slip is very high, hence the starting current is very high. This kind of high starting current is very much detrimental for the machine since the machine windings are designed mainly to carry the rated currents. So to reduce this starting current manual starters are used like direct online, star delta and autotransformer.

AC motor starters which uses power semiconductors are being increasingly used to replace mechanical line starters and conventional reduced voltage starters. This is because of their controlled soft starting capability with lower starting current during the soft start period.

Of these soft starters which apply reduced voltage to the motors are cheap, simple and reliable and occupy less volume and hence are a practicable solution to the starting problem of medium voltage large AC motors in applications where the starting torque requirement of the load is not excessively high.

Soft starter is an electrical device specializes with controlling AC motor with soft start, soft point, light-load energy saving and a good deal more protection features. The soft starters work on the principle that by controlling the firing angle of the solid state switches the voltage applied to the motor is varied.

Fuzzy Logic Controller has found various applications in the past decade. It has proved to be effective for complex, nonlinear and imprecisely defined process for which standard model based control techniques are impractical and impossible. Fuzzy Logic deals with problems which have vagueness, uncertainty and uses membership functions with values varying from 0 to 1.

## 1.2 MOTIVATION

Electrical machines are a very important part of Electrical Engineering and applications of machines in electric drives make them much more interesting. The current of an induction motor can go above its rated value at the time of fault or at the time of starting. Obviously whenever the fault takes place it is not in our hand or rather it is unpredictable. But during starting the current will go high and can be controlled. Hence to design a simple controller which can limit this starting current is the main aim of the project.

## 1.3 OBJECTIVE OF THESIS

The main objective of the thesis is to limit the starting current of the motor to three times the rated value. Also it is required to formulate proper rules to design a fuzzy logic controller which would limit the starting current to three times the rated value.

## 1.4 THESIS ORGANIZATION

Chapter 1 deals with the introduction, motivation and the objective of the thesis.

Chapter 2 deals with Literature Review.

Chapter 3 deals with soft starting. In this chapter how soft starting helps the motor is discussed.



Also its applications are discussed here.

Chapter 4 deals with Fuzzy Logic Controller and its design. Here the rules are discussed and why these rules have been made are also designed.

Chapter 5 mainly deals with the block diagram of the overall system, filter design and as to how the control strategy is implemented.

Chapter 6 deals with simulation and results. Here all the waveforms are given for the simulated system for both open loop and closed loop.

Chapter 7 deals with conclusion and scope for future work.

# CHAPTER 2

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## LITERATURE REVIEW

# Literature Review

Direct Online starting may create problems when the ac supply is weak because it may cause low voltage at the starting which is a constraint as during starting too much reduction in voltage is detrimental. [5].

An uncontrolled start may cause a functioning of the overvoltage or under voltage relay, resulting in starting failure. Further the motor cannot be energized until it cools down to an allowable temperature in a long time period. Thus the current and torque profiles of the machine are to be tailored properly depending upon the load [5] [6].

AC Motor starters incorporating power semiconductor devices are used increasingly these days, putting back the conventional reduced voltage starters because of their controlled soft start capability with limited starting current. Among these thyristor-based soft starters which employ reduced voltage to the motors are of low cost, reliable and occupy lesser volume and hence are feasible solution for starting medium voltage large ac motors in applications where the starting torque requirement of the load is not so high [1].

Depending upon the initial switching instants of all the three phases to the supply, an induction machine may produce severe pulsations on the electromagnetic torque, regardless of whether it is regulated with direct online or soft starter [1].

When an ac induction motor is run at less than full load conditions, it consumes more energy to perform work. This excess energy is thrown off by the machine in the form of heat. With fuzzy logic controller, it is possible to control the peak amplitude of starting current and also save more energy during this starting period. In addition to this the cost and complexity of controller is reduced when it is designed using fuzzy logic method because it doesnot require the exact mathematical model of the system [8].

Soft start schemes show that gradual increase across the motor so that rated voltage will be applied across the motor at the end of soft start, thus increasing stator copper loss and undesirable harmonics to least at light loads. It was studied that efficiency was low and power factor was poor in that kind of soft starters under no load and light load conditions [9,10,11]. Sometimes the drive system lead to undesirable oscillations [12]. The novel soft start schemes reported in [13] have eliminated the above problems of the conventional soft starts and they

apply close to optimal voltage at the end of soft start, thus maintaining high efficiency better power factor and reduced copper loss.

In the proposed scheme the main focus is that by controlling the torque of the machine, the starting current is to be limited during the soft starting period. The induction machine is fed through an inverter. To reduce the current during starting, the voltage applied to the stator of the machine needs to slowly increased to rated value. This can be achieved by controlling the modulation index of the inverter. This kind of proposed scheme can be used in hybrid electric vehicles.

# CHAPTER 3

---

## SOFT STARTING

3.1 Soft Starting

3.2 Types of Soft Starters

3.3 How Soft Starting helps to protect motors

3.4 Applications of Soft Starting

## 3.1 Soft Starting

Soft starters are electrical device which can control the AC motor in soft starting, soft stopping, light-load energy saving and for additional protection options. The soft starter's main components include three phase antiparallel thyristors between power source and the AC motor and related control circuits. The soft starters work on the principle that by controlling the firing angle of the solid state switches like thyristors, IGBT's, Mosfets the voltage applied to the motor is varied. Therefore the main motive is elimination of mechanical starters like star delta, autotransformer and direct online starters.

## 3.2 Types of Soft Starters

### 3.2.1 Primary Resistor Startup

This is one of the simple techniques which were used earlier. When the motor is started, the resistors resist the current flow leading to a drop in voltage. A timer is present which closes a group of contacts once the motor has accelerated to a pre-determined point. This removes the resistors from the circuit and lets full power go through to the motor. The main disadvantage is that there will be copper losses in the resistances.

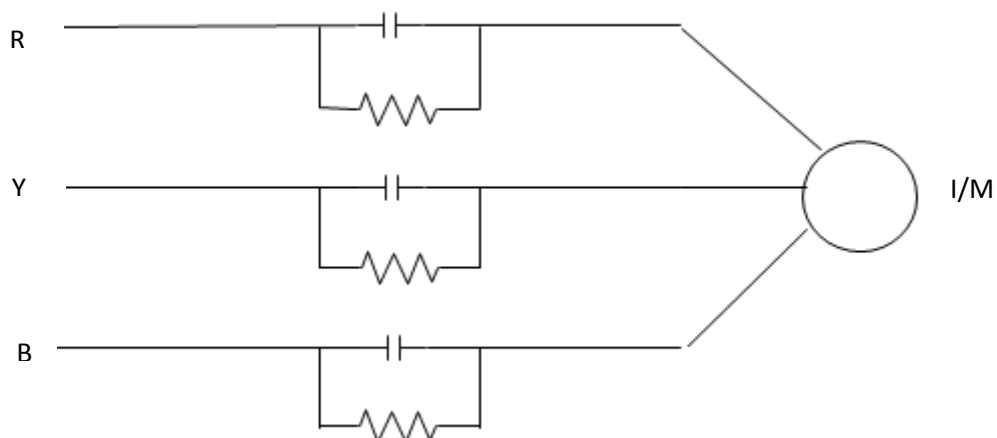


Fig 3.1 Typical Electric Diagram for primary resistor reduced voltage starter

### 3.2.2 Auto-Transformer Startup

Auto transformer starting is also a traditional method of soft starting. It is preferred over primary resistor starting when the starting current to be drawn from the line is minimum, but maximum starting torque per line current is required. Instead of using resistors, this starter uses taps on the transformer windings to control the power supply to the motor. Taps are usually set up to provide 80%, 65% and 50% of the line voltage, respectively and hence the voltage applied to the motor can be varied.

These taps give flexibility to the system. In Fig. 3.2 the motor is receiving voltage through the second of the three taps.

Starting current in autotransformer starter is less than DOL starter but the starting torque of autotransformer starter is low compared to DOL starter.

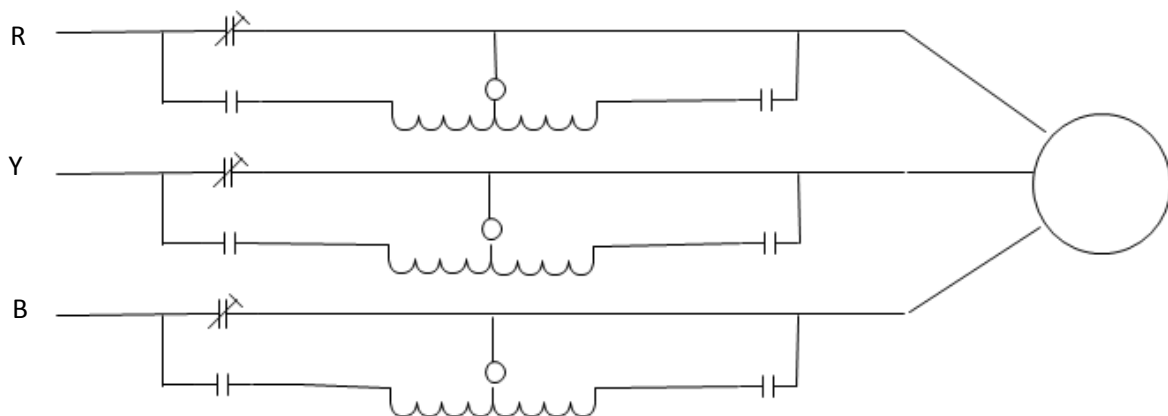


Fig 3.2 Typical Electrical Diagram for an autotransformer reduced voltage starter

### 3.2.3 Wye Delta

In case of star delta starter at the starting the motor is connected in star and after some time it is converted to delta using some switch. Obviously this transition will give a jerk to the machine and that can be harmful. Actually contactors are present which help during transition. During starting in star connection lesser voltage is impressed to the stator of the machine and hence

starting current will be low. In delta full voltage is impressed to the motor windings and hence the machine achieves full speed. Starting current in case of star delta starter is one third that of DOL starter whereas starting torque of star delta starter is one third that of DOL starter.

