IMPROVEMENT OF BLDC MOTOR PERFORMANCE THROUGH INTELLIGENT CONTROLLERS

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CERTIFICATE

I, **Vishal Srivastava**, Roll No. 2K12/C&I/024, a student of M.Tech. (Control & Instrumentation), hereby declare that the dissertation titled "**Improvement of BLDC Motor Performance through Intelligent Controllers**" is a bonafide record of the work carried out by me under the supervision of **Prof. Madhusudan Singh** of Electrical Engineering Department, Delhi Technological University in partial fulfillment of the requirement for the award of the degree of Master of Technology and has not been submitted elsewhere for the award of any other Degree or diploma.

Place: Delhi **(Vishal Srivastava)**

Date:

(Prof. Madhusudan Singh)

SUPERVISOR

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ABSTRACT

This dissertation deals with, “Improvement of BLDC motor performance through intelligent controllers”. Implementation of different control strategies for Permanent Magnet Brushless DC Motor in different modes of operation is carried out through MATLAB/simulation. The controlled electric motors play a vital role in the industrial automation. It is well known that electrical motors consume a significant percentage of electrical energy and even small improvement in operating efficiency could result in large reduction in consumption of energy. Therefore new techniques are required to extract ultimate performance from these drives. There has also been tremendous research for providing suitable speed controller for PMBLDC motor. Many control strategies have been proposed in literature. The main drawback of fixed gain controllers is that their performance deteriorates as a result of changes in motor parameters & its operating conditions. In recent times hybrid controllers such as Fuzzy Logic and Adaptive neuro-fuzzy (ANFIS) have emerged as one of the most attractive non-linear controller for application in the industrial processes giving robust performance in the face of parameter variation and load disturbance effects. The main objective is to compensate for overshoots and oscillation in the response of the PMBLDC motor for wide speed range of opearation. The performance is defined in terms of accuracy, smooth operation and simplicity. The controller performance is defined in terms of rise time, Settling time, overshoot, undershoot and behavior with non-linarites.

In this thesis, the PMBLDCM drive is modeled and simulated in MATLAB/SIMULINK environment. The controller such as Proportional Integral controller, Fuzzy logic controller, Adaptive- Neuro controller (ANFIS), series hybrid controller(known as Fuzzy precompensated PI controller) and self-tuning PI controller(Fuzzy tuned PI controller) are implemented for speed controller in the MATLAB/SIMULINK environment and drive performance using these controllers is observed and compared. The performance comparison is done in terms of several performance measures such as settling time, peak time, rise time, overshoot, undershoot, and load variations and stable performance under all operating conditions.

Every controller has their own merits and demerits. It is observed that PI controller would be a good choice for simplicity and ease of application. PI controllers are observed to have no steady state error but are slow in response. The Fuzzy logic controller offer good performance in the presence of nonlinearity but Fuzzy logic controller has offset at steady state. Adaptive neuro fuzzy controller provides excellent transient response in terms of quickness of the response. Series hybrid and self- tuning PI controller offer good response in different operating conditions but main drawback is that, processing time of controllers are high.

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LIST OF SYMBOLS AND ABBREVATIONS

ω_r^*	Reference Speed
ω_r	Rotor Speed
e	Speed error
Δe	Change in Speed error
y_c	Precompensated reference
e_2	Speed error with the precompensated reference
Δe_2	Change in Speed error with precompensated reference
T*	Torque from controller
I*	reference current generated from reference torque
a(n)	Output fuzzy variable, corresponding to K_p
b(n)	Output fuzzy variable, corresponding to K_i
K_p	Proportional Controller gain
K_I	Integral Controller gain
R	Stator Resistance
L_s	Stator Inductance
M	Mutual Inductance
e_a, e_b, e_c	Induced EMF Per Phase
v_{an}, v_{bn}, v_{cn}	Stator Voltage Per Phase
PMBLDCM	Permanent Magnet Brushless DC Motor
FLC	Fuzzy Logic Controller
ANFIS	Adaptive Neuro –Fuzzy Inference System

CHAPTER 1

INTRODUCTION

1.1 General

The availability of modern permanent magnets (PM) with considerable energy density lead to the development of DC machines with PM Field excitation in the 1950s. The introduction of permanent magnets to replace electromagnets, in motors which have windings and require an external electrical energy source, resulted in compact DC Machines. The synchronous machine with its conventional field excitation in the rotor is replaced by PM excitation, dispensing the slip rings and brush assembly. With the advent of switching power transistors and SCRs, the replacement of mechanical commutator with an electrical commutator in the form of a inverter was achieved. These two developments contributed to the PM synchronous and the Permanent magnet brushless DC machines (PMBLDCM), with this configuration, the armature of DC machine need not be on rotor with the electrical commutator replacing its mechanical version. Therefore, the armature of the machine can be on the stator, enabling better cooling and allowing higher voltages to be achieved. The excitation field that used to be on the stator is transferred to the rotor with the PM poles. These machines are nothing but **"an inside out DC machine"** with the field and the armature interchanged from the stator to rotor, and rotor to stator respectively. In Industry automation mainly developed around motion control systems where the controlled electric motors play an important function in modern process automation. The performance is defined in terms of accuracy, smooth operation and also on the simplicity of the controlling technique. The recent developments have helped the field of motor drives by shifting complicated hardware control structures onto software based control algorithms. The result is a considerable improvement in cost while providing better performance of the overall drive system. In the present work, operation and controlled performance of Brushless DC motor with different controllers and effect of operating condition like sudden application of load, change of reference speed, is discussed in details.

1.2 The Permanent Magnet Brushless DC Motor Drive

The permanent magnet synchronous machines are classified on the basis of the wave shape of the induced emf, in their stator windings i.e. sinusoidal and trapezoidal. The sinusoidal type is known as the permanent magnet synchronous machine, the trapezoidal type is called the PM brushless DC machine. The PMBLDC machines have more power density than PM synchronous machine. The major reason for the popularity of this machine over its counterpart is control simplicity.

1.2.1 The Basic construction of a BLDC Motor

In brushed DC motor commutation controlled mechanically while in the BLDCM commutation is controlled electronically.

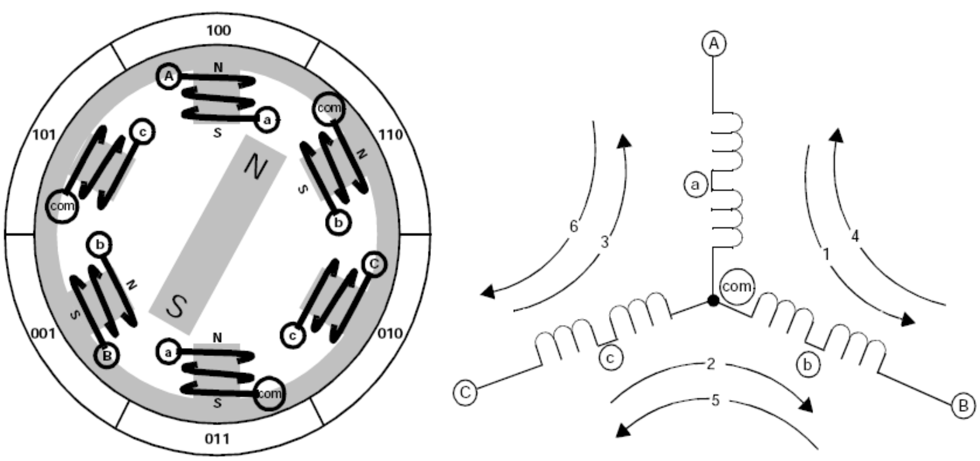

Fig. 1.1 Simplified BLDC motor diagram

To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which windings will be energized following the energizing sequence. To initiate the onset and commutation of a current to the phase of the machine, the beginning and end of the constant portion of the induced emf has to be tracked.

This amounts to only six discrete positions for a three phase machine in an electrical cycle. These Signals could easily be generated with three Hall sensors displaced from easily other by 120 electrical degrees. The Hall sensors are mounted facing a small magnet wheel fixed to the rotor and having the same number of poles as the rotor of the PMBLDCM, or an extended rotor beyond the stack may provide the same information to the sensor. Rotor position is sensed using Hall Effect sensors embedded into the stator. For the PMBLDCM position feedback, it requires only six discrete absolute positions for a three phase machine. Further the control involves significant vector operation in the PMSM drive, whereas such operations are not required for the operation of the PMBLDCM drive.

There may be more numbers of pole pairs are available. For motors with any number of pole pairs, for each electrical revolution we get six hall patterns but the number of mechanical revolution depends on the number of pole pairs of rotor. For a motor with a single pole pair, the number of mechanical and electrical revolution are equal and hence the electrical angle and mechanical angle. But for a motor with more than one pole pairs, the number of mechanical and electrical revolutions is not equal.

The relationship can be described with the following equation:

Number of electrical revolutions = Pole pairs * Number of mechanical revolution

Therefore, Electrical angle = Pole pairs * Mechanical angle

As the number of pole pair increase with the motor, more electrical revolutions occur, Hall pattern changes will be faster, and commutation changes will also be faster. For higher speed operations this necessitates for higher PWM Frequency to achieve good precision control.

1.2.2 Principle of operation of Brushless DC (BLDC) Motor

Brushless DC Motor or the BLDC Motor is a rotating electric motor consisting of stator armature windings and rotor permanent magnets whereas in a conventional brushed DC motor the stator is made up of permanent magnets and rotor consists of armature windings. Typically BLDC motors have three phase windings that are wound in star or delta fashion and need a three phase inverter bridge for the electronic commutation. In BLDC motors the phase windings are distributed in trapezoidal fashion in order to generate the trapezoidal BEMF waveform. The commutation technique generally used is trapezoidal or called block commutation where only two phases will be conducting at any given point of time.

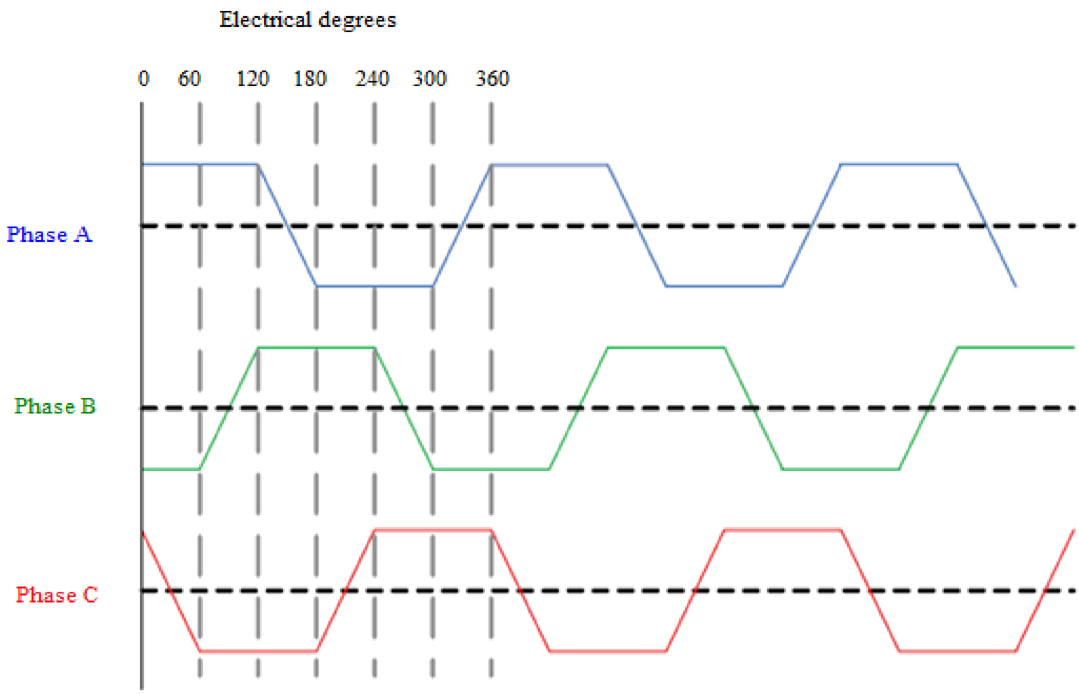

Fig. 1.2 Trapezoidal back EMF Waveform of a BLDC motor

The trapezoidal commutation method is the simplest way to control BLDC motors and easy to implement the control aspects of it. For proper commutation and for motor rotation, the rotor position information is very crucial. Only with the help of rotor position information, the electronic switches in the inverter bridge will be switched ON and OFF to ensure proper direction of current flow in respective coils. Hall effect sensors [Hall2, Hall1, Hall0] are used in general as position sensors for trapezoidal commutation. Each hall sensor is typically placed 120 degrees apart and produces I" whenever it faces the North Pole of the rotor. The hall sensor patterns for a single pole pair BLDC motor during its 360 degree of rotation is shown in the figure. The hall sensor shown in red indicates that it outputs.