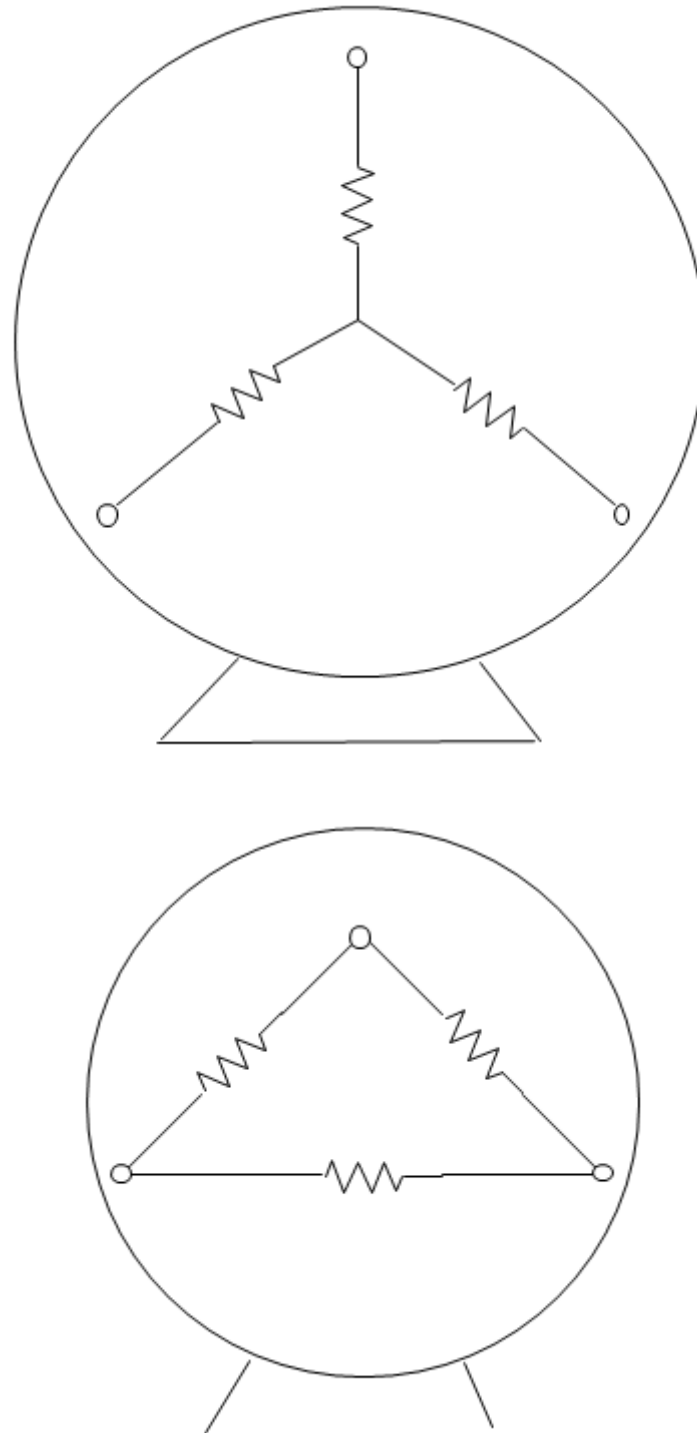


Fig 3.3 Wye connection at start and delta as the motor reaches full speed



### 3.2.4 Solid State

The latest use of solid state devices such as thyristors (SCR), IGBTs, Mosfets are used for soft starting purpose. It eliminates mechanical components with electrical components. When the motor accelerates, this device controls motor voltage, current and torque. Fig. 3.4 shows how the solid state soft starter controls the current drawn and the starting torque. The SCR has the capability to rapidly switch heavy currents. This allows the soft starter to provide smooth stepless acceleration - the smoothest of any of the soft start methods. It is used for constant speed induction motors where the stator voltage is applied gradually to limit the starting current. As seen in the figure there are two thyristors in each phase connected in antiparallel.

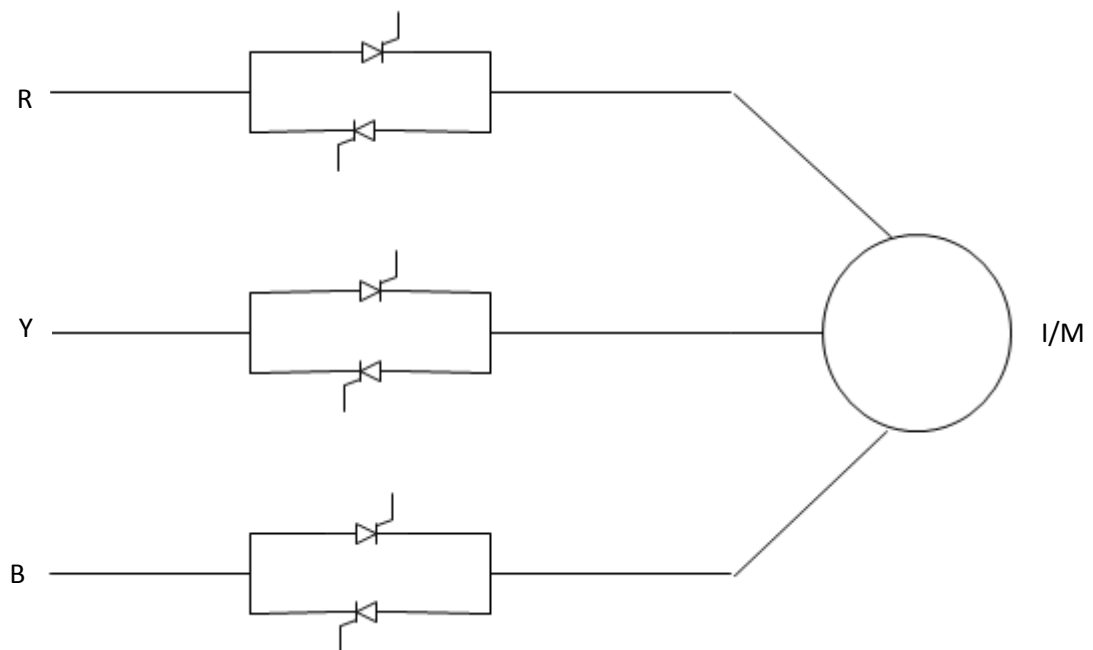


Fig 3.4 Solid State Reduced Voltage Starter

### 3.3 How soft starters protect the motor ?

- ✓ Soft Starters help to reduce overheating
- ✓ They also help to know whether there is any phase loss in the motor. This is very helpful because any loss of phase will lead to tremendous unbalance in the system.
- ✓ Current controllers are present in soft starting schemes which help in overload protection.

### 3.4 Applications of Soft Starter:

- ✓ They can be used for high inertia loads successfully.
- ✓ They can be used to start pump with grid then switch to generator to avoid starting current.
- ✓ They are used in variable speed drives nowadays.



Fig 3.5 Soft Starter

# CHAPTER 4

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## FUZZY LOGIC CONTROLLER AND ITS DESIGN

4.1 Introduction

4.2 Configuration of FLC

4.3 Steps to design a FLC

4.4 Designing of Fuzzy Logic Controller

4.5 Selecting and Designing Membership Functions

4.6 Rule Base

4.7 Summary

## 4.1 Introduction

Fuzzy control is a control system based on AI is defined as intelligent control. A fuzzy control system essentially takes the experience and intuition of some human plant operator and sometimes those of a designer or researcher of a plant. The mathematical model of the plant is not required in fuzzy control. It is an adaptive and nonlinear control and gives robust performance for both linear and nonlinear plants with parameter variation. It is also easy to implement.

## 4.2 Configuration of FLC

Principal components of Fuzzy Logic Controller

1. Fuzzification Block or Fuzzifier
2. Knowledge base
3. Descision Making Block
4. Defuzzification block or Defuzzifier

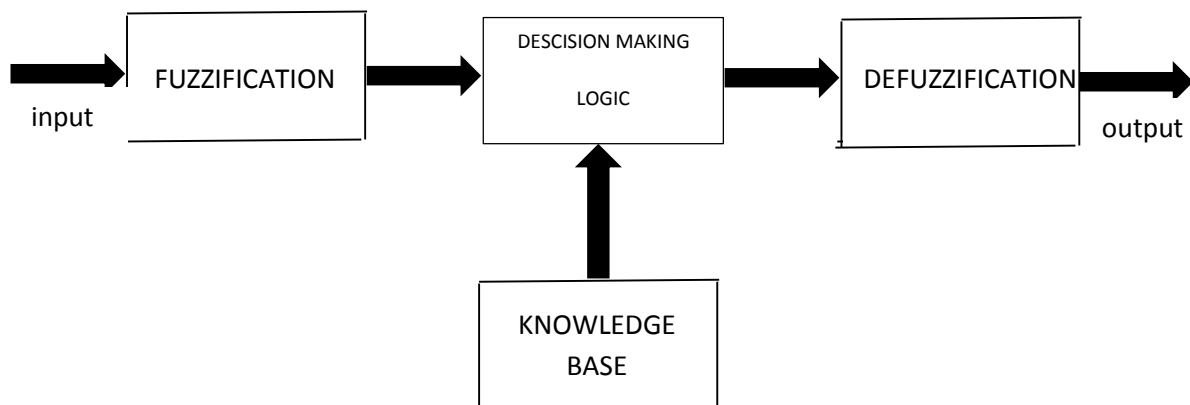


Fig 4.1 Fuzzy Block Diagram

### 4.2.1 Fuzzifier

As discussed fuzzy logic is based on linguistic variable but since input given to the FLC block is in numeric form so first thing to be done is to convert the numerical data or variable into

linguistic variable and this task is performed by the fuzzifier. So fuzzifier converts the numerical variable given to the FLC into linguistic variable. This fuzzification task includes choosing proper membership functions for the variables so that the crisp inputs can be converted into fuzzy sets.

### 4.2.2 Knowledge Base

It consists of data base and rule base. The main aim of data base is to provide necessary definitions needed to define the linguistic control rules and the aim of rule base is to characterize the control goals and policies by using a set of linguistic or If-then rules. In the If-then statement, the if part is called antecedent and the then part is called consequence.

### 4.2.3 Decision Making Block

It is the most important block of a fuzzy controller because it is the block that decides the output depending on the input. Based on fuzzy concepts, data and rule bases, it provides reasonable outputs.

### 4.2.4 Defuzzifier

It performs the task just opposite to that of a fuzzifier. So the task of the defuzzifier is to convert the linguistic variable into a crisp one. There are different types of defuzzification techniques present for defuzzification.

1. Centroid of Area(COA)
2. Bisector of Area(BOA)
3. Mean of Maximum(MOM)
4. Smallest of Minimum(SOM)
5. Largest of Maximum(LOM)

In our control design centroid of area technique is used for defuzzification.

## 4.3 Steps to design a Fuzzy Logic Controller

So the steps to design a fuzzy logic controller are as follows

1. Selecting the input to the FLC

2. Selecting proper MFs both for input and output variables
3. Fuzzification of the input variables
4. Preparing a fuzzy rule base for the controller
5. Selecting proper defuzzification technique
6. Defuzzification of output that is to be given to the system for desired operation

#### 4.4 Designing of Fuzzy Logic Controller

The input to the fuzzy logic controller is the error between the currents in dc form. The three phase currents are converted into two phase currents and then the magnitude is taken. This is then converted into per unit by dividing with the rated current as shown below. This is then compared with one to get the error. The error is fed to the fuzzy logic controller. The output of the fuzzy logic controller is converted from dq to abc to get the three reference sinusoid, which is compared with carrier wave to generate the pulses to be fed to the inverter.