1.2.3 Control Schemes of PMBLDCM Drive

The control schemes for PMBLDC motor has been show in figure 1.3. There are two control schemes for PMBLDC.

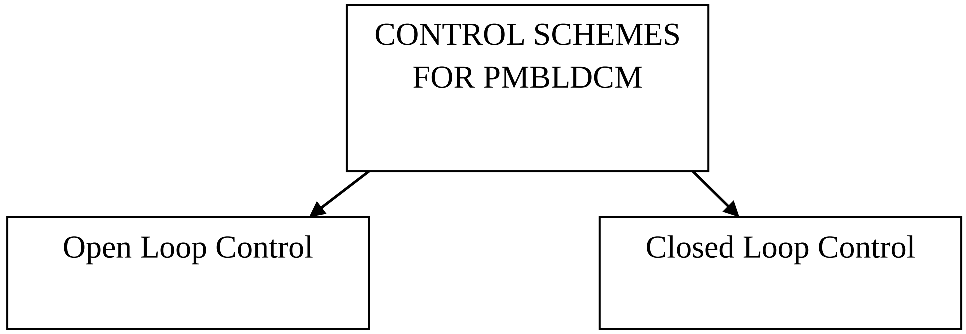

Fig. 1.3 Control Scheme of PMBLDCM

1.2.3.1 Open loop Seed Control of BLDC motor

For BLDC motor, two strategies can be employed for speed control in open loop mode. Open loop control of BLDC motor does not require any speed comparison for negative feedback. The hall sensor output is fed to the PWM control unit which decides the sequence of pulses based on the output of the hall sensor.

1.2.3.2 Closed loop Seed Control of BLDC motor

Close loop control for PMBLDC motor is shown in this section. There are two control schemes for Speed control of BLDCM which is shown below.

1.2.3.2.1 Speed Feedback

Figure 1.4 the speed feedback control is computed from the V-I measurement at the terminals of the BLDC motor.

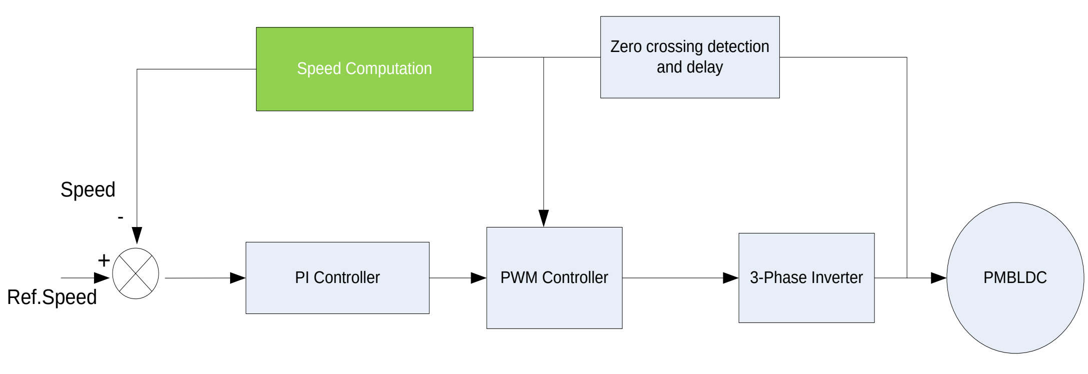

Fig. 1.4 Speed feedback Control Scheme of PMBLDCM

The hall sensor output is used for synchronization and PWM control, while the speed that is calculated from the BLDC motor is fed back as negative feedback for calculating the error. The error is fed back to the PI controller which is again used in PWM generation. The above mentioned control system is advantageous as V-I measurement is easy at the terminals of the output.

1.2.3.2.2 Current Feedback

The second type of control strategy as described in the Figure 1.5. The block diagram employs a current control loop configuration

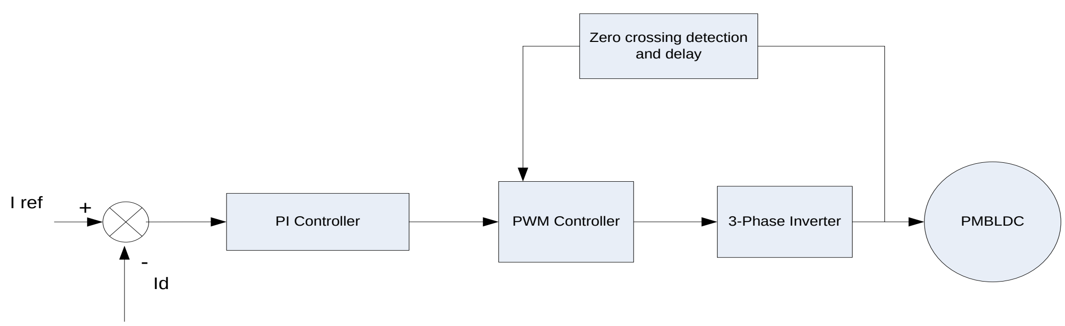

Fig. 1.5 Current Feedback Control Scheme of PMBLDCM

In method this only a reference current is fed to the PID controller. V-I measurement is again done at the terminals of the BLDC motor. The current is used to generate the gate pulses for the inverter.

1.2.3.2.3 Speed and current feedback approach

Speed and Current feedback control scheme is shown in Figure 1.6.This method of BLDC motor closed loop speed control has similar feedback as seen in the first scheme. However, the feedback is fed at different points of the control path. The speed is first compared to the reference speed. The error is passed through a PI controller and reference current is calculated

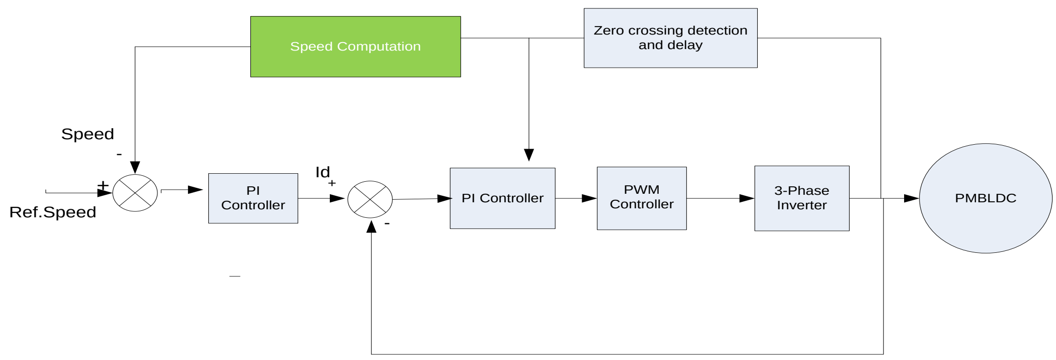

Fig. 1.6 Speed and Current Feedback Control Scheme of PMBLDCM

The current is then compared to the current at the terminal of the output and this is again fed through a PID controller for further tuning. By far the most complex strategy, the scheme requires two stages of tuning and more circuitry. The output of the PID controller is then fed to the PWM control unit which generates the logic pulses for the PWM control.

1.2.4 The PMBLDCM Drive

The terminology Brushless DC motor or BLDC is used for this machine because usually the motor is combined with an optical encoder, Hall sensors for current commutation, and an amplifier and feedback controller so that it behaves like a DC motor. That is indicated in the figure; the currents and motor position are fed back to the controller, the controller then uses PI current loops of the form of force the currents to track the references.

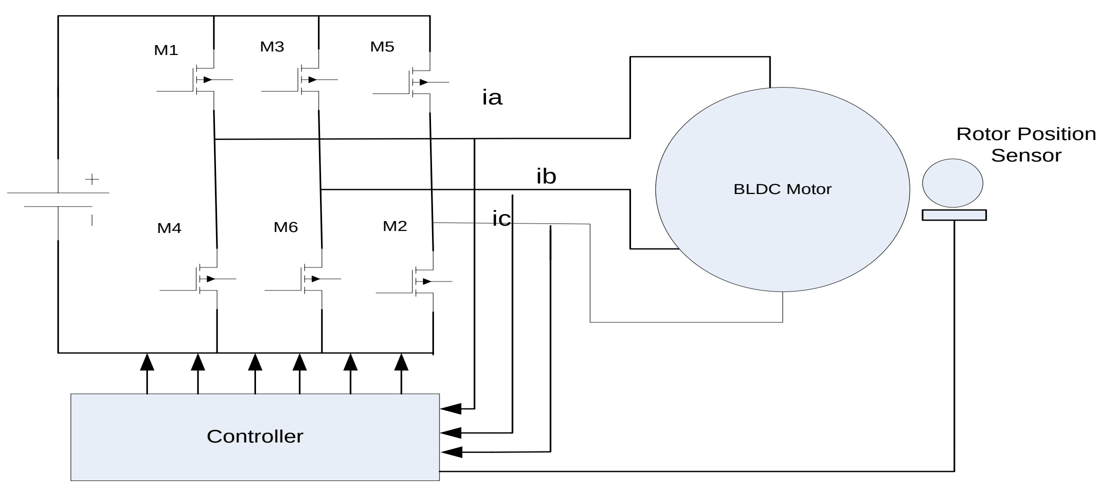

Fig.1.7 Brushless DC Motor Drive system

The input to the controller is simply current so that with the inner current control loops working properly.

Torque equation of the motor becomes

$J \frac{d\omega}{dt} = T_e - T_l$ where "ω" is the angular velocity, T_e is electromagnetic Torque and T_l Load Torque.

This is the same form as the current command DC motor with torque constant, 'K' The position sensor for the current commutation, that is for tracking the current references is done with Hall-effect sensors. To track the current references, the phase current plots the position of the rotor at multiples of $\frac{\pi}{3}$ or 60 degrees as the current in any particular phase changes only at some multiple of 60 degrees.

1.2.5 Advantages of the PMBLDCM over Brushed DC motor

Brushless DC motors are rapidly gaining popularity in the appliance, automotive, aerospace, consumer and industrial automation industries. Due to absence of mechanical commutators and brushes and the permanent magnet rotor, brushless dc motors have several advantages over the brush dc and induction motor such as low inertia and Electronic commutation, less maintenance, safety in explosive environments, achievable high speed limits with no mechanical constraints, low rotor inertia and efficiency.. However the requirements of a complex controller for even a constant speed operation and high cost of building are the disadvantages over its counterpart.

1.3 Concepts of Controllers

In a control theory, a Controller is a device which monitors and effects the operational conditions of a given dynamical system. The operational conditions are typically referred to as output variables of the system which can be affected by adjusting certain input variables. Based upon the behavior of the output, the control action is taken, such that the set point value is reached. The factor based on which the control action is taken differs from one method to another. The different kinds of control method available are discussed.

1.3.1 Proportional Integral Controller

With PI control the P gain provides similar operation to that in P controller, and the 'I' gain provides DC Stiffness but more overshoot. The primary short coming of the P controller i.e. the DC offset can be readily eliminated by adding an integral gain to the control law. Because the integral will grow over larger with even small DC offset error, sufficient value of the integral gain will eliminate the DC offset droop, Integral gain is added to add long term precision to a control loop. The main drawback is that the integral controllers are more complicated to implement. The Integral controller lacks a windup function to control the integral value during saturation.

1.3.2 Fuzzy Logic Controller

With a control problem for a complicated physical process, the control engineer usually follows a predetermined design procedure, which begins with the need for understanding the process and the primary control objectives. Fuzzy controls provide a formal methodology for representing, manipulating and implementing a human's heuristic knowledge about how to control a system. Fuzzy controller design involves incorporating human expertise i.e. how to control a system into a set of rules or rule base. The inference mechanism in the fuzzy controller reason over the information in the knowledge base, the process outputs, and the user specified goal to decide what inputs to generate for the process so that closed loop fuzzy control system will behave properly Overall focus in Fuzzy control is on the use of heuristic knowledge to achieve good control, where as in conventional control the focus is on the use of a mathematical model for control systems developments and subsequent use of heuristics in implementation. There are four principal elements to a fuzzy logic controller:

A. Fuzzification
B. Knowledge Base
C. Decision making block
D. De-fuzzification

1.3.3 Adaptive Neuro –Fuzzy Inference System Controller (ANFIS)

ANFIS is a hybrid controller which having characteristics of Fuzzy logic controller and Neural network. ANFIS Controller is capable of adapt the plant or system situation. The characteristics of fuzzy control are:

(i) Approximate knowledge of plant is required
(ii) Knowledge representation and inference is simple with form of "IF-THEN"
(iii)Implementation of rules easily.

The characteristics of a neural network are:

(i) Neural network can adapt itself to changing control environment and can learn just by the type of Input and output.
(ii) Neural network can work real time performing random data mapping by parallel distributed processing, so any kind of non-linear mapping is possible.
(iii)Neural network does not require difficult theories of control, knowledge of system or other environment.

1.3.4 The Series Hybrid (Fuzzy Precompensated PI) Controller

A PI controller when used in combination with FLC such that near steady state operation, PI controller takes over the control eliminating the disadvantage of the FLC. Similarly when away from the operating point FLC dominates and eliminates the occurrence of overshoots and undershoots in drive response. Standard controllers used in practice, such as PI, PID controllers suffer from poor performance when applied directly to system with unknown nonlinearities like dead zone, saturation , limit cycles etc. The tuning process may be non-trivial and could be consuming more time. The FLC has been designed by an expert; the limitations it may have to face may be given as below:

(i) Will the behaviors observed by an expert include all situations that can occur due to disturbances, noise, or plant parameter variations?
(ii) Can the human expert realistically problems that could arise from closed loop system limit cycles?

(iii) Will the expert be able to effectively incorporate stability criteria and performance objectives i.e. rise time, overshoot, and tracking specification into a rule base to ensure that reliable operation?

(iv) Can an effectively and widely used synthesis procedure be devoid of mathematical modeling and subsequent use of proven mathematical analysis tools?

1.3.5 Self-tuning PI Controller

The basis of the self-tuning PI controller corresponds to condition when the error is high i.e the actual speed is much less than the set point speed, the proportional gain plays the key role for faster system response., when the speed is near the set point, the integral gain comes into action to completely eliminate the steady state error .

The gain of the PI speed controller are constantly modified by the self-tuning controller in parallel depending on the speed error and the change in the speed error such that the drive system achieves adaptive nature to the variation in the operating conditions like load variations.

The advantages of Self-tuning PI controller are:

(i) Adaptive performance during load variations with minimum deviation from the set point speed.

(ii) Minimum rise time in the starting response with no or very less overshoot.

(iii) Smooth response even in the presence of unknown non-linarites in the drive system such as friction, dead zone etc.

1.4 Objective of the Thesis

The objective of the thesis is to evaluate the performance of PMBLDCM in various modes and with different controllers. The motor is operated in open loop mode as well as closed loop mode. By choosing a suitable controller the dynamic performance of the machine can be improved to a great extent. It is therefore required that, various controllers for the speed control of the PMBLDCM should be studied, modeled and simulated to identify the suitable controller for appropriate condition. Detailed work of thesis as follows-

(i) Mathematical model and Simulink model for PMBLDCM drive has been developed.
(ii) Simulink model of different speed controllers such as PI, FLC, ANFIS, Series Hybrid and Self-tuning PI has been developed in MATLAB/ SIMULINK environment.
(iii) Simulink model for speed control of PMBLDC motor is developed. Performance analysis is done with different controllers such as PI, FLC, ANFIS, Series hybrid and Self-tuning PI Controller
(iv) Comparative study and performance analysis in terms of performance parameter such as rise time, settling time, overshoot etc. has been done.

1.5 Thesis Outline

Chapter 1

The basic construction, operating principle, applications and the advantages of the PMBLDC machine have been discussed in detail. The different types of controllers and the scope of the work were also discussed.

Chapter 2

This chapter describes elaborately the Literature review of the different speed controllers and the significant developments in their respective areas. It also covers the various applications using the controllers PI, PID, Fuzzy, ANFIS, Series-hybrid and proposed Self tuning controller.

Chapter 3

In this chapter the mathematical models of the supply and electrical and mechanical parts of the motor and drive system are discussed in brief.

Chapter 4

In this chapter the modeling and simulation of different Speed controllers such as PI, FLC, ANFIS, Series hybrid and proposed self-tuning controller and various components of the drive system are discussed in detail

Chapter 5

This chapter contains Simulation results and discussion for Permanent magnet Brushless DC motor. Simulation is carried out for different controllers and in different modes. The result is discussed in detail in this chapter.

Chapter 6

This chapter contains the main conclusion based on the investigation carried out on the work. It also enlists the scope for he further investigation in the speed control of the PMBLDC machine.

CHAPTER 2

LITERATURE REVIEW

2.1 General

From the available literature, it is revealed that the use of specific controllers for speed control of a PMBLDCM has been used for enhancing the performance of the drive for a specific application. Motor control using Fuzzy logic is a promising technique for extracting good performance from the available range of motors. Fuzzy logic offers a convenient way of designing controller from experiences and experts knowledge about the process being controlled. The heuristic performance can enhance the performance reliability and robustness of the closed loop system more than the conventional controllers. Research has proved that a properly designed Fuzzy controller can outperform a conventional PID controller such that the overall performance can be substantially improved. The major limitation of a fuzzy logic control is the lack of a systematic methodology for developing fuzzy rules.

During the past few years several approaches for developing self-organizing fuzzy controllers have been proposed. Dedicated simulation software like MATLAB with Simulink and fuzzy logic toolbox has made the modeling and simulation of the system efficient and simple. The advancement in the speed control techniques from proportional control to fuzzy logic and other advanced techniques like gain scheduling control, Sliding mode control, Self tuning control, etc., have resulted in a remarkable improvement in the response of the drive. Estimation of steady state error, overshoot and oscillation has lead to the practical implementation of such control techniques in the real time. PMBLDCM have higher efficiency, higher power to weight ratio, higher power density , higher torque to current ratio, faster dynamic response, less maintenance, better power factor and better output power as compared to conventional motors.

2.2 Literature Review

The existing literature review available on Permanent Magnet motors are classified in two categories.

2.2.1 Literature Review on PMSM

Pragasan Pillay et al. [1] studied the two types of permanent magnet ac motor drives available in the drives industry. These are the PM synchronous motor (PMSM) drive with a sinusoidal flux distribution and the PM BLDC motor drive with a trapezoidal flux distribution. Performance differences due to the use of pulse width modulation (PWM) technique and hysteresis current controllers are also examined, but the main attention is paid to the motor torque pulsations and speed response.

R.Krishnan [2] reviewed the operation of the PMSM drives when it is constrained to be with in the permissible envelope of maximum inverter voltage and current to produce the rated power. Due to the constraints on the available dc link voltage and current rating of an inverter, the motor input voltage and current ratings also get limited. The limited voltage and current impact the maximum torque producing capability of the motor drive system. It is required and desirable to produce the rated power with the highest attainable speed for many applications such as electric vehicles, golf carts forklifts machine tool spindle drives etc. The rated power is for steady state operation and multiple times that is preferred for that acceleration and deceleration during transient operation. From these considerations, this paper addresses the steady state operation, and control techniques for the PMSM drives in the field weakening region.

Pragasan Pillay et al. [3] presented the dynamic model and equivalent circuits of the PM machines. It has shown that the PMSM and the BLDCM are similar in construction; their modeling takes different forms .The d-q model of the wound rotor is easily adapted to the PMSM while an abc phase variable model is necessary for BLDCM if a detailed study of its behavior is needed. Because of the non-sinusoidal variation of the mutual inductances between the stator and rotor in the BLDCM, It is also shown in this paper that no particular advantage exists in transforming the abc equation of the BLDCM to the d-q frame. Hence the solution of the original abc equations is proposed for the BLDCM.

Javad Soleimani of al. [4] presented the mathematical model of a 3-phase PMSM based on d-q axial model presents and for different permanent magnets having same volume and thickness, extracted necessary, parameters for modeling. Torque response and power factor for each material investigated and it has been investigated that the increment of mechanical torque applied to the motor, using permanent magnet with low B and H, in the motor presents to reaching synchronous state. In other word, motor is not is not compatible with this load. While permanent magnet's volume is suitable, using hard magnetic material with B and H have remarkable effect on time of synchronization or settling time and torque ripple.

2.2.2 Control methods of PMSM

Salih Baris Qzturk et al. [5] presented a direct torque control (DTC) scheme for PM synchronous motors using Hall-effect sensors in constant torque region. This scheme requires no dc- link sensing and removes some common problems those conventional DTC drives suffer from such as the effect of resistance change, low speed operation drift, and the initial rotor position requirement.

Badre Bossoufi et al [6] presented modeling of unit PMSM, inverter of tension and order known as DTC under MATLAB/SIMULINK. The DTC scheme allows independent control for the torque and flux, an optimal response time; it does not have the mechanical sensors and allows obtaining excellent dynamic performances.

Lang Baohua ey al. [7] presented a space vector modulation method which is applied to direct torque control system structure. The scheme maintain the characteristics of the traditional direct torque control but improves the torque ripple effectively and makes the inverter switching frequency constant. The fundamental difference between these two methods is that traditional DTC has only effective voltage vector and uses hysteresis controllers, while the SVM-DTC can use any linear combination of required voltage source and so can more accurately control the stator flux.

Bhim Singh et al. [8] presented the DSP based implementation of a sliding Mode (SM) speed controller for DTC of Permanent Magnet Synchronous Motor (PMSM) drive. The drive system consists of power circuit and control hardware. The former has IGBT based voltage source inverter (VSI) and gate driver circuit, while the later has voltage and current sensors and the interfacing circuits. The assembly language programming used for the implementation on DSP has resulted in giving faster and good response. Any modification in control structure is easily possible by changing the software to meet the requirements of a specific application. The rotor speed estimation from the sensed position signals, SM speed controller torque, flux and the vector estimator and optimum voltage vector selection table for gating pulse generation of VSI are implemented in assembly language of DSP-ADMC401.

M.B.B sharifian et al. [9] presented the two popular methods and powerful methods i.e. Field oriented control and space vector modulation (SVM). The FOC-SVM method has been incorporated with a predictive current control technique. This method estimates the desirable electrical torque to track mechanical torque at a reference speed of PMSM. The estimated torque is then used to calculate the reference current based on FOC. In order to increase the performance of the traditional SVM a predictive current control(POC) method is established as a switching pattern modifier. The performance of the controller is terms of torque and the transient response to step variations of the torque command.

2.2.3 Literature Review on BLDC

Pragasan Pillay et al. [10] presented the modeling, simulation and analysis of a BLDCM drive. The simulation included the state space model of the motor and speed controller and real- time model of the inverter switches. Every instance of a power device turning on or off is simulated is calculated the current oscillations and resulting torque pulsations. The results indicate that the small and large signal responses are similar. This results are valid only when the timing of the input phase currents with the back EMF is correct. The Brushless DC motor has a permanent magnet rotor, and the stator windings are wound such that the Back Electromotive (EMF) is trapezoidal, therefore it requires rectangular shaped stator phase currents to produce constant torque. The trapezoidal back-EMF implies that the mutual inductance between the stator and rotor is non-sinusoidal. Therefore no particular advantages exist in transforming the machine equations into the two-axis equations, which is done in case of machines with sinusoidal back EMF’s i.e. PMSM.

Ji Hua, Zibo et. Al [11] presented the mathematical model of the BLDCM the modeling and simulation of the control system of brushless DC motors (BLDCM). The simulation model of control system for BLDCM has been established using this simulation model built for BLDCM, control algorithms can be verified conveniently.

Vinatha U.et.al. [12] Presented a modeling procedure that helps in simulation of various operating conditions of BLDC drive system. The performance evaluation results show that, such modeling is very useful in studying the drive system before taking up the dedicated controller design, accounting the relevant dynamic parameters of the motor.

Balogh Tibor et al, [13] described a model of brushless Dc motor considering behavior of the motor during commutation. The torque characteristic of BLDCM is important factor to design and for operation of BLDC drive system. So it is important to predict the precise value of torque, which is determined by waveforms of back-EMF. After the development of mathematical model of the BLDC motor with Sinusoidal and trapezoidal waveforms of back-EMF the motor is simulated in the MATLAB/SIMULINK environment. The performance evaluation results show that , such a modeling is very useful in studying the drive system before taking up the dedicated controller design, accounting the relevant dynamic parameters of the motor.

Wonbok Hong et al [14] described an advance model which considers behavior of commutation and waveform of Back-EMF for comprehensive analysis and prediction of dynamic characteristic of BLDC motor drives. The proposed model consists largely of four components: 120 degree conduction signals generator, voltage source inverter, and electrical part of BLDC and has mechanical part of BLDC. Proposed model has been implemented under Simulink environment in modular manner. This proposed model can be used very effectively in analysis and design of control algorithm of the BLDC motor drive system.

2.2.4 Review on control methods of Sensored BLDCM

Yoseph Bachnik et al [15] proposed a method to detect and control the speed and the position of a BLDC motor with a low resolution position encoder in very low speeds of several rad/sec. The low resolution encoder should be the Hall Effect sensor that has a resolution of maximum 60 electrical degrees, according to the pole number of the motor.