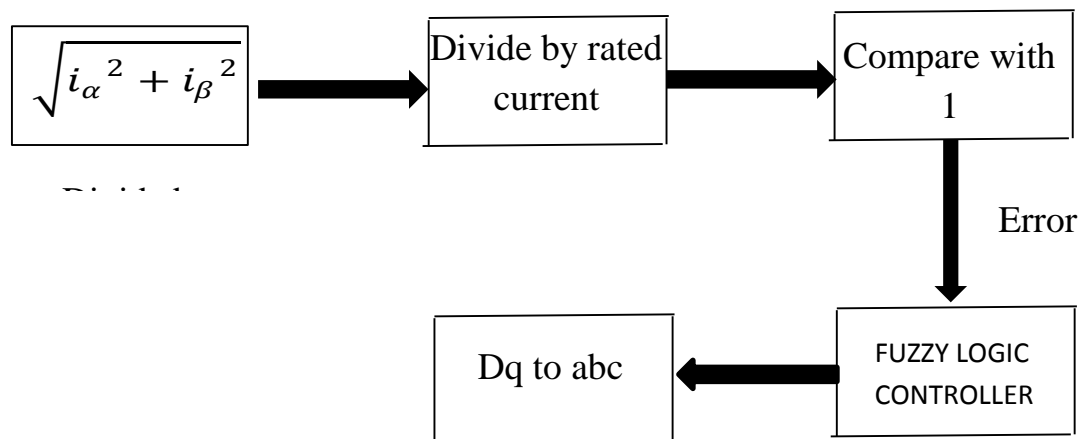


Fig 4.2 Block Diagram of control circuit

## 4.5 Selecting and Designing Membership functions

Fuzzy Set	Range of MFs	Membership Function chosen
NegativeE(error)	-0.3193 to -0.1693 -0.1693 to 0.1	Triangular
LowE(error)	-0.1 to 1 1 to 2	Triangular
MediumE(error)	1.8 to 3 3 to 4	Triangular
HighE(error)	3.9 to 5 5 to 7	Triangular

Table 4.1 Fuzzy Set and MFs for input current error

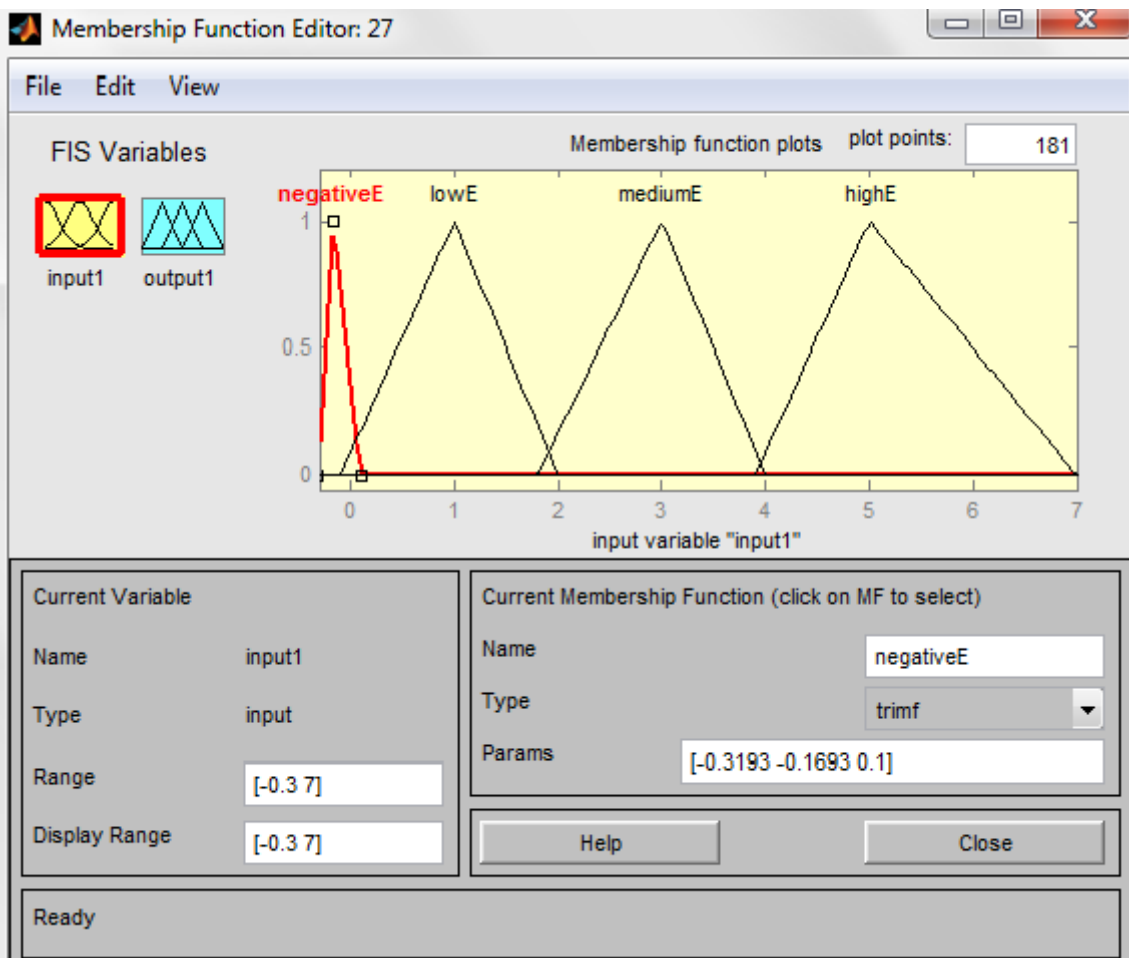


Fig 4.3 Membership Function of Input Error

Fuzzy Set	Range of MFs	Membership Function chosen
Very Low	0 to 0.15 0.15 to 0.3	Triangular
Low	0.28 to 0.45 0.45 to 0.6	Triangular
Medium	0.55 to 0.7 0.7 to 0.94	Triangular
High	0.93 to 0.97 0.97 to 1	Triangular

Table 4.2 Fuzzy Set and MFs for output

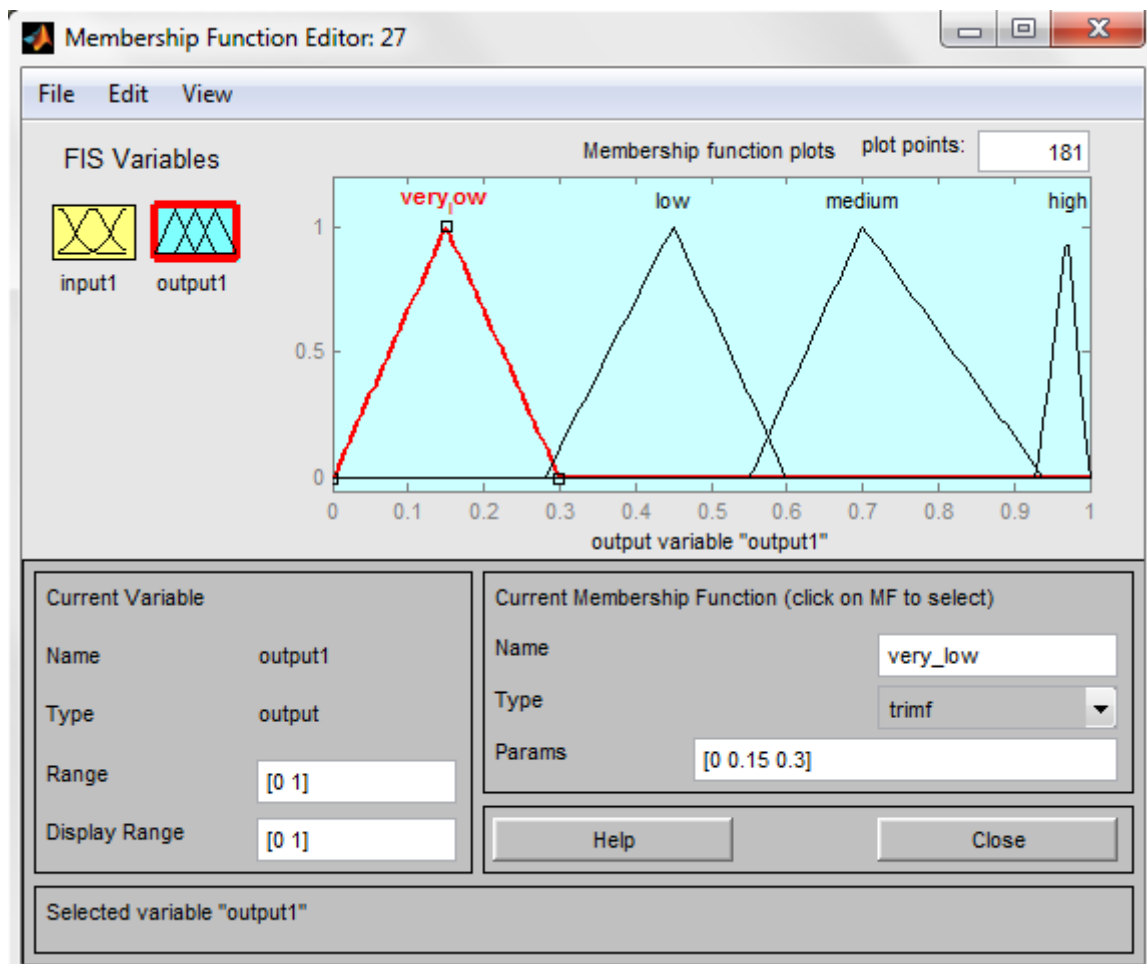


Fig 4.4 Membership Function of output



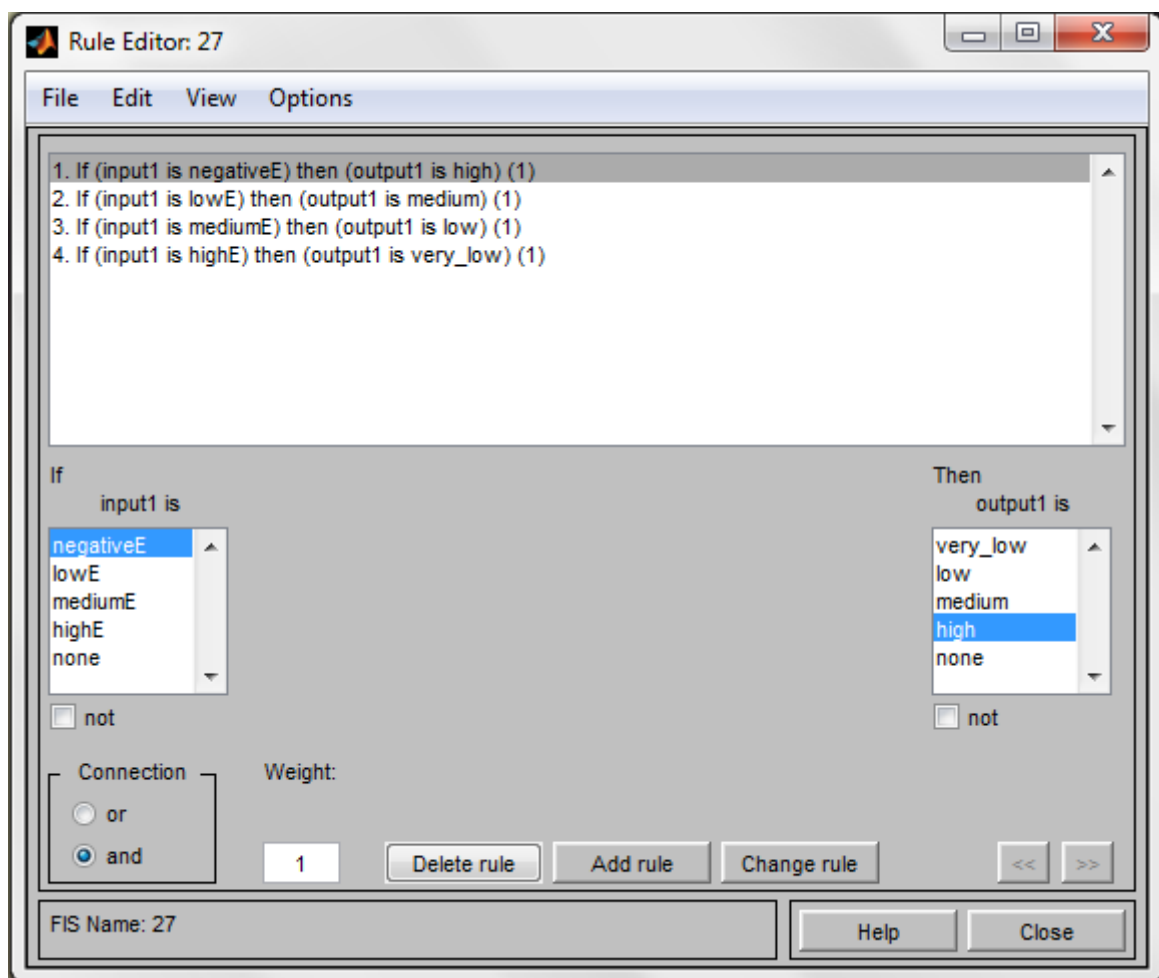
## 4.5 Rule Base

The rules that are incorporated in the Fuzzy Logic Controller are as follows

- If input is negativeE then output is high
- If input is lowE then output is medium.
- If input is mediumE then output is low
- If input is highE the output is very low

The main aim over here is that by seeing the error profile in the open loop system we have incorporated the above set of rules.

Fig 4.6 Rule Editor Window



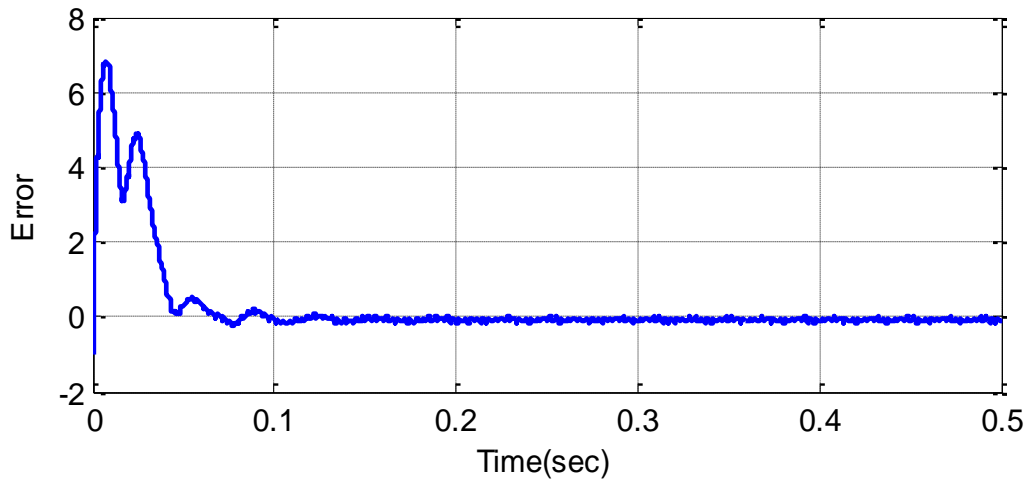


Fig 4.6 Error in current

We have decided that when the error is negative, we have set the modulation index around 0.95. When the error is one to two times we have set the modulation index to 0.7. When the error is two to four times we have set the modulation index to 0.4. When the error is four to seven times we have set the modulation index to 0.15. This is the main basis upon which the Fuzzy Logic Controller was designed and the values were taken care of accordingly.

## 4.6 Summary

In this chapter the control strategy as to how to implement the fuzzy logic controller is discussed. The logic behind the rules are also explained.

# CHAPTER 5

---

## FUZZY LOGIC BASED SOFT STARTING OF INDUCTION MOTOR WITH CURRENT CONTROL

- 5.1 Introduction
- 5.2 Low pass filter design
- 5.3 Block diagram
- 5.4 Control strategy
- 5.5 Summary

## 5.1 INTRODUCTION

The inverter output contains square wave. It has harmonics which needs to be eliminated from the system. For this purpose a Low Pass Filter is used which allows lower order harmonics to pass through and higher order harmonics to be eliminated. This contains an inductor in series and a capacitance in shunt. A small amount of resistance cannot be neglected. It is important aspect that the filter designed should not cause loading effect to the induction machine. Hence its design is an important aspect.

In this chapter a strategy is shown in which the starting current is limited. The induction motor is fed through an inverter. The inverter is switched through sinusoidal pulse width modulation technique. The output of the inverter is filtered using a low pass filter. This is then fed to an induction motor. The three phase currents are then converted into two phase currents using transformations. The magnitude of this two phase current is taken and converted to per unit. It is then passed through a fuzzy logic controller (FLC) controller after comparing with a reference value. Finally the FLC output is averaged and then converted from dq to abc. Thus by controlling the amplitude of reference wave the inverter output is controlled and hence the starting current is limited.

## MACHINE SPECIFICATIONS

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Rated Power	5.4HP, 4KW
Rated Voltage	400 V
Rated Frequency	50Hz
Rated Speed	1430 rpm
Type of Rotor	Squirrel Cage type
No of Poles	4
$R_s$	1.405 $\Omega$
$L_{ls}$	0.005839 H
$L_m$	0.1722 H
$R_r'$	1.395 $\Omega$
$L_{lr}'$	0.005839 H
Rated Torque	25.46 Nm
Rated Current	10.9 amp
Rated Speed	157 rad/sec

Table 5.1 Machine Specifications

### 5.2 L-C filter design

For the design of the filter, the Fast Fourier Transform of the line voltage was taken, where the frequencies were seen and the contribution of the harmonics. The important factor to be kept in mind while designing the L-C filter is resonance. We have to choose the resonating frequency in such a way so that the contribution of harmonics is low or else it will be amplified and affect the inverter voltage.

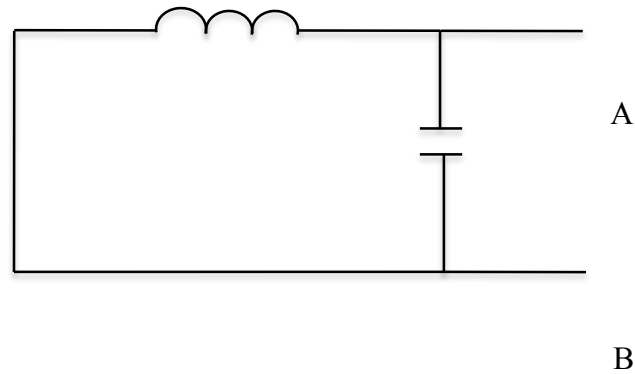


Fig 5.1 Equivalent Circuit of the filter

To avoid the loading effect the impedance seen along AB should be much smaller than the minimum load that we can connect.

$$Z_{AB} = \frac{X_L * X_C}{X_L + X_C} = \frac{Z_{Lmin}}{10}$$

$$Z_{Lmin} = (R_s + R_r') + j(X_{ls} + X_{lr}')$$

$$\text{At resonance } X_L = X_C$$

where  $Z_{AB}$  is the impedance seen along A and B,

$X_L$  is the inductive reactance,

$X_C$  is the capacitive reactance,

$R_s$  is the stator resistance,

$R_r'$  is the rotor resistance,

$X_{ls}$  is the stator leakage reactance,

$X_{lr}'$  is the rotor leakage reactance and

$Z_{Lmin}$  is the minimum impedance as seen from A and B.

Considering resonance to occur at 1350 Hz the values of L and C were computed and found out to be  $L=1.459$  mH,  $C=9.52$   $\mu$ F.

### 5.3 Fast Fourier Transform of line voltage

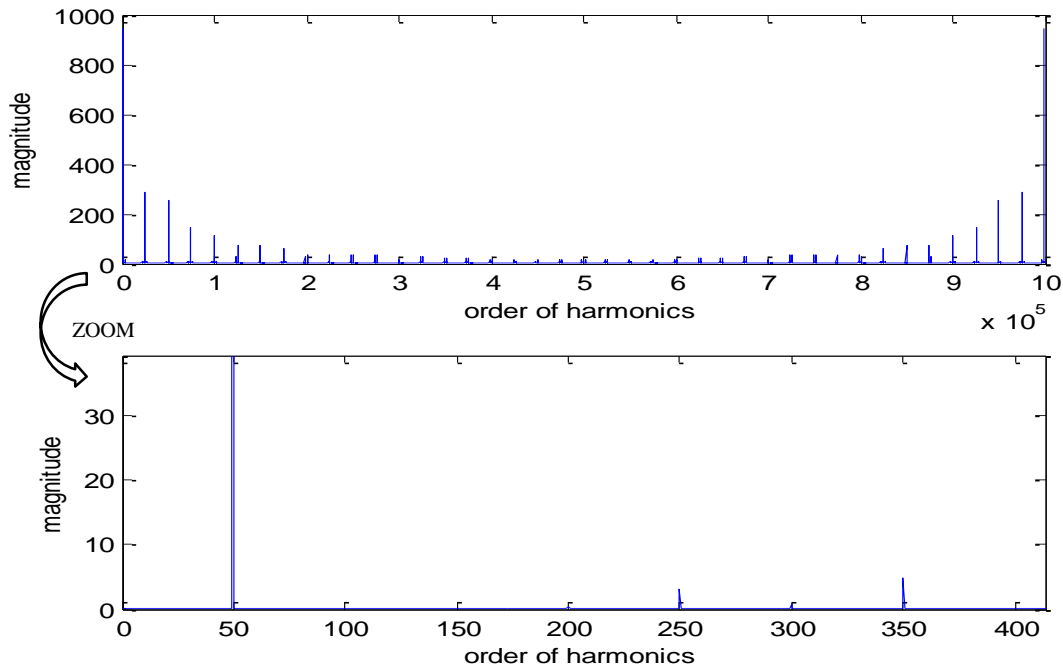


Fig 5.2 FFT of line voltage

The Fast Fourier Transform (FFT) of the line voltage is taken and the order of harmonics is seen and their corresponding magnitude. This is significant for the L-C filter design because there will be resonance and we need to choose proper resonating frequency so that at resonance the contribution of harmonics should be low or else it would be amplified to around ten times.