Mary George et al [16] described a simple digital pulse width modulation control technique for trapezoidal brushless DC (BLDC) motor drives. The digital control treats BLDC motor as digital system and regulates speed with the help of two predefined state variable techniques, which makes the concept of controller extremely simple for design and implementation. The scheme reduces the cost and complexity of motor control hardware and in turn can boost the demand of BLDCM for mass production applications. Compared with the conventional scheme, this is simple to implement. Simulation has been done with BLDCM to study the proposed motor drive system.

Y.S Jeon et al [17] described a method for the reduction of error in simulation for that purpose new simulation model of BLDC motor with nearly real back EMF waveform. When using the ideal trapezoidal waveform the error occurs .The model of BLDC motor with real back EMF waveform is needed instead of its approximation model .So for the reduction of errpr in simulation a new simulation model of BLDC motor with nearly real back EMF waveform is proposed which is proposed which contains FFT and IFFT method to improve simulation result of BLDC motor.

Somesh Vinayak et al [18] proposed a method of minimization of torque ripple of brushless dc (BLDC) motors. For practical reasons like no- uniformity of magnetic material and design it is hard to produce desired trapezoidal wave shape. Therefore torque ripple appears in conventional control. In this scheme, the duty cycle of the pulses is calculated in the torque controller in both normal and in combination with a given commutation sequence fed to the inverter gates so as to minimize ripple.

Jianwen Shan et al [19] proposed that the direct back –Electromotive force (EMF) detection method for sensor less brushless DC (BLDC). Direct Back-EMF sensing scheme requires a minimum PWM off time to sample the back EMF signal, the duty cycle is limited to something less than 100%. So an improved direct Back-EMF detection scheme that samples the motor back EMF synchronously during either PWM on time or the PWM off time is proposed to overcome the problems.

Yen-Shin et al [20] presented a field programmable gate array –based BLDCM driver system set up to calculate the zero-crossing point of back EMF at both low and high speed regions. The experiential results show the duty can be smoothly controlled from 5% to 95%. While not invoking any position and current sensors. The Zero crossing point of back EMF which is used for generating proper commutation control of inverter is calculated by sampling the voltage of floating phase. Therefore no current and position sensors are required for the implementation. The method can be easily implemented using digital controller.

Tze-Yee Ho et al. [21] presented BLDC motor drive with direct torque control (DTC) for a washing machine over a variable speed range. The flux controller are derived and realized accordingly. The performance of the BLDC motor drive employing DTC is compared with that of BLDC utilizing the PI current control.. The simulation is carried out prior to realization of the system implementation.

J.X.Sen et al. [22] described the application of third harmonic Back-EMF based brushless machines by detecting the third harmonic back electromagnetic When the zero crossing of the phase back-EMF waveforms are not detectable. However as with all EMF-based sensor less methods, an open loop starting procedure still has to be employed.

2.2.5 Review on control methods of Sensor-less BLDCM

Maher Fareq [23] presented an improved sensor less controllers using third harmonic back-EMF with software phase locked loop has been developed to get precise commutation sequence. This method shows a good improvement in commutation pulse at high speed thus the phase current is minimally delayed from the back EMF, and hence leading to improve power factor and higher torque production than those obtained using a conventional back EMF zero crossing method. The average falls rapidly as the rotor speed, hence motor will frequently be found to have insufficient torque at higher speed.

Satoshi Ogasawara [24] presented a position sensor less brushless dc motor in which the position information is given on the basis of the conducting state of freewheeling diodes in an open phase.. The open phase current under chopper operation results from the back emf’s produced in the motor windings. It is possible to detect the rotor position over a wide speed range from 45 to 2300 r/ min conventional method that directly detects the back emf. This sensor less position detecting method however requires the inverter to be operating in a chopping mode in order for the algorithm to work properly.

R. somanatham et al. [25] presented a scheme for the modeling and simulation of sensor-less control of permanent magnet Brushless DC (PMBLDC) motor using zero crossing back emf technique. The motor is commutated at zero crossing point of back emf . When the motor reaches the minimum speed to facilitate zero crossing detection of back emf the control is transferred to zero crossing detecting circuit. The main advantage of the scheme is that the sensor-less operation can be easily implemented without the natural point.

Boyang – Hu et al. [26] described a novel sensor-less drive method of 180 degree commutation of BLDCM, inverter gate signals are generated by comparing the polarities of the estimated back EMF signals. The estimated trapezoidal back-emf signals are obtained by sensing the three phase current of motor and the inverter output voltage. Rather than the conventional estimated methods, the proposed method cancels the complicated calculation steps.

K.S.Rama Rao et al. [27] proposed a scheme for sensor-less control of a brushless dc (BLDC) motor by direct back EMF detection method. A mathematical model of the drive system is simulated with MATLAB/SIMULINK toolbox. The DSP-ADC feature utilized to sense the back EMF proves the validity of sensor-less control over a wide speed range.

Wook_jin Lee et al. [28] presented a novel method to detect the rotor position of the Brushless DC (BLDC) motor at standstill and a startup method to accelerate the rotor up to a certain speed where the conventional position sensor-less control method based on the back EMF could work reasonably. The principle of the estimation is based on the variation of the current response caused by the magnetic axis. This method can be implemented using only one current sensor at DC link of the inverter. It does not depend on the model of the motor, and it is robust to motor parameter variations. By the method it has been demonstrated that the motor can restart smoothly, without failure even after disturbance during the starting procedure.

A.Ungurean et. al. [29] described a novel sensor-less control of brushless dc permanent magnet (BLDC-PM) motor based on I-f principle for starting with seamless commutation to BEMF zero crossing detection above a certain speed. The starting method assures a fast response and the criteria for switching to speed senseless control introduces short transients.

P.Damodharan et al. [30] described a position sensor-less operation of permanent magnet brushless direct current (BLDC) motor. The position sensor-less BLDC drive proposed is based on detection of back electromagnetic force (back EMF) zero crossing from the terminal voltages. This difference of line voltages provides an amplified version of an appropriate back EMF at its zero crossings. The commutation signals are obtained without the motor neutral voltage.

E.Kaliappan ey.al.[31] described a simple and improved sensor-less technique for position and speed control of PMBLDC motor. In the technique instead of the zero crossing time, the back EMF voltage at the middle of commutation period is used as a control variable. Without using the motor neutral voltage, the Back EMF of the floating phase which is detected during the PWM off time is used. This simplified and improved sensor less technique does not require any filtering.

The performance evaluation results show that such a modeling is very useful in studying the drive system before taking up the dedicated controller design. The improvement of the speed response of the drive has been the topic of research in the present time. The quality of the performance of the drive is generally defined through performance indices such as starting time, rise time, settling time, steady state error and the adaptability of the drive. The response of the drive is highly affected by the type of speed controller used in the control structure. The different configurations of proposed controller are studied in this section.

2.2.6 Review on Controllers for BLDCM

The performance parameters are calculated and the action is taken by the controller. For better performance controller should take action accordingly, which is depend upon applications. Thus a suitable controller design is very important for better performance of the system. Different types of controllers are available such as conventional controller, intelligent controller. Every controller has their merit and demerit which is discussed below.

2.2.6.1 Review on Conventional controllers

A conventional PI controller is most widely used in industry due to its simple control structure, easy to design, and low cost. The PI type controller only cannot give a good performance; it suffers from disadvantages of slower response, larger overshoots and oscillations.

Jan Jantzen [32] presented the most widely used controller in the industrial applications is PID controller because of their simple structure and good performance in a wide range of operating conditions. In the literature the PID controllers can be divided into two parts: In the first parts, the controller parameters are fixed during control operation. These parameters are selected in an optimal way by known methods such as the Zeigler Nichols .Hand tuning method is also one of the method s used today for PID tuning. The fixed gain PID controllers are simple but cannot always effectively control systems with changing parameters or having a strong nonlinearity and may need frequent on line returning. In the second part, the controllers have an identical structure to PID controllers but their parameters are tuned online based on parameters estimation of the process. Such controllers are known as adaptive PID controllers.

2.2.6.2 Review on Intelligent Controllers

Fuzzy logic controller is known for their fast response and good performance in the presence of non-linearizes. The Fuzzy logic controller cannot react to change in operating conditions. The fuzzy logic controller needs more information to compensate nonlinearities when the operating conditions are change. When the number of fuzzy logic inputs increase the dimension of the rule base increases thus the maintenance of the rule base is more time consuming. Another disadvantage of Fuzzy logic controllers is the lack of systematic, effective and useful design methods which can use a proper knowledge of plant. To overcome these disadvantages of the conventional Fuzzy logic controller, different controller configuration of different structure and for self-tuning of the fuzzy controller parameters have been proposed.

OmarKaraskal [33] In this literature, various structure of fuzzy PID (including PI and PD) controllers and fuzzy non-PID controllers have been proposed. Fuzzy PI control is known to be more practical than fuzzy PD because it is difficult for fuzzy PD to remove steady state error. The fuzzy PI control is known to give poor performance in transient response for higher order processes due to the internal integration operation.

The configuration resulted in a normal Fuzzy-PID (FPID) controller. The performance of the current configuration has been further improved by adjusting factors that correspond to the derivative and integral coefficients of the fuzzy PID controller using a fuzzy inference mechanism in an online manner.

Rajrani K Mudi [34] The configuration of FPID can be called as elative rate observer based Self-tuning FPID controller. A similar self-tuning controller scheme is presented in which configuration, the output gain factor of the FLC is undergone tuning depending on the operating point of the system, hence generating the appropriate control signal.

I,K Bousserhane [35] when designing an FLC , different values of gain and scaling factors are set by the operator. The FLC is also expected to give a better performance by allotting the values of gain by some optimizing methods. Genetic algorithm has been used successfully to solve the latter’s purpose. Another way of approach to improve the performance of a fuzzy PID controller by using some complex and more efficient fuzzy reasoning methods can be considered.

Han-Xiong Li [36] A robust performance wise improved FLC can be achieved by incorporating the optimal fuzzy reasoning into the well- developed FPID type of control framework. The performance comparison of the FPID controller was done by using four types of fuzzy reasoning methods.

The optimal fuzzy reasoning mechanism proposed exhibited good response in terms of robustness. It is observed in literature that, The PI controllers attain the set point speed at the steady state eliminating the offset occurring in normal proportional controller.

But disadvantage of the PI controller is the sluggish response and occurrence of overshoot, which may not be desirable in some applications. As discussed above the fuzzy controller apart from having advantages of fast dynamic response and the good operation in the presence of non-linearities has some disadvantages like exhibiting offset in the response, inability to react to change in the operating conditions. For this purpose, a controller can proposed which is a Hybrid of both the controllers i.e. the FLC and the conventional PI controllers. In addition to being able to adapt automatically to a new environment, this controller can further simplify the task of developing rules.

Jan Jantzen [32] A series Hybrid combination of the Fuzzy logic controller and a conventional PI controller has been proposed.

Jong-Hwan and Bhim Singh [37, 38] the fuzzy controller processes the original speed error and provides a modified reference signal in the PI controller and the main control action is taken by the PI. This process of modifying the reference signal continuously is called the precompensation. The principle advantage in implementing this scheme of control is that, an existing PID controller can be easily modified in to this configuration just by adding a fuzzy precompensator in series with the PID controller. The described controller configuration is successfully implementable with the electric drives and efficiently compensates for the overshoots and undershoots.

Oyas and Nordin [39] As mentioned in the literature, even though a fuzzy logic controller delivers fast response and functions well even in the nonlinearities, a PI controller is always preferred to be functioning in the front supported by the FLC at the back end. The designing of a FLC requires time, experience and skills of the designer for the tedious fuzzy tuning exercise.

A conventional PI controller is most widely used in industry due to its simple control structure, easy to design, and low cost. The PI type controller only cannot give a good performance; it suffers from disadvantages of slower response, larger overshoots and oscillations. PMBLDC machine has nonlinear model, the linear PI control is not a good option. The main disadvantage of a the constant gain PI controller is, when operating with systems having constant variation of operating conditions is that a frequent tuning of gains is required as per the conditions. This task is very tedious and complex. This task of tuning the PI gains can be accomplished by a fuzzy logic controller in parallel. Based on the error value and the change in error the FLC outputs a value used in computing the proportional, Integral and derivative gains as the particular operating condition.

Bhim Singh [40] intelligent techniques have been developed and extensively used to improve or to replace conventional control techniques because these techniques do not require a precise model. The results from the comparison of conventional and fuzzy logic control techniques in the form of an FL controller and fuzzy precompensator have shown that the fuzzy logic can reduce the effects of nonlinearity in a PMBLDC motor and improve the performance of a controller.