In this chapter the LC low pass filter is designed. The values of L and C are found to be  $L=1.459$  mH , $C=9.52$   $\mu$ F. The three phase inverter output is filtered corresponding ac output voltage is obtained which is nearly a sine wave. This filtered output is connected to the induction machine.

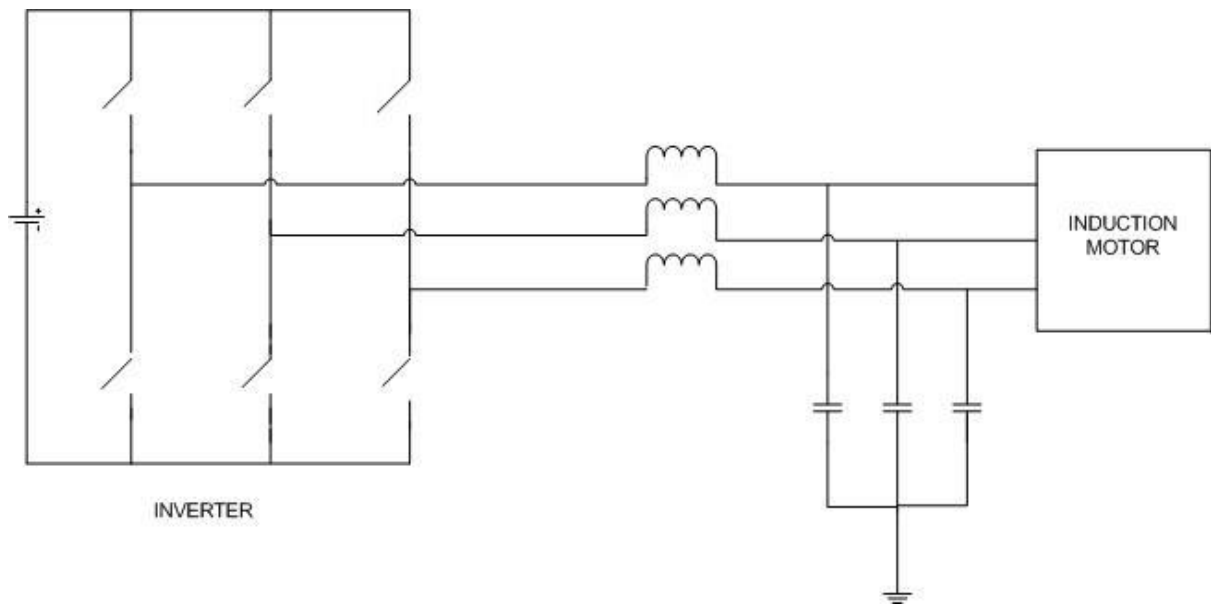


Fig 5.3 System scenario with LC filter

#### 5.4 BLOCK DIAGRAM

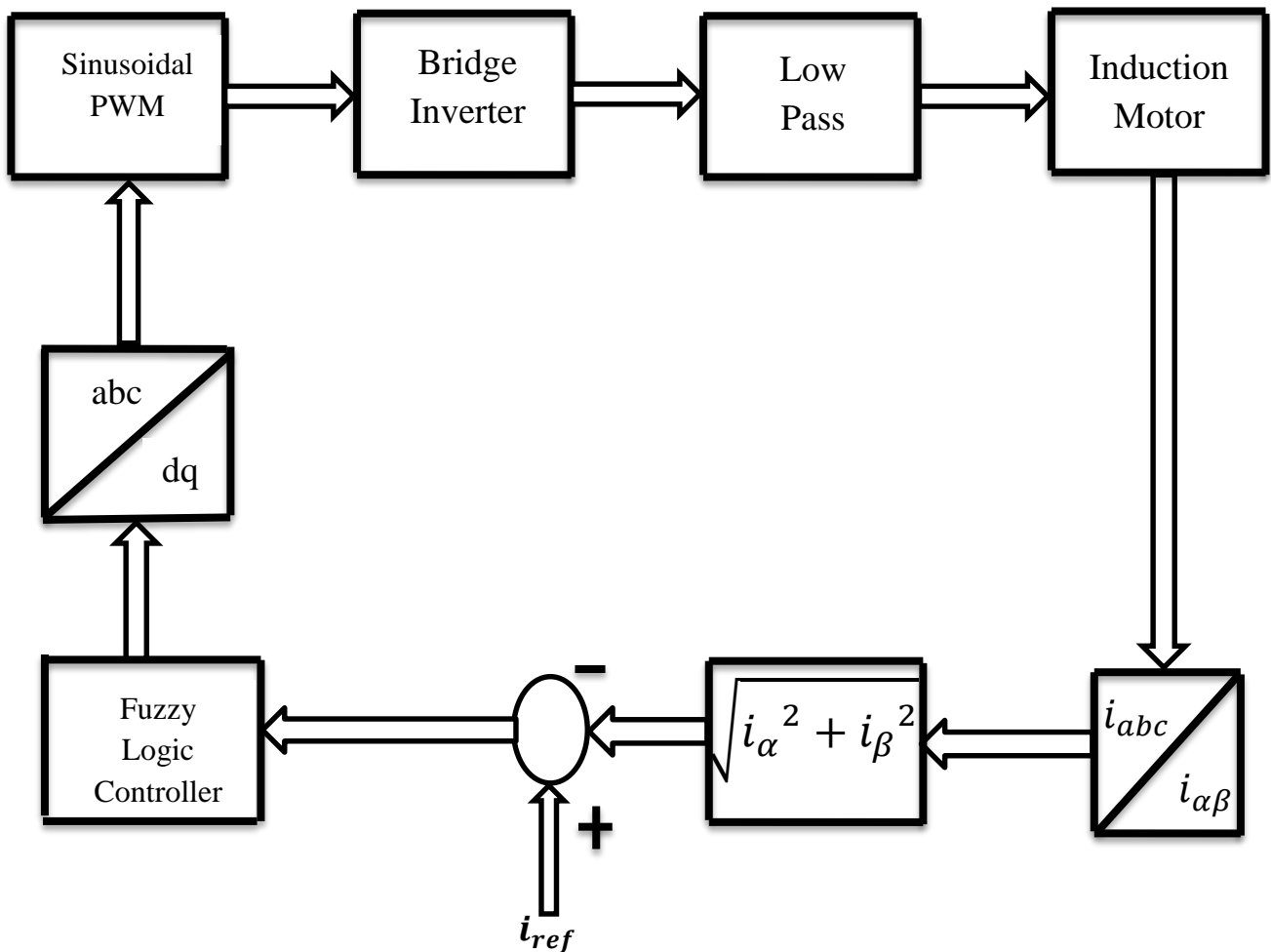




Fig 5.4 Block Diagram of SIMULINK MODEL

## 5.5 CONTROL STRATEGY

Fig 1 shows the schematic of the proposed model. The main aim here is to reduce the voltage applied to the stator during the starting few seconds. For that purpose we need to control the amplitude of the sinusoid. We have used sinusoidal pulse width modulation (spwm) technique for generating the pulses for the six inverter switches. In case of spwm technique we know,

$$m_a = \frac{v_{control}}{v_{tri}}$$

$$m_f = \frac{f_s}{f}$$

where  $m_a$  is the amplitude modulation ratio,  $v_{control}$  is the magnitude of control voltage i.e the sinusoid,  $v_{tri}$  is the magnitude of triangular wave,  $m_f$  is the frequency modulation ratio,  $f_s$  is the switching frequency,  $f$  is the supply frequency.

For an inverter the expression of phase voltage is given by

$$\begin{aligned} v_{A_0} &= \frac{v_{control} V_d}{v_{tri}} \frac{1}{2} \\ &= m_a \frac{V_d}{2} \end{aligned}$$

Where  $V_d$  is the dc link voltage of the inverter. Hence it is seen the output voltage of the inverter is directly proportional to the control voltage. Hence by controlling the amplitude of the sinusoid, the control was possible.

The inverter output is filtered with a L-C low pass filter. This is then applied to the specified Induction Motor. The three phase stator currents are converted to two phase with the following relation,

$$\begin{aligned} i_\alpha &= \frac{2}{3} i_a - \frac{1}{3} i_b - \frac{1}{3} i_c \\ i_\beta &= -\frac{1}{\sqrt{3}} i_b + \frac{1}{\sqrt{3}} i_c \end{aligned}$$

The magnitude of this current i.e  $\sqrt{i_{\alpha}^2 + i_{\beta}^2}$  is calculated which is nothing but the dc form of the stator current. It is then converted into per unit(pu). This is then compared with the rated value. This error is then passed through a Fuzzy Logic Controller(FLC). Moving average of the output of the FLC is taken. It is then converted from dq to abc. Hence by controlling the amplitude of the control voltage, the inverter output voltage is controlled. Hence the starting current is controlled.

## 5.6 SUMMARY

In this chapter, the main control strategy is discussed. The block diagram depicts the main procedure in which it is implemented. By adopting such strategy it is possible to eliminate mechanical starters like DOL, Star Delta and Autotransformer starters. This kind of scalar control technique can be easily implemented and use of fuzzy logic controller increases the adaptive capability of the system.

# CHAPTER 6

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## SIMULATION AND RESULTS

- 6.1 Machine Specifications and System Parameters
- 6.2 Performance of system without FLC
- 6.3 Performance of system with FLC
- 6.4 Comparison of system in open loop and closed loop
- 6.5 Summary

## 6.1 MACHINE SPECIFICATIONS AND SYSTEM PARAMETERS

### Machine Specifications

Rated Power	5.4HP, 4KW
Rated Voltage	400 V
Rated Frequency	50Hz
Rated Speed	1430 rpm
Type of Rotor	Squirrel Cage type
No of Poles	4
$R_s$	1.405 $\Omega$
$L_{ls}$	0.005839 H
$L_m$	0.1722 H
$R_r'$	1.395 $\Omega$
$L_{lr}'$	0.005839 H
Rated Torque	25.46 Nm
Rated Current	10.9 amp
Rated Speed	157 rad/sec

### System Parameters

The switching frequency is 25KHz.

The load torque is assumed to be in the form

$$T_L = T_b \left[ 0.1S(\omega_{rm}) + 0.9 \left( \frac{\omega_{rm}}{\omega_{bm}} \right)^2 \right]$$

The dc input to the inverter is  $800 * \sqrt{\frac{2}{3}}$

For the low pass filter value of inductance and capacitance are 1.4 59 mH and 9.52  $\mu$ F.

## 6.2 PERFORMANCE OF SYSTEM WITHOUT FUZZY LOGIC CONTROLLER (OPEN LOOP)

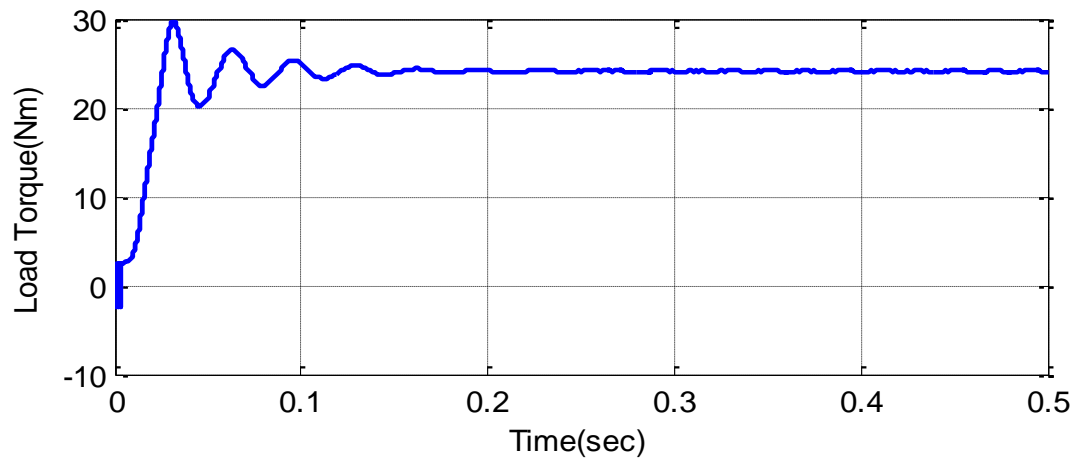


Fig 6.1 Open Loop Load Torque profile

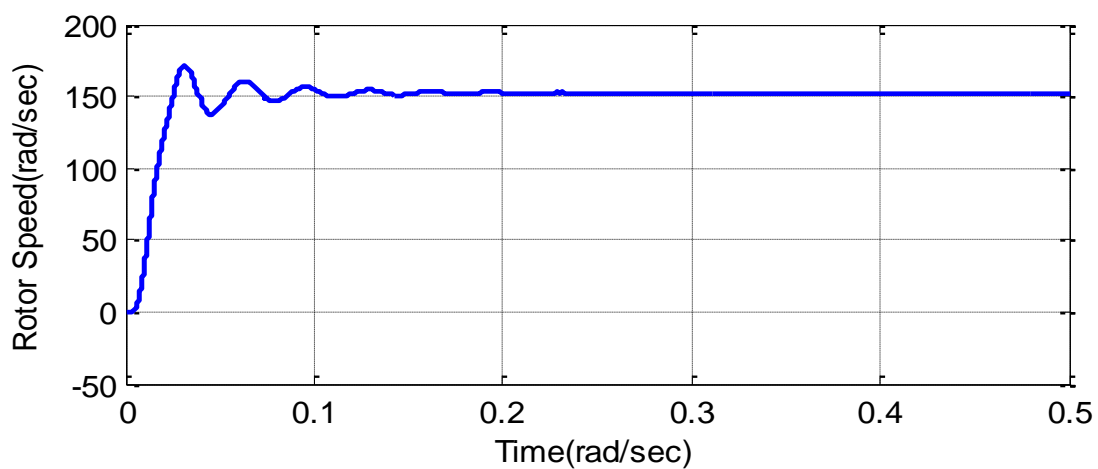


Fig 6.2 Open Loop Rotor Speed profile

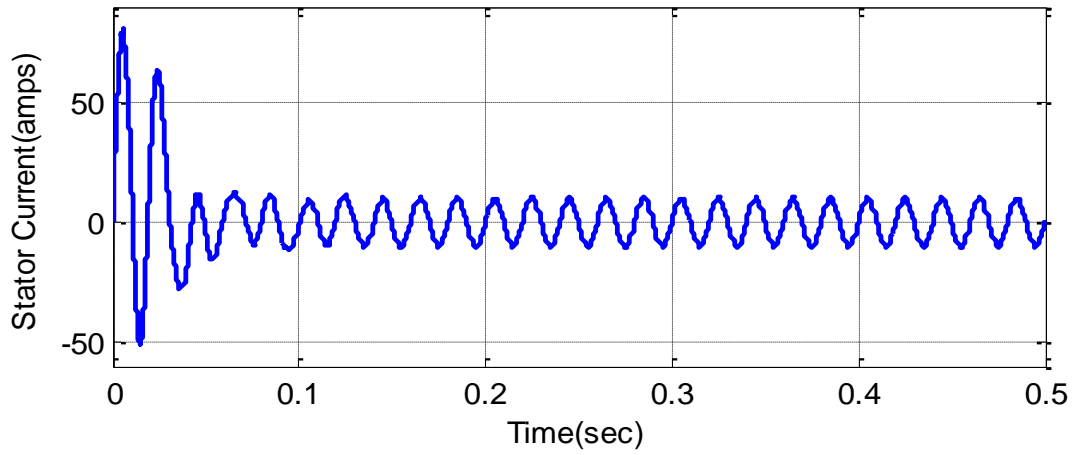


Fig 6.3 Open Loop Stator Current profile

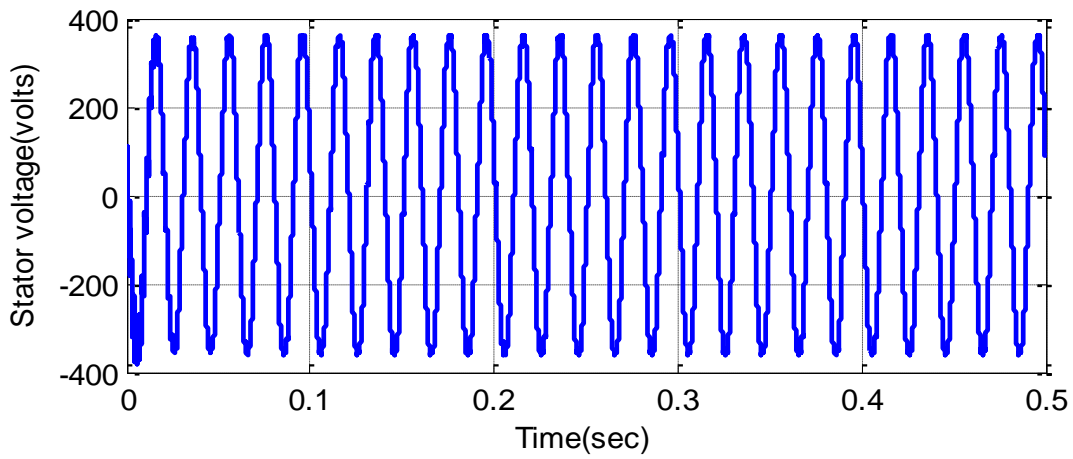


Fig 6.4 Open Loop Stator Voltage profile

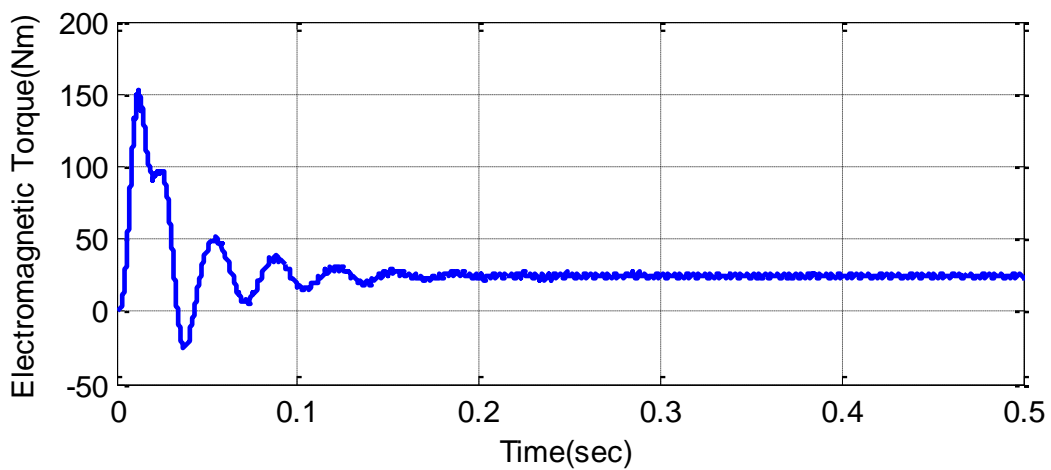


Fig 6.5 Open Loop Electromagnetic Torque profile

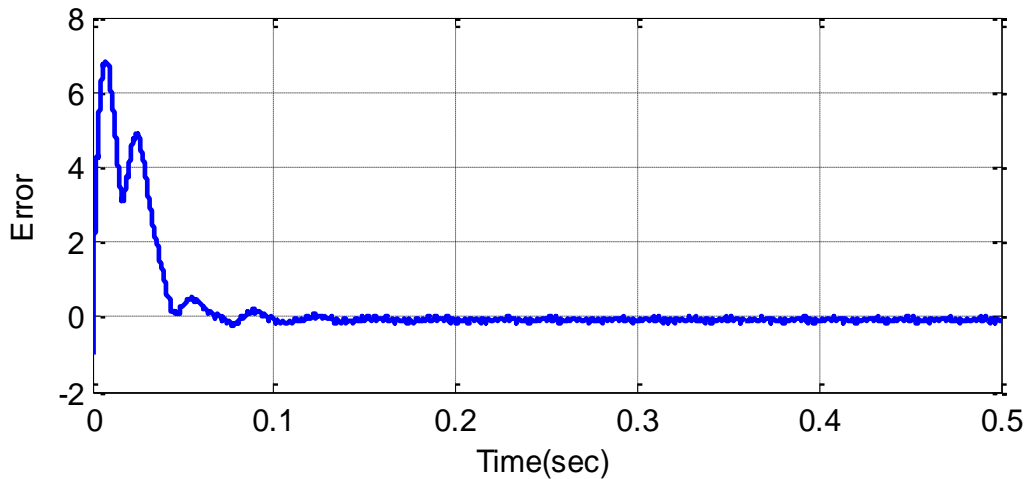


Fig 6.6 Open Loop Error profile

The load applied to the squirrel cage induction motor is a fan type load. The waveform of which is shown above in Fig 6.1. At the steady state condition the load is around 24Nm. The rotor speed initially goes higher than the rated value at the transient condition but at steady state reaches 157 rad/sec, the rated speed of the machine as shown in Fig 6.2. The stator current initially for the first two cycles is very high around 85 amps as shown in Fig 6.3. The peak to peak value of filtered stator voltage is around 400 volts as shown in Fig 6.4. The Electromagnetic Torque developed by the machine is according to the load that is applied, but at the transient state the torque goes to a very high value as shown in Fig 6.5. The error profile is shown in Fig 6.6, it is the error between the rated current and actual current (dc) taken in per unit (pu).