Bhim Singh [41] Fuzzy logic controller has been implemented on many platforms such as digital signal processor, microcontroller. These platforms have different advantages and disadvantages. The FLC developed on DSP or PC can quickly process fuzzy computation to generate designed control action, but the physical size of the system may become too big and quite expensive for a small motor application. On the other hand microcontroller to implement a FLC is inexpensive and physical size of the system is small. when the FLC is employed on the control of a drive, the cost and complexity of control are more, instead of using an FLC , the scope for efficiently varying the PI gains without an FLC has been explored, thus decreasing the complexity of control and making the drive more economical. The gain scheduling control scheme for a proportional integral controller (PI) for speed control of PMBLDC motor drive has been proposed. In the proposed scheme the PI gains are allowed to vary with in the pre-determined range, by varying the gain values as the functions of speed error. Low cost practical implementation of the procedure is possible without employing expensive dedicated computing systems. This Scheme is very easy to implement in practice since an existing PI controller is tuned automatically.

Hybrid feedback controller for linear and nonlinear control system provides maximum flexibility for achieving multiple performance objectives and, is consistent with computer based implementation. It can be mentioned that hybrid control or logic based switching control has been extensively utilized in practical engineering control systems.

2.3 Conclusion

The exhaustive literature review has revealed that research work carried out on different controller configurations and on speed control of Brushless DC motor and other motor derives is influenced most by the advancements and developments in power electronics, microelectronics different simulation software and the other sensor technologies. Better operating performance have been achieved with sensors and without sensor. A lot many controllers have been used in order to test the performance characteristics of PM motors, which have also resulted in improved performance. Almost all the development covered in the section aim in the direction of increasing the robustness of the system for different operating conditions. The control hardware reduction was also the main criteria. Therefore these developments improve the motor speed control to a stage where the motor can be used extensively on various applications. Fuzzy logic methods can be used effectively to complement conventional control methods for improving performance and robustness, especially in the presence of severe and unknown nonlinearities. The Hybrid controller configuration has helped to improve the performance of the controller, in terms of transient and steady state response. When the conventional controllers and the intelligent controller are used in a suitable configuration, it is concluded that the disadvantages of both the controllers can be eliminated and a much better performance is achievable. The developed controllers can be implemented on PC, DSP etc. The implantation through microcontroller is more economical. The control technique also matters; cost factor is not too high for the low power rating machines.

CHAPTER 3

MODELING OF THE PMBLDCM DRIVE SYSTEM

3.1 General

The concept and types of various controllers under study, applications of the brushless dc motors and an exhaustive literature review have been covered in the preceding chapters. A mathematical modeling is an analytical description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modeling. Each component of the drive system is modeled by a set of mathematical equations such sets of mathematical equations such as equations when combined together represent the mathematical model of the complete system. The modeling of the different components of the drive system described below. The present chapter deals with modeling and simulation of the drive system with the different controllers such as PI, PID (conventional controller), Fuzzy logic controller, ANFIS controller, series hybrid controller in the MATLAB/SIMULINK.

3.2 The PMBLDC Drive System

The figure 3.1 describes the basic building blocks of the PMBLDCM drive. The drive

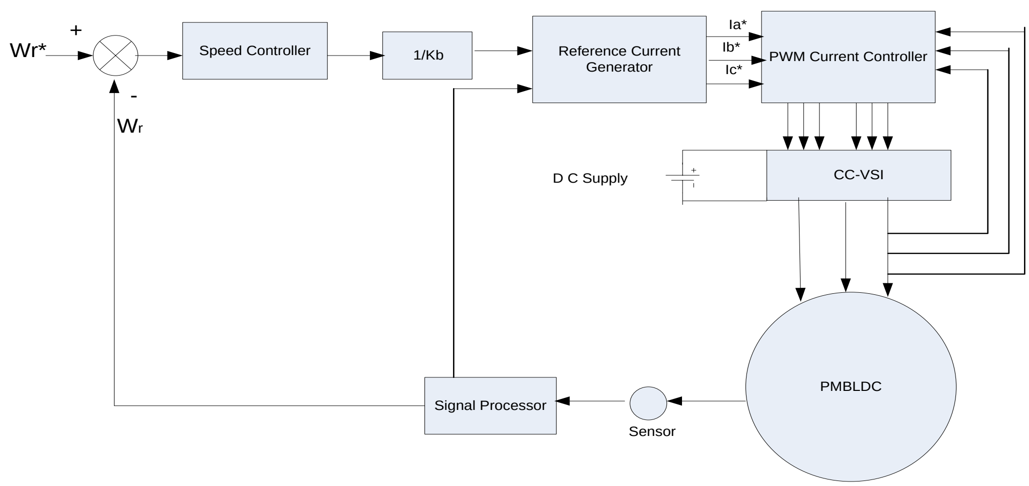

Fig 3.1 The Block Diagram of the PMBLDCM drive

consists of speed controller,, reference current generator, PWM current controller, position sensor, the motor and IGBT based current controlled voltage source inverter (CC-VSI). The speed of the motor is compared with its reference value and the speed error is processed in Proportional – Integral (PI) speed controller. The output of this controller is considered as the reference torque. A limit is put on the speed controller output depending on permissible maximum winding currents. The reference current generator block generates the three phase currents (i_a*,i_b*,ic*) using the limited peak current magnitude decided by the controller and the position sensor. The reference currents have the shape has the shape of quasi- square wave in phase with respective back emfs to develop constant unidirectional torque. The PWM current controller regulates the winding currents (i_a*,i_b*,ic*) within the small band around the reference currents (i_a*,i_b*,ic*).The motor currents are compared with the reference currents and the switching commands are generated to drive the inverter devices.

A. Reference Current Generator

The magnitude of the three phase current (I*) is determined by using reference torque(T*) and the back emf constant (K_b) as I*= T*/$K_{b.}$ Depending on the rotor position signal obtained from the Hall sensors, the reference currents generator block generate the three phase reference currents (i_a*,i_b*,ic*) by taking the value of reference current magnitude as I*, -I* and zero. The reference current generation is as shown below.

Rotor position Signal	Reference Currents		
θ_r	i_a*	i_b*	i_c*
0° - 60°	I*	-I*	0
60° - 120°	I*	0	-I*
120° - 180°	0	I*	-I*
180° - 240°	-I*	I*	0
240° - 300°	-I*	0	I*
300° - 360°	0	-I*	I*

B. PWM Current Controller

The PWM Current controller contributes to the generation of the switching signals for the Inverter device. The switching logic is formulated as given below.

If $i_a < (i_a^* - h_b)$ switch 1 ON and switch 4 OFF

If $i_a > (i_a^* + h_b)$ switch 1 ON and switch 4 ON

If $i_b < (i_b^* - h_b)$ switch 1 ON and switch 4 OFF

If $i_b > (i_b^* + h_b)$ switch 1 ON and switch 4 ON

If $i_c < (i_c^* - h_b)$ switch 1 ON and switch 4 OFF

If $i_c > (i_c^* + h_b)$ switch 1 ON and switch 4 ON

Where, h_b is the hysteresis band around the three phase reference currents. The value of 'h_b' chosen here in simulation is 0.1 A.

C. Modeling of PMBLDC Motor

The BLDCM Produces a trapezoidal back electromotive force(EMF) and the applied current waveform in rectangular shaped. In order to simply analyze,3-phase 6 state BLDCM with Y-connected windings and two-phase excitation. The three phase windings are symmetrical, magnetic saturation is neglected, hysteresis and eddy current losses are not considered, and the inherent resistance of each of the motor windings is 'R', the self-inductance is L_s and the mutual inductance is M. Hence the three- phase stator voltage balance equation can be expressed by the following equation.

3.3 Mathematical Modeling of Permanent Magnet BLDC Motor

3.3.1 Three phase stator Equations

The coupled circuit diagram of three phase stator is shown in fig 3.2 .The equation of the stator Stator windings in form of motor electrical constants are

$$v_{an} = R_a i_a + \frac{d}{dt}(L_{aa} i_a + L_{ba} i_b + L_{ca} i_c) + e_a \qquad (3.3)$$

$$v_{bn} = R_b i_b + \frac{d}{dt}(L_{aa} i_a + L_{ba} i_b + L_{ca} i_c) + e_b \qquad (3.4)$$

$$v_{cn} = R_a i_c + \frac{d}{dt}(L_{aa} i_a + L_{ba} i_b + L_{ca} i_c) + e_c \qquad (3.5)$$

Where

$R_a, R_b, R_c = R$ Stator resistance per phase, assumed to be equal for all phases.

$L_{aa}, L_{bb}, L_{cc} = L_s$ Stator inductance per phase, assumed to be equal for all phases

L_{ba} ,L_{ab}, L_{ac},L_{ca}, L_{ba},L_{cb} = M Mutual inductance between the phases, assumed to be equal for all phases.

i_a, i_b,i_c Stator current/phase

v_{an}, v_{bn} , v_{cn} Stator voltage /phase

e_a, e_b,e_c Induced emf/phase

As the stator is star connected so taking $i_a + i_b + i_c = 0$, the equations (3.3) to (3.5) becomes

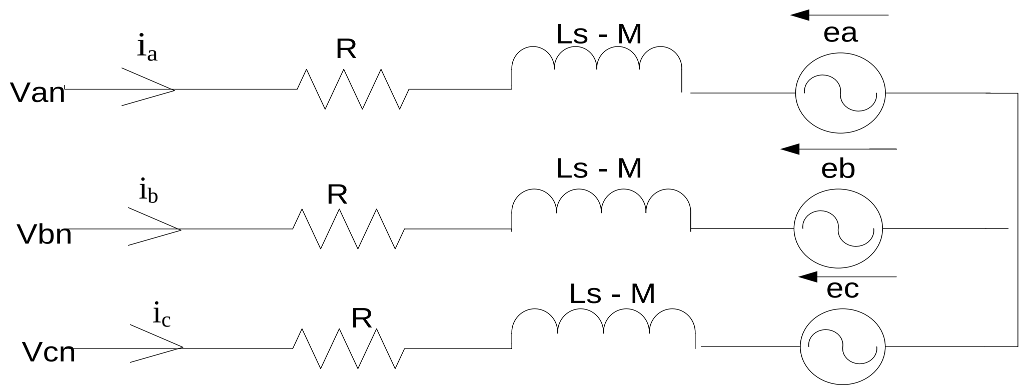

Fig. 3.2 Three phase stator Voltage circuit representation of PMBLDC motor

$$v_{an} = R\, i_a + (L_s - M) \frac{d}{dt} i_a + e_a \tag{3.6}$$

$$v_{bn} = R\, i_b + (L_s - M) \frac{d}{dt} i_b + e_b \tag{3.7}$$

$$v_{cn} = R\, i_c + (L_s - M) \frac{d}{dt} i_c + e_c \tag{3.8}$$

The instantaneous induced emf is given by

$$e_a = f_a(\theta_r)\, \lambda_p\, \omega_m \tag{3.9}$$

$$e_b = f_b(\theta_r)\, \lambda_p\, \omega_m \tag{3.10}$$

$$e_c = f_c(\theta_r)\, \lambda_p\, \omega_m \tag{3.11}$$

Where ω_m is the mechanical speed of the rotor (rad/sec) , θ_r is the electrical rotor position (rad) and λ_p is the linking flux.

The electromagnetic torque produced by the BLDC motor is given as

$$T_e = \lambda_p [\, f_a(\theta_r)\, i_a + f_b(\theta_r)\, i_b + f_c(\theta_r)\, i_c] \tag{3.12}$$

3.3.2 Mechanical Equations

The mechanical equation of motion for simple system is

$$T_e = J \frac{d}{dt}\omega_m + T_l + B\,\omega_m \tag{3.13}$$

Where T_e, the electromechanical torque is produced by the motor ,T_l is the load torque, J is the inertia and B is the frictional constant.

Speed can be calculated from equation 3.13 as

$$\frac{d}{dt}\omega_m = \frac{1}{J}(T_e - T_l - B\,\omega_m) \tag{3.14}$$

Once the angular speed is calculated the motor's mechanical position as well as electrical position can be estimated. The relation between angular velocity and angular position is given by

$$N = \frac{30}{\Pi}\,\omega_m \tag{3.15}$$

Where N is the speed in rpm

$$\frac{d}{dt}((\theta_r) = \frac{P}{2}\,(\omega_m) \tag{3.16}$$

Where P is the total number of poles and θ_r is the electrical position.

3.3.3 Relation between Electrical and Mechanical equation

The Back-emf (e_a,e_b, and e_c) of the permanent magnet BLDCM is a function of state variable((θ_r), rotor electrical position, which is given as trapezoidal function and is written as function.

$$f_a(\theta_r) = 1 \qquad 0 < \theta_r < \frac{\pi}{3}$$

$$= \left(\frac{\pi}{2} - \theta_r\right) \qquad \frac{\pi}{3} < \theta_r < \frac{2\pi}{3}$$

$$= -1 \qquad \frac{2\pi}{3} < \theta_r < \Pi$$

$$= -1 \qquad \pi < \theta_r < \frac{4\pi}{3}$$

$$= \left(\theta_r - \frac{3\pi}{2}\right) * \frac{6}{\pi} \qquad \frac{4\pi}{3} < \theta_r < \frac{5\pi}{3}$$

$$= 1 \qquad \frac{5\pi}{3} < \theta_r < 2\pi \tag{3.17}$$

Similarly for phase b and c

$$f_b(\theta_r) = f_a\left(\theta_r + \frac{2\pi}{3}\right) \tag{3.18}$$

$$f_c(\theta_r) = f_a\left(\theta_r - \frac{2\pi}{3}\right) \tag{3.19}$$

Table 3.1 Trapezoidal Back-Emf as a function of rotor position

θ_r / $f(\theta_r)$	0° - 60°	60° -120°	120° - 180°	180° - 240°	240° - 300°	300° - 360°
$f_a(\theta_r)$	1	$-\frac{6\,\theta_r}{\pi}+3$	-1	-1	$\frac{6\,\theta_r}{\pi}-9$	1
$f_b(\theta_r)$	$\frac{6\,\theta_r}{\pi}-1$	1	1	$-\frac{6\,\theta_r}{\pi}+7$	-1	-1
$f_c(\theta_r)$	-1	-1	$\frac{6\,\theta_r}{\pi}-5$	1	1	$-\frac{6\,\theta_r}{\pi}+11$

Similarly the rectangular currents in the stator windings is also a function of rotors electrical position and is expressed as

$$i_a(\theta_r) = 1 \qquad 0 < \theta_r < \frac{\pi}{3}, \frac{5\pi}{3} < \theta_r < 2\pi$$

$$= 0 \qquad \frac{\pi}{3} < \theta_r < \frac{2\pi}{3}, \frac{4\pi}{3} < \theta_r < \frac{5\pi}{3}$$

$$= -1 \qquad \frac{2\pi}{3} < \theta_r < \frac{4\pi}{3} \tag{3.20}$$

Similarly for phase b and c

$$i_b(\theta_r) = i_a\left(\theta_r + \frac{2\pi}{3}\right) \quad (3.21)$$

$$i_c(\theta_r) = i_a\left(\theta_r - \frac{2\pi}{3}\right) \quad (3.22)$$

Table 3.2 Rectangular Current in PMBLDCM as a function of rotor position

θ_r / $i(\theta_r)$	0° - 60°	60° -120°	120° - 180°	180° - 240°	240° - 300°	300° - 360°
$i_a(\theta_r)$	1	0	-1	-1	0	1
$i_b(\theta_r)$	0	1	1	0	-1	-1
$i_c(\theta_r)$	-1	-1	0	1	1	0

Table 3.1 and 3.2 summarizes the value of back-emf and corresponding current function respectively.

3.4 Mathematical Modeling of Permanent Magnet BLDC Motor (Sensor-less)

In this mode of operation the motors parameters and current status of voltages and currents is being used to carry out the commutation. Speed and Back-Emf estimation from the line voltages, Using Equations 3.6, 3.7 and 3.8 the phase voltages are expressed as

$$v_{an} - v_{bn} = v_{ab} = R(i_a - i_b) + (L_s - M)\frac{d}{dt}(i_a - i_b) + e_a - e_b \quad (3.23)$$

$$v_{bn} - v_{cn} = v_{bc} = R(i_b - i_c) + (L_s - M)\frac{d}{dt}(i_b - i_c) + e_b - e_c \quad (3.24)$$

$$v_{cn} - v_{an} = v_{ca} = R(i_c - i_a) + (L_s - M)\frac{d}{dt}(i_c - i_a) + e_c - e_a \quad (3.25)$$

Assuming $(L_s - M) = L$ and $(i_a + i_b + i_c = 0)$ because of Star or Y connection of stator then, subtracting (3.21) from (3.20),(3.21) from (3.22) and (3.20) from (3.22) we have,

$$v_{ab} - v_{bc} = v_b = R(-3\, i_a) + L\frac{d}{dt}(-3i_b) + e_a + e_c - 2\, e_b \quad (3.26)$$

$v_{bc} – v_{ca} = v_c = R (-3 i_c) + L\frac{d}{dt} (-3i_c) + e_a +e_b -2 e_c$ (3.27)

$v_{ca} – v_{ab} = v_a = R (-3 i_a) + L\frac{d}{dt} (-3i_a) + e_c +e_b -2 e_a$ (3.28)

From above (3.23), (3.24) and (3.25) equations,

$v_b = R (-3 i_a) + L\frac{d}{dt} (-3i_b) + e_a +e_c -2 e_b$ (3.29)

$v_c = R (-3 i_c) + L\frac{d}{dt} (-3i_c) + e_a +e_b -2 e_c$ (3.30)

$v_a = R (-3 i_a) + L\frac{d}{dt} (-3i_a) + e_c +e_b -2 e_a$ (3.31)

At the commutation instant of phase B

$i_b = - i_c$ and $i_b = 0$ (3.32)

Also $e_a = -e_c$ (3.33)

3.5 Conclusion

This chapter describes a detail mathematical modeling of BLDC motor operation with position sensor and without speed sensor. The block diagram of BLDC drive system and related equations for drive system is discussed. Mechanical coupling equations for the drive are also discussed in this chapter.

CHAPTER 4

MODELING OF SPEED CONTROLLERS

4.1 General

The concept and types of various controllers of the brushless dc motors is described in this chapter in detail. The present chapter deals with modeling and simulation of the PMBLDC drive system with different controllers such as PI, Fuzzy logic controller, series hybrid controller and self-tuning controller in MATLAB/ SIMULINK environment. Conventional controllers does not perform in sudden nonlinearities and other operating conditions so with the time performance of the drive become poor, because controller cannot adapt the condition of system or drive. To overcome with this problem intelligent and adaptive controllers are used which can improve the performance index and adapt the situation of the plant.

4.2 Speed Controllers

Five different types of speed controllers have been considered for the speed control of a PMBLDCM in this dissertation. Basic structure and mathematical representation and Simulink diagram is carried out in this chapter. Speed controllers are designed and for intelligent speed controller rule base are also designed. With the use of proper speed controllers can enhance the performance of the drive.

4.2.1 Proportional Integral (PI) Controller

The Fig. 4.1 shows the general schematic block diagram of PI controller As shown in the drive system explained above the speed error is computed and used as an input to

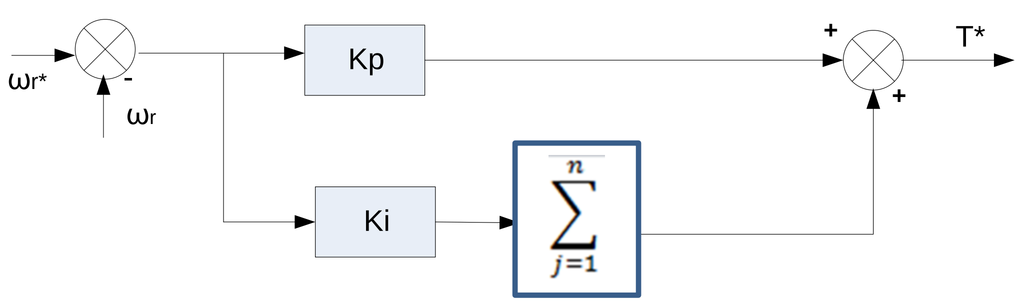

Fig .4.1 The Structure of PI controller

the speed controller. The output is the reference current signal fed to the hysteresis current controller block which generates the gating pulses corresponding to the required current. The inverter supplies the required currents to the three phases of the machine. The output of the controller in discrete at the n^{th} instant is given as:

The Speed error at the n^{th} instant of time is given as:

$$e(n) = \omega_r^*(n) - \omega_r(n) \tag{4.1}$$

where $\omega_r^*(n)$ is the reference speed at the n^{th} instant, $\omega_r(n)$ is the rotor speed in the n^{th} instant, and $e(n)$ is the speed error at the n^{th} instant.

$$T^*(n) = T^*(n-1) + K_p\,[e(n) - e(n-1)\,] + K_i\, e(n) \tag{4.2}$$

Where K_p and K_i are the proportional and integral gain parameters of the PI speed controller and (n-1) is previous state of n^{th} instant.

The gain parameters are selected by observing their effects on the response of the drive. The numerical values of the controller gains used in the simulation are given in the appendix.

4.2.1.1 Simulink Model for PI Controller

4.2.1.1.1 Speed Controller

The Fig. 4.2 shows the MATLAB/SIMULINK model for the PI Controller. The basic operating conditions have been stated in the previous section. Using the Proportional (K_p) and the Integral (K_i) gain parameters the reference torque (T*) is generated by the PI controller, hence the desired motor speed is achieved.

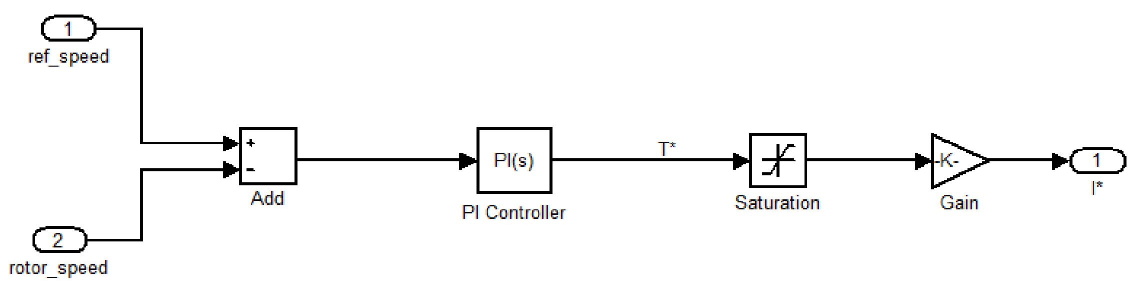

Fig. 4.2 Simulink model of a PI Speed Controller

4.2.1.1.2 Current Controller

If there is no control over the current then current shoot up may take place at any time at any value. Therefore to avoid that kind of situation, the current controller block is included in the Simulink model.

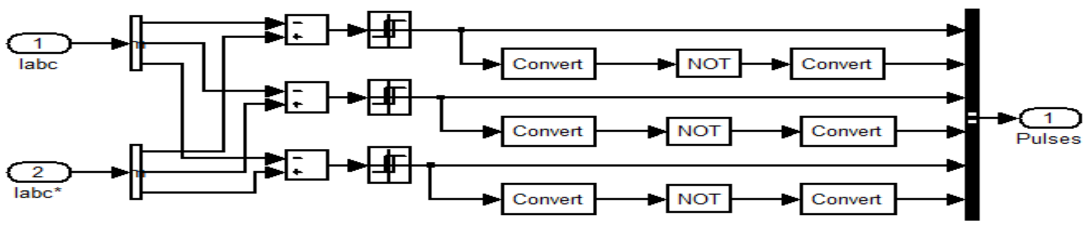

Fig. 4.3 Simulink model of a Hysteresis Controller

The error between the reference Speed and measured Speed is processed in PI Controller and depending upon the magnitude of processed error, PWM pulse is generated by the PWM Controller. This pulse along with the hall sensor signals will constitute the three phase reference current which when compared with the actual three phase current using the Hysteresis comparator as shown in fig 4.3 would generate the PWM pulses to control the gate triggering of inverter .Hysteresis band is assumed to be of width 0.01

4.2.2 Fuzzy Logic Controller

The internal structure of the fuzzy logic speed controller is as shown in the Fig.4.4. The fuzzy controller is composed of the following four elements:

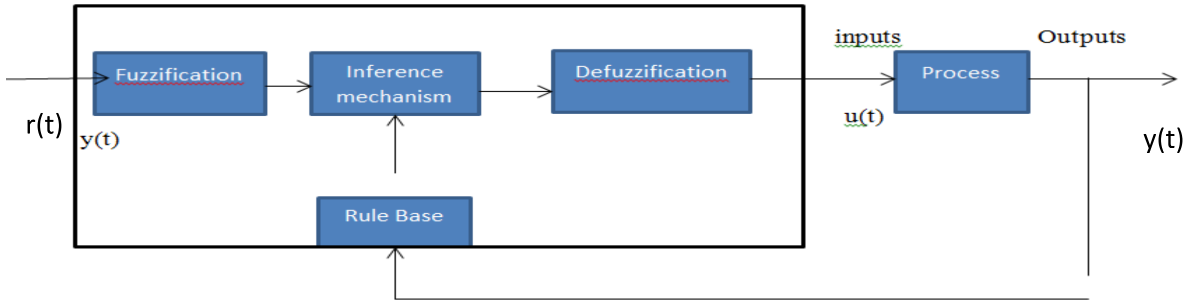

Fig.4.4 Internal Block Diagram of a Fuzzy Logic Controller

A. Fuzzification interface, which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.

B. Rule – Base is a set of “If-THEN” rules, which contains a fuzzy logic quantification of the expert’s linguistic description of how to achieve good control.