### 6.3 PERFORMANCE OF SYSTEM WITH FUZZY LOGIC CONTROLLER (FLC) (CLOSED LOOP)

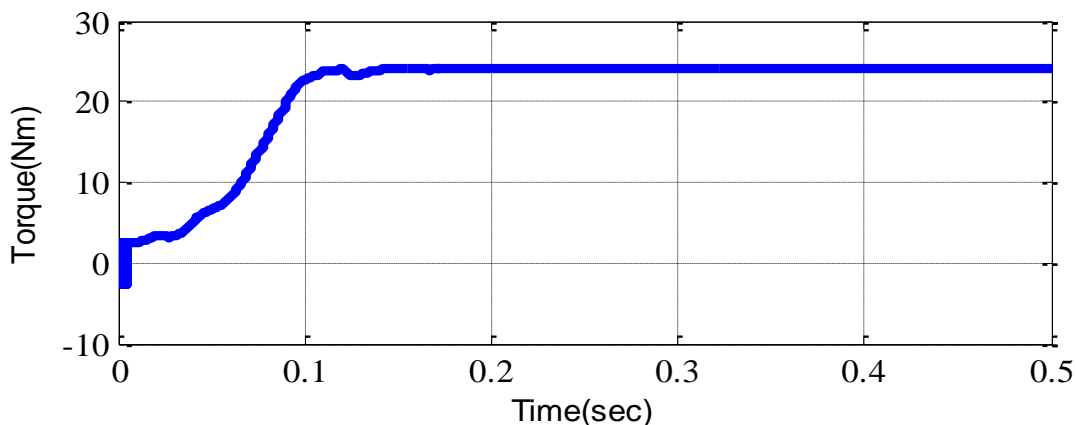


Fig 6.7 Closed Loop Load Torque profile

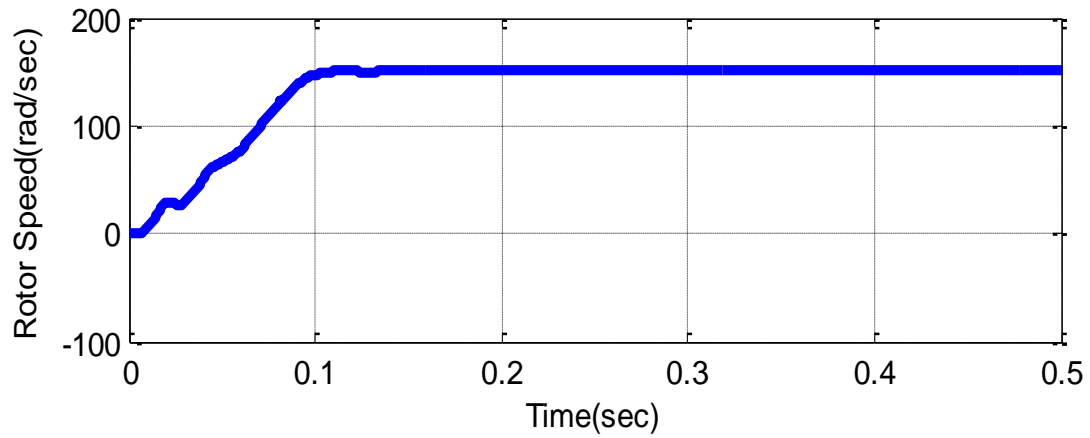


Fig 6.8 Closed Loop Rotor Speed profile

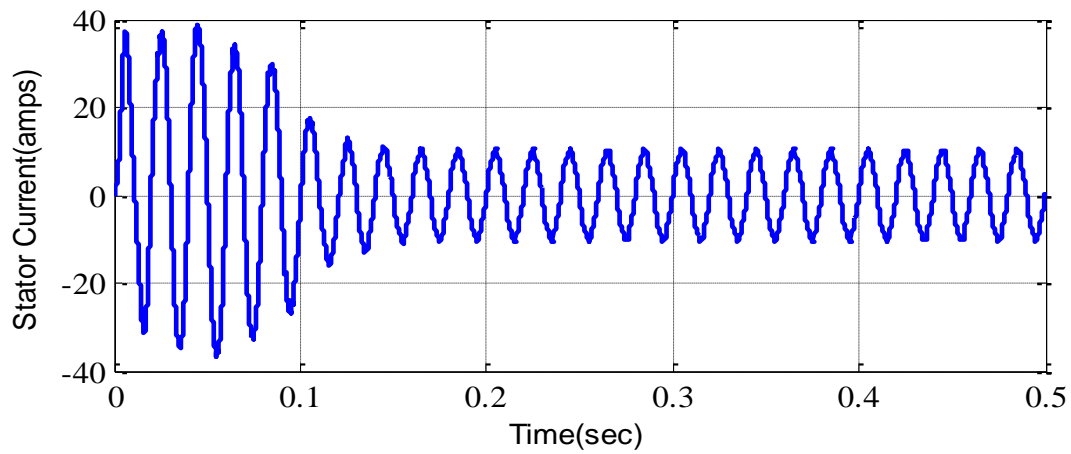


Fig 6.9 Closed Loop Stator Current profile

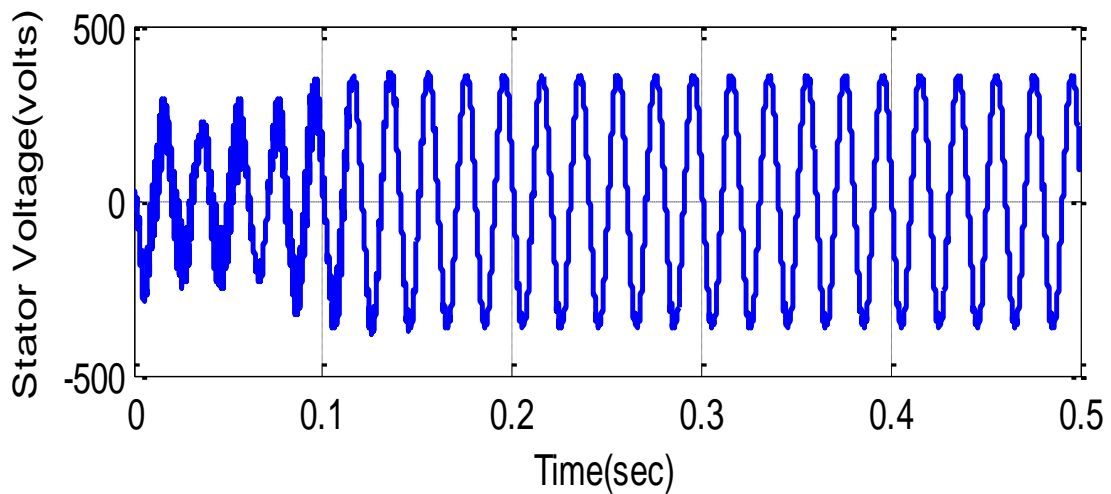


Fig 6.10 Closed Loop Stator Voltage profile



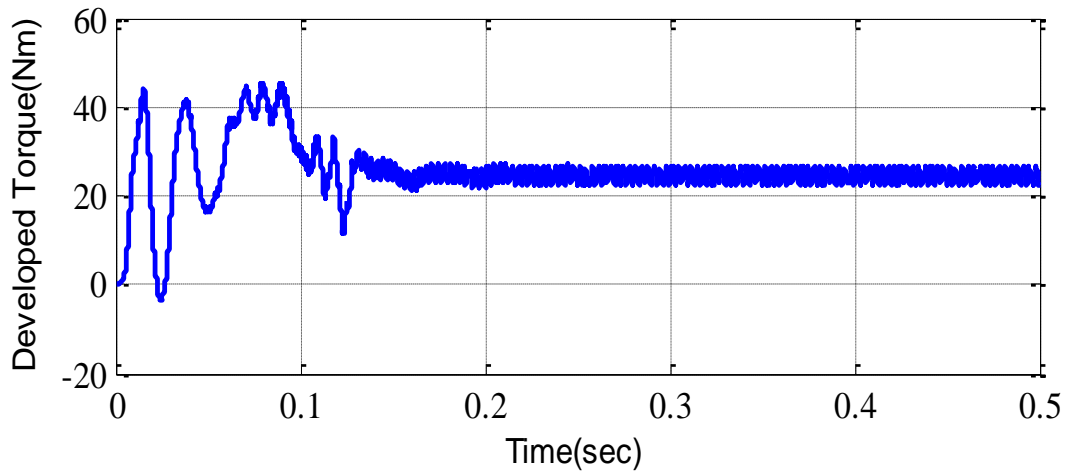


Fig 6.11 Closed Loop Electromagnetic Torque profile

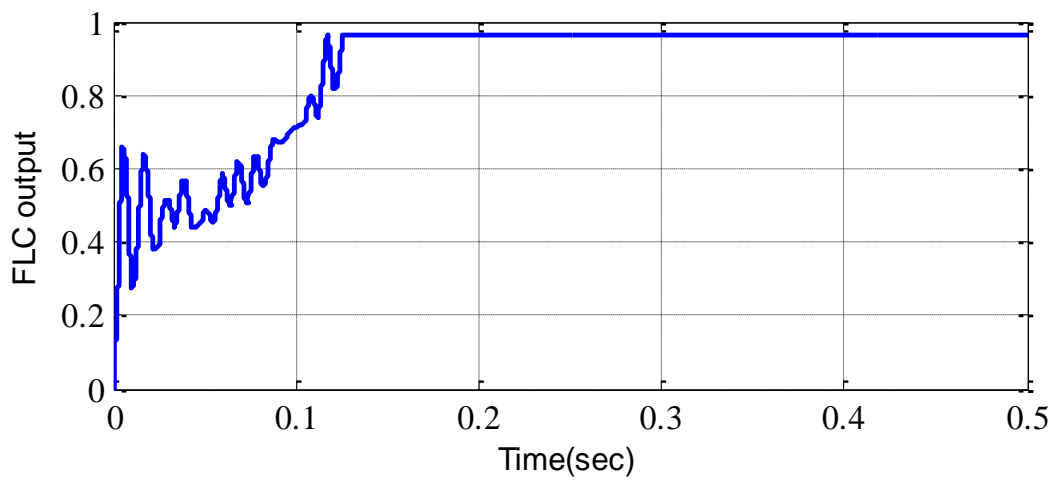


Fig 6.12 Closed Loop Averaged Fuzzy Logic Controller output profile

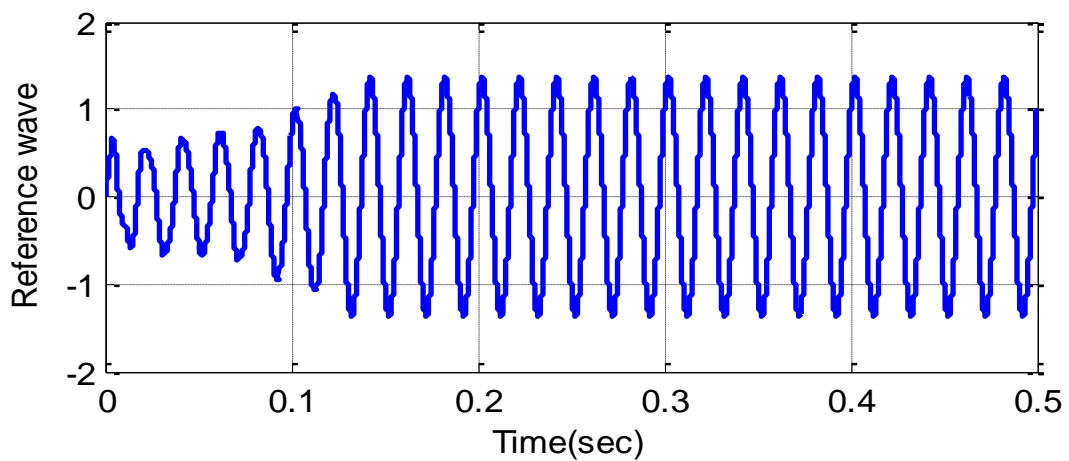


Fig 6.13 Closed Loop Reference Sinusoid profile

Fig 6.7 shows the profile of load torque applied to the induction motor. It has got a steady state value of 24 Nm. The rotor speed profile is shown in Fig 6.8. It is seen that as compared to the open loop it takes much more time to reach steady state value of 157 rad/sec. the stator current profile is shown in Fig 6.9 where during the first few cycles the current goes to around 40amps i.e four times the rated value. Hence the starting current has been limited from 85amps to 40amps. The stator voltage variation is seen in Fig 6.10, where it can be seen that the voltage gradually increases in the starting period and then reaches the steady state after 0.1seconds. This mainly helps to reduce the starting current of the machine. The developed electromagnetic torque profile is seen in Fig 6.11 where there is a bit of oscillation mainly due to the fuzzy logic controller output. The fuzzy logic controller output is nothing but the modulation index. It is seen from Fig 6.12 that the output slowly increases from 0 to 0.9. This fuzzy logic controller output after conversion from dq to abc gives rise to the reference sine wave which is seen in Fig 6.13. It can be seen that the amplitude of this wave increases slowly to 1.

#### 6.4 COMPARISON OF SYSTEM IN OPEN LOOP AND CLOSED LOOP

	OPEN LOOP	CLOSED LOOP