C. Interference mechanism also called “interference engine” or Fuzzy inference system, which emulates the expert’s decision making in interrupting and applying knowledge about how best to control the plant.

D. Defuzzification interface, which converts the conclusion of the interface mechanism into actual inputs for the process.

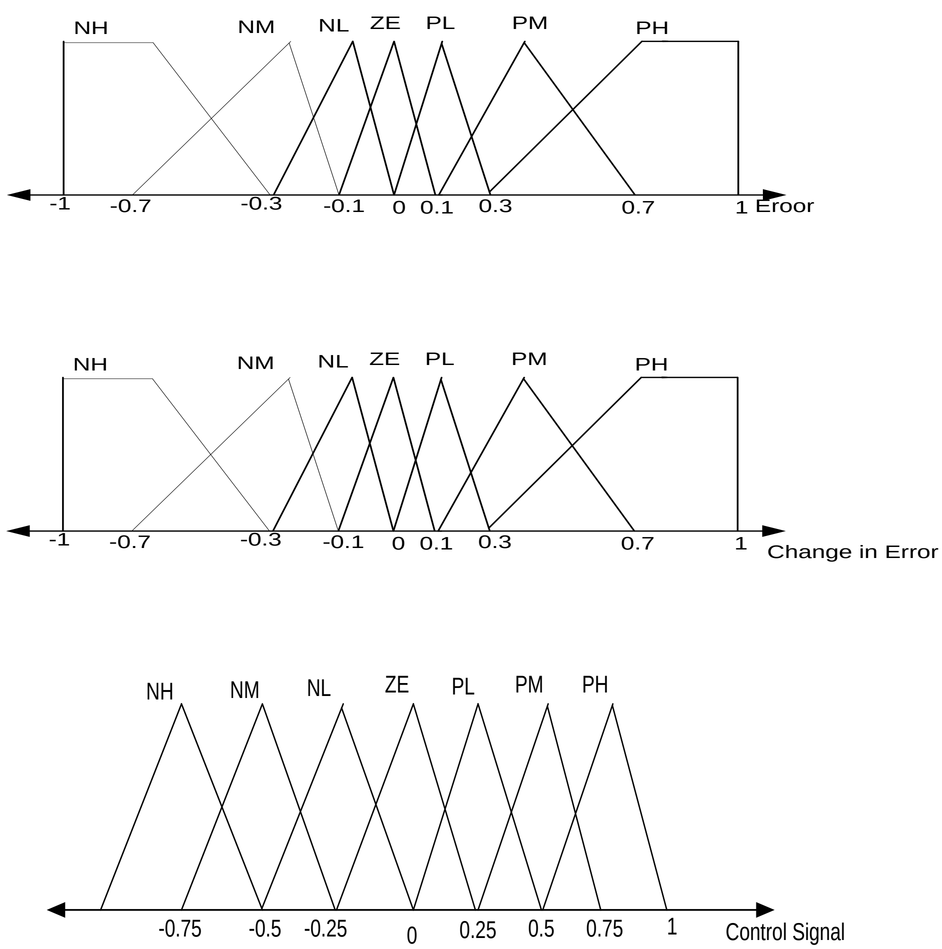

Fig. 4.5 Fuzzy membership function for both the two input variables

Membership function values range is shown in fig. 4.5. With the help of these ranges and rule base we are able to design the fuzzy logic controller.

The Fuzzy rules are given in Table 4.1. The Output of the decision maker passes through the De-fuzzifier where in the linguistic format signal is converted back into the numeric form or crisp form. The decision making block used are in the format of "IF-THEN" rule base.

Table 4.1 Rule Base Table for Fuzzy Logic Controller

E / CE	NH	NM	NL	ZE	\`PL\`	PM	PH
NH	NH	NH	NH	NH	NH	NM	PM
NM	NH	NH	NH	NH	NM	NL	PH
NL	NH	NH	NH	NM	ZE	PM	PH
ZE	NH	NH	NH	ZE	PL	PH	PH
PL	NH	NH	ZE	PL	PM	PH	PH
PM	NH	NM	PM	PM	PH	PH	PH
PH	NM	PM	PH	PH	PH	PH	PH

4.2.2.1 Simulink Model for Fuzzy Logic Controller

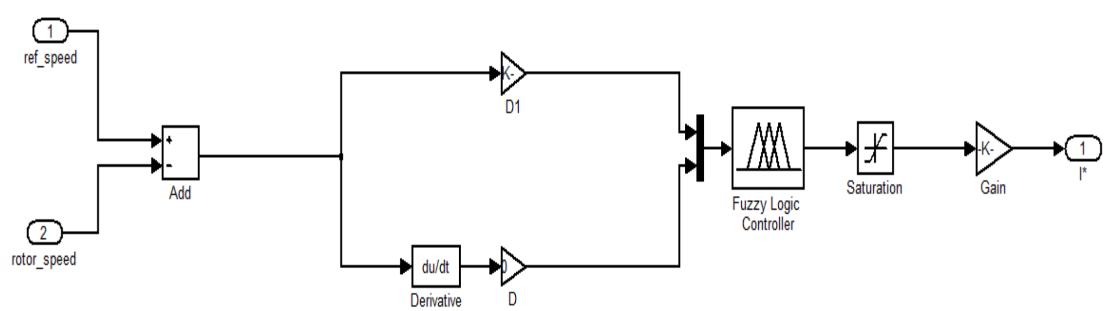

Fig 4.6 Simulink model for the FLC Speed Controller

Fig. 4.6 shows the MATLAB model diagram for the Fuzzy logic speed controller. The two inputs namely, Speed error and change in speed are properly scaled and fed to the

MATLAB fuzzy logic controller. The rescaled defuzzified output of the fuzzy logic block after limiting forms the outputs of the controller block is used as magnitude of reference winding current(I*).

Given the combination of two inputs, the membership of the corresponding output is taken as minimum membership value of the two respective inputs.

Mathematically, α = Min [u (input 1), μ (input 2)]

Crisp value = ($\sum$ (pm) α) / $\sum \alpha$ (4.3)

Where μ refers to the membership value, the output membership is stored in α and 'pm' refers to the peak of membership function.

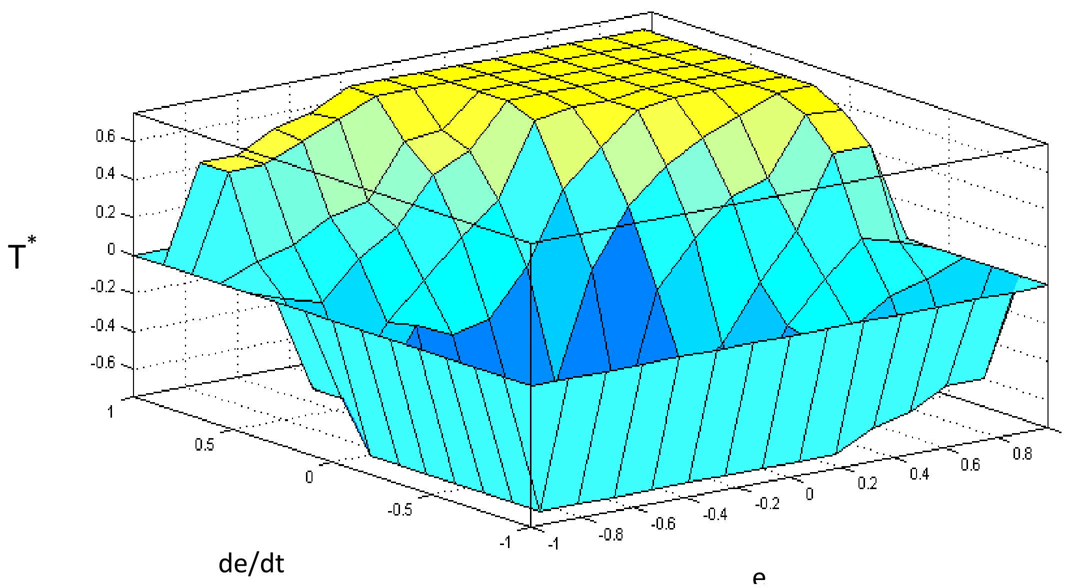

Fig 4.7 The Fuzzy surface for the fuzzy logic controller

It is defined by the understanding of the behavior of the system. Rules of different functionalities can be found here. Rules for maintaining speed error zero (steady state rules), rules that avoid motor speed overshoot and the rules that provides rapid response to large error resulting from command change. Fuzzy logic controllers have three significant advantages over conventional techniques such as;

4.2.3 Adaptive Neuro –Fuzzy Inference System (ANFIS) Controller

The recently studied intelligent controller, ANFIS is one of them which is a Hybrid of FLC and Neural. Fuzzy control using expert's knowledge or linguistic variables and neural network with, learning capability.

4.2.3.1 Structure of Neuro-Fuzzy controller

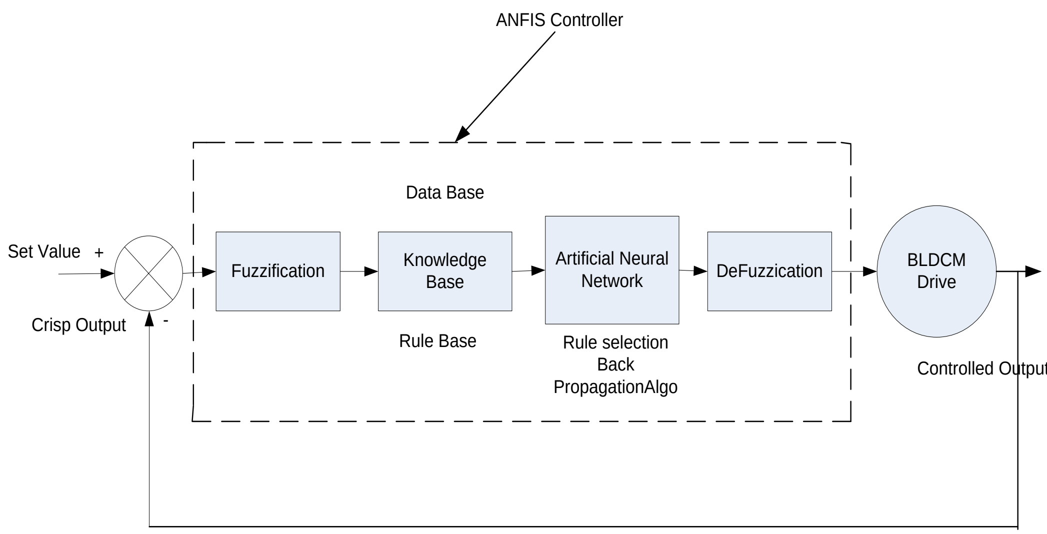

Fig.4.8 Block diagram of the ANFIS control scheme for BLDCM

Figure 4.8 shows the block diagram of ANFIS control scheme. The parameters associated with the membership functions changes through the learning process. The computation of these parameters (or their adjustment) is facilitated by a gradient vector. This gradient vector provides a measure of how well the fuzzy inference system is modeling the input/output data for a given set of parameters. When the gradient vector is obtained, any of several optimization routines can be applied in order to adjust the parameters to reduce some error measure. This error measure is usually defined by the sum of the squared difference between actual and desired outputs. Fig. 4.8 shows the basic structure of ANFIS controller. Fuzzy and neural networks use the combination of both, which leads to neuro-Fuzzy controllers. The basic concept of neuro-fuzzy control models is first to use structure-learning algorithm is to find the appropriate fuzzy rules and then use parameters learning algorithms to fine tune the membership functions and other parameters. In this hybrid structure ,the input and output nodes represents the input states and output control or decision signal respectively and in hidden layer there are nodes functioning as membership functions and fuzzy logic rules. Critic evaluates the performance of neuro-fuzzy controller and with respect to error and variation of error. It generates stress signal in the range of [-1 +1] . Critic can be described like a simple PD control system or for enhancing the training of ANFIS is considered as a simple fuzzy system. The neuro-adaptive learning method works similarly to that of neural networks. Neuro-adaptive learning techniques provide a method for the fuzzy modeling procedure to *learn* information about a data set.