Starting Current	It is around 85amps and persists for three cycles.	It is around 40amps and persists for two cycles.
Stator Voltage	Peak to peak voltage is around 400 volts from the starting.	Peak to peak voltage slowly increases to 400 volts.
Rotor Speed	Initially the speed is high and goes to steady state value within 0.05seconds.	The speed slowly increases to steady state value but takes much more time around 0.1 seconds.

Table 6.1 Comparison of system in open loop and closed loop

# OPEN LOOP SIMULATION DIAGRAM OF THE SYSTEM

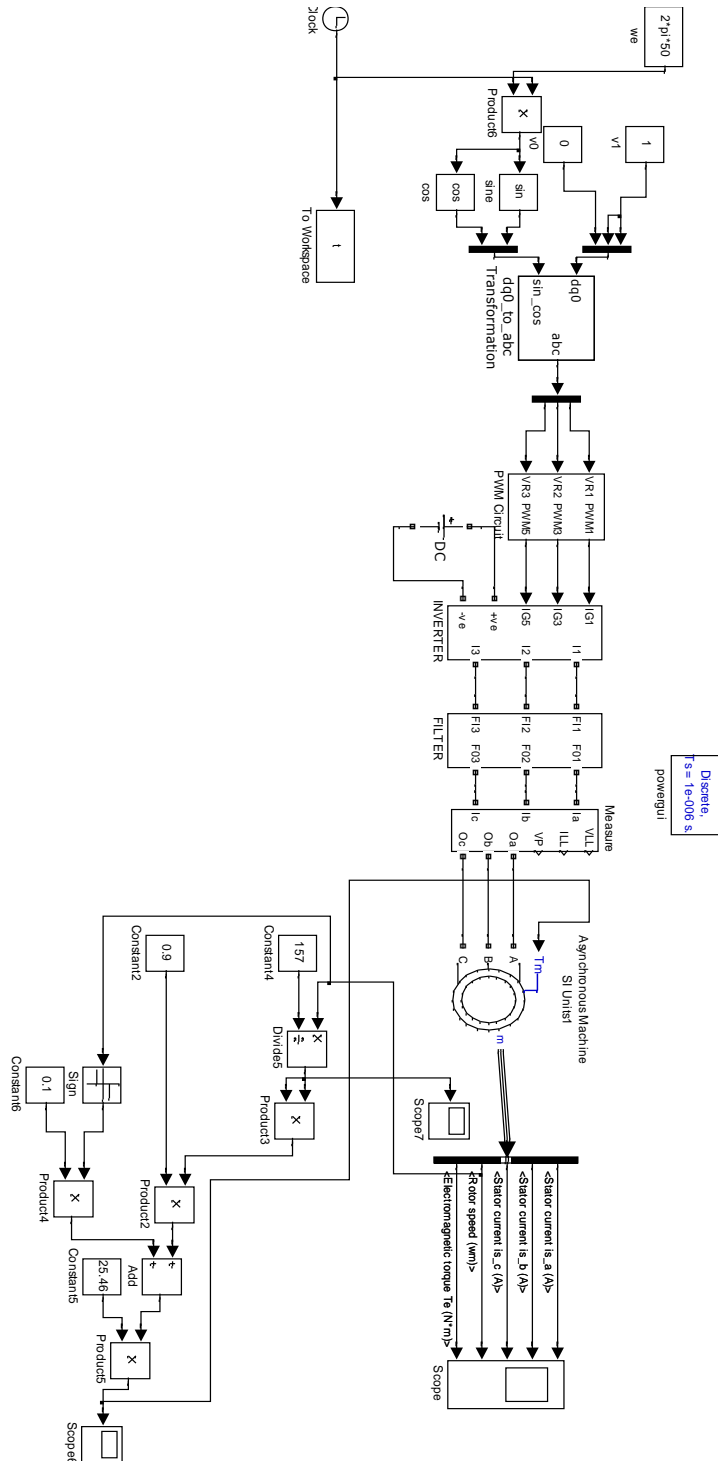


Figure No 6.14

# CLOSED LOOP SIMULINK MODEL OF THE SYSTEM WITH FUZZY LOGIC CONTROLLER

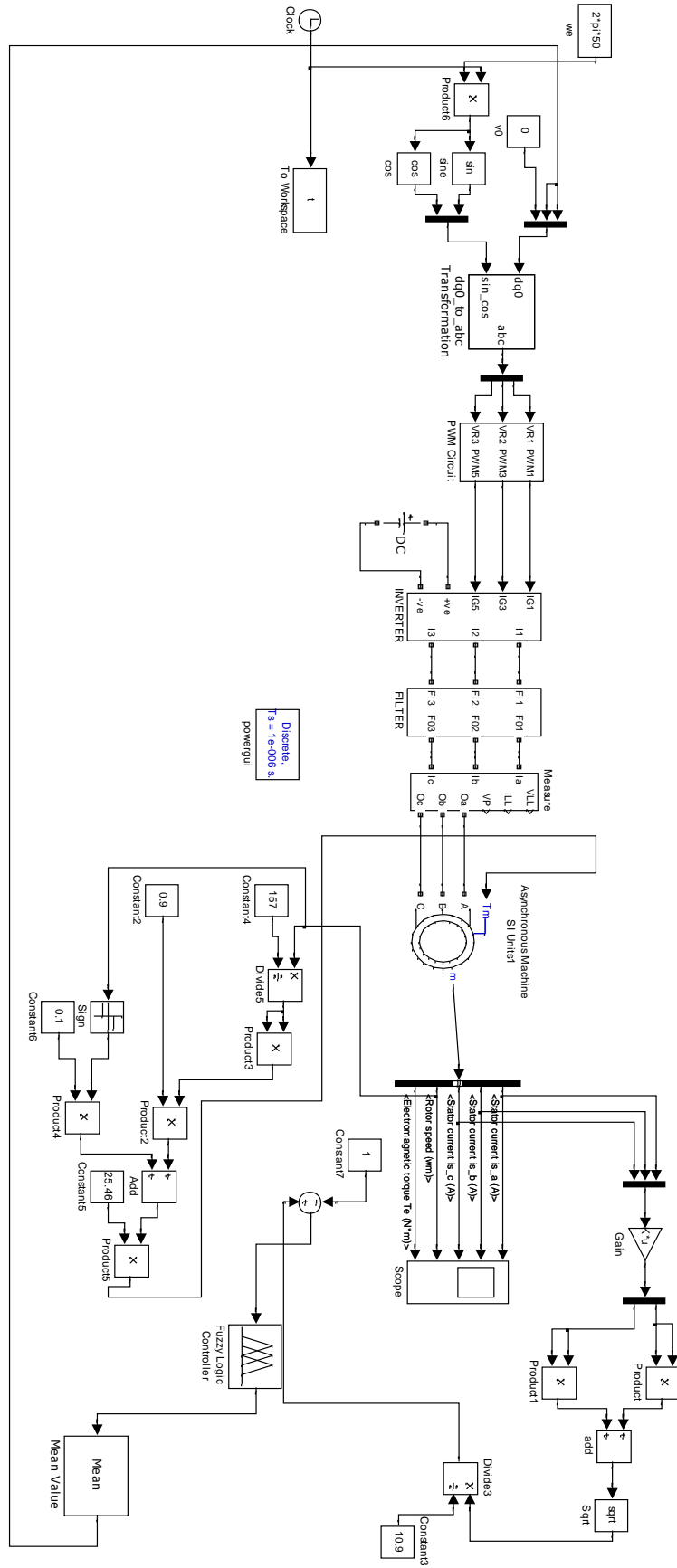


Figure No 6.15

## 6.4 SUMMARY

In this chapter, the results of the simulation performed is shown. Both for open loop and closed loop. The Simulink diagram for open loop and closed loop is also given. A comparison has been made between the performance of the system with and without Fuzzy Logic Controller.

# CHAPTER 7

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## CONCLUSION AND SCOPE FOR FUTURE WORK

7.1 Conclusion

7.2 Scope for future work

## 7.1 CONCLUSION

The starting current of an induction motor is around eight to nine times. This high current persists for a few cycles. Since the windings of the machine are designed to carry maximum of rated current, this high current during starting is detrimental. Hence the aim of our project as based on this.

The main objective of the project was to limit the starting current of the induction machine without the use of mechanical starters and using soft starting technique. Fuzzy Logic Control is used and the starting current is limited to four times as compared to nine times in open loop.

## 7.2 SCOPE FOR FUTURE WORK

The work done so far is scalar control. The controller designed is simple and would be cheap. In future this kind of controller can be designed in hardware using microcontroller. Also vector control technique can be applied for better performance but that would make the system costly.

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