4.2.3.2 Simulink Model for ANFIS Controller

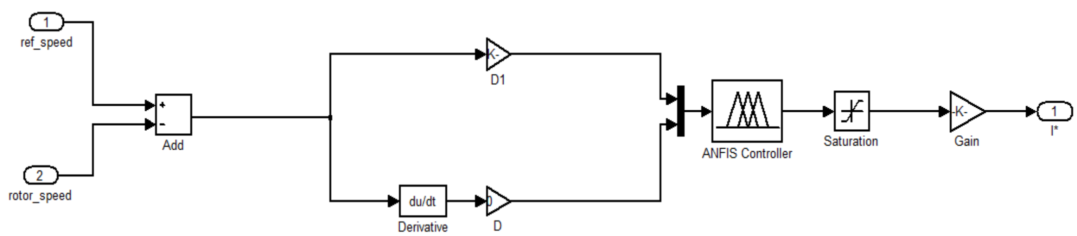

Fig.4.9 Simulink model for the ANFIS Speed Controller

Fig. 4.9 shows the MATLAB model diagram for the ANFIS speed controller. The two inputs namely, Speed error are properly scaled and fed to the MATLAB ANFIS controller.

4.2.4 The Series Hybrid Controller (Fuzzy Pre compensated PI Controller)

The basic structure of the control is shown in fig. 4.10. The purpose of the control scheme is based on trying to compensate for overshoots and undershoots

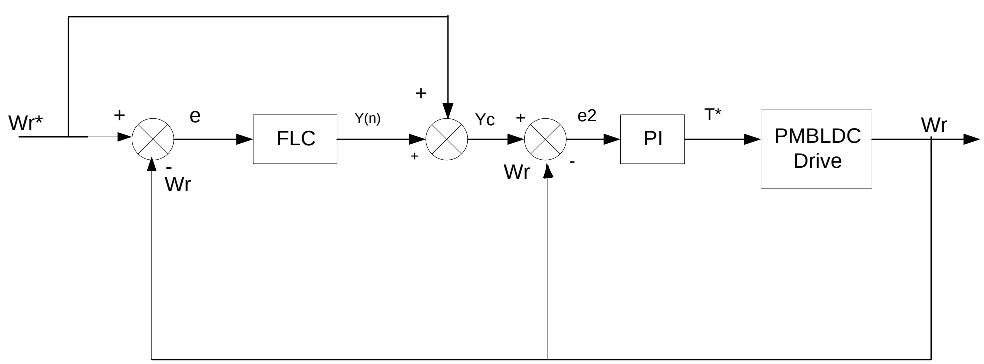

Fig.4.10The Block diagram of the series hybrid controller

in the transient response.. Fuzzy Logic control is generally opted when intelligence and fast dynamic response are among the prime requirements. The major disadvantages in using solely this type of control logic are the presence of steady state error on no load. To eliminate this disadvantage, it is necessary to combine fuzzy logic with another suitable control technique, which is capable of removing the disadvantages existing in fuzzy logic control. Therefore a PI controller is used in combination with fuzzy logic. At operating point, PI controller is used in combination with fuzzy logic such that at operating point, PI controller takes over eliminating the disadvantage of the FLC. Similarly when away from the operating point FLC dominates and eliminates the error due to PI controller such as occurrence of overshoots and undershoots in drive response Such a Controller where weighted combination of two controller outputs contributes to the net output is called a hybrid controller. The structure and the functionally of the controller is described in the section below.

4.2.4.1 Control Structure

The figure 4.10 shows the basic control scheme of the Series Hybrid Controller. The scheme consists of a conventional PI control structure together with our proposed fuzzy pre compensator. The fuzzy pre compensator uses the command input ω_r^* and the plant output ω_r to generate a pre compensated command signal y_c, described by the following equations

$$e(n) = \omega_r^*(n) - \omega_r(n) \tag{4.4}$$

$$\Delta e(n) = e(n) - e(n-1) \tag{4.5}$$

$$y(n) = f\,[e(n), \Delta e(n)] \tag{4.6}$$

$$y_c(n) = \omega_r^*(n) + y(n) \tag{4.7}$$

In the above, $e(n)$ is the tracking error between the command input ω_r^* and the plant output ω_r and $\Delta e(n)$ is the change in the tracking error. The term $f\,[e(n), \Delta e(n)]$ is a nonlinear mapping of $e(n)$ and $\Delta e(n)$ based on fuzzy logic which is given below. The term $y(n) = f\,[e(n), \Delta e(n)]$ represents a compensation or correction term, so that the compensated command signal $y_c(n)$ is simply the sum of external command signal ω_r^* and $y(n)$. The correction term is based on the error $e(n)$ and the change of error $\Delta e(n)$. The compensated command $y_c(n)$ is applied to a conventional PI scheme, as shown in Fig 4.10. The equations governing the PI controller are as follows.

$$e_2(n) = y_c(n) - \omega_r(n) \quad (4.8)$$

$$\Delta e_2(n) = e_2(n) - e_2(n-1) \quad (4.9)$$

$$T^* = T^*(n-1) + K_p \Delta e_2(n) + K_i e_2(n) \quad (4.10)$$

The quantity $e_2(n)$ is pre compensated tracking error between the pre compensated command input $y_c(n)$, and $e_2(n)$ is the change in the pre compensated tracking error. The control is applied to the input of the plant. The purpose of fuzzy pre compensator is to modify the command signal to compensate for the overshoot and undershoot present in the output response. When the plant has unknown nonlinearities which can result in significant overshoots and undershoots conventional PI control scheme is unable to compensate their effects.

Table 4.2 Rule Base for Fuzzy Precompensator

E / CE	NH	NM	NL	ZE	PL	PM	PH
NH	NH	NH	NH	NH	NM	NL	PM
NM	NH	NH	NH	NM	NL	PL	PH
NL	NH	NH	NM	NL	NL	PM	PH
ZE	NH	NM	NM	ZE	PL	PH	PH
PL	NM	NM	NL	PL	PM	PH	PH
PM	NM	NL	PL	PM	PH	PH	PH
PH	NM	PL	PH	PH	PH	PH	PH

The set of rules used in our fuzzy pre compensator is given the Table 4.2.The rules are derived by using a combination of experience, trial and error and our knowledge of the response of the system. To explain how these rules were obtained, consider for example the rule (ZE, NM, NH) in table 4.2. Suppose that the command signal is a constant the error e(n) is zero, and the change of error $\Delta e(n)$ is a negative number. Similarly consider the rule

(PM, PM, PH) in table. Now consider the case where e(n) is positive ,and so is Δe(n) . This means that plant output ω_r (n) is below the command signal and is still decreasing (i.e, we are in the middle of undershoot).This explains the control structure and functioning of the series hybrid controller. To compensate for this, we need to increase the command signal by a positive amount. This corresponds to applying a positive value of FLC output. . Hence the rule 'if error is positive Medium and change of error is Positive Medium, then output a Positive High correction," The other are obtained is Positive Medium, Then output a positive High correction". The other rules are obtained in a similar manner.

4.2.4.2 Simulink Model for the Series hybrid Controller

The Fig. 4.11 shows the MATLAB model diagram for the Series Hybrid Controller. Such a controller has the modified reference speed (precompensated) signal by the FLC to the PI Controller. The PI Controller produces the required control signal. The controller's operation has been discussed in the previous sections.

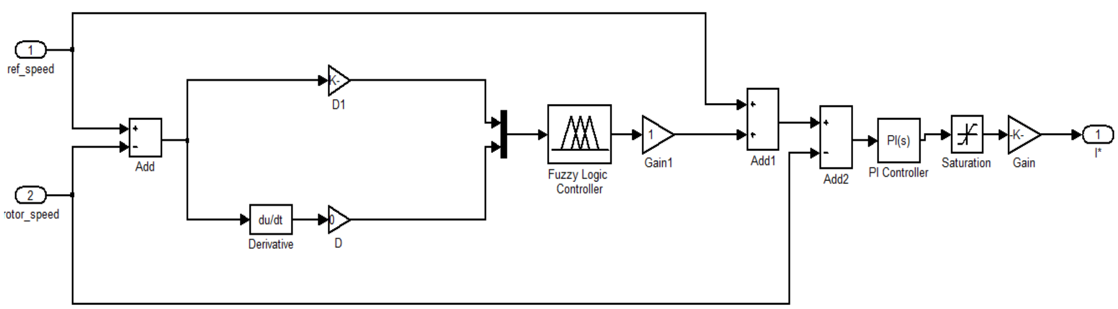

Fig.4.11 Simulink model for the Series hybrid Speed Controller

4.2.5 The Self tuning PI Controller

Fuzzy logic based self-tuning scheme for the conventional PI controllers uses fuzzy computing along with conventional control methods for enhancement of the drives performance. The Self-tuning PI controller is expected to reduce the rise time and the settling time and also reduce the overshoot which generally occurs in a conventional PI controller. The structure is easy to understand and is capable of accommodating without much change to the actual system. It works on the same basic principle of a conventional PI controller, but unlike the fixed gain PI controller. In this controller the values of the proportional and integral gains are modified continuously based upon the operating condition. We know that as per the control structure of a normal PI controller in continuous time domain, the control action, $u(t) = K_p\, e(t) + K_i \int e(t)dt$, in the proportional term control action is proportional to the "product of proportional gain K_p and error value" and in the integral term , it is proportional to the "product of the integral gain K_i and integral of the error.

This means proportional gain provides the control action effectively when the error is more and the integral gain delivers efficiently when the system is operating near the set point value, i.e. when the system has offset. Hence the control method follows that when the speed error is large, the proportional gain must be kept large and when the operating point is near the set point; the integral gain comes to action and reaches the maximum after reaching the steady state value. Fuzzy logic rules are written as per this control strategy such that the proportional gain (K_p) must be maximum when the error is large and should be started varying to the minimum when the drive system is near the set point. The Integral gain is point and attains maximum value when it operates near to the set point.

4.2.5.1 Control Structure

Fig 4.12 shows the basic control structure of the proposed self-tuning controller. It consists of a fuzzy logic controller in parallel with a conventional PI controller.

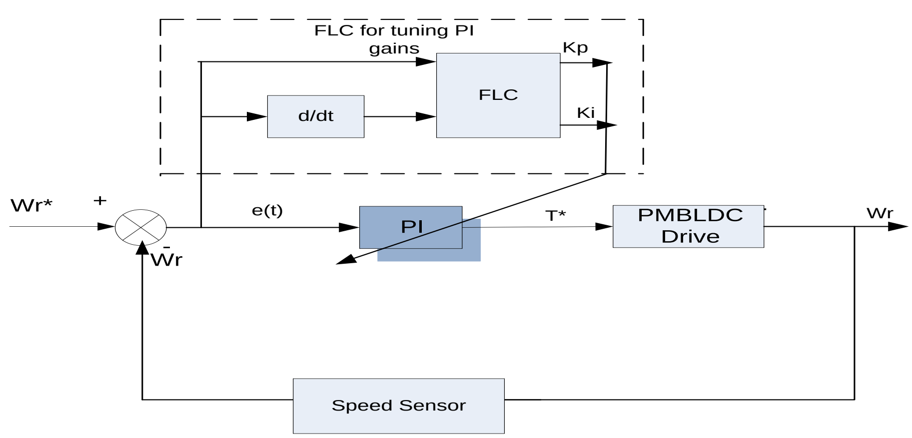

Fig. 4.12 The Basic structure of the Self-tuning Controller

The fuzzy logic controller uses the tracking error e(n) between the command speed and the present rotor speed and the change in the speed error $\Delta e(n)$ as the inputs.

$$e(n) = \omega r^{*}(n) - \omega_r(n) \tag{4.11}$$

$$\Delta e(n) = e(n) - e(n-1) \tag{4.12}$$

These values are multiplied by suitable gain constraints and are fed to the FLC. The FLC computes and gives corresponding values a(n) and b(n) as outputs based on the defined fuzzy rules which can be shown as

$$a(n)= f_1 [e(n) ,\Delta e(n)] \tag{4.13}$$

$$b(n) = f_2 [e(n) ,\Delta e(n)] \tag{4.14}$$

These outputs of FLC are multiplied by the corresponding scaling factors to get the appropriate values of the proportional and the integral gains denoted by K_p and K_i. These calculated gain values are supplied to the PI controller. The control Torque T* can be calculated from these values in the PI controller in the discrete domain as:

$$T^{*} = T^{*}(n-1) + K_p \Delta e(n) + K_i e(n) \tag{4.15}$$

Where e(n) is error and $\Delta e(n)$ is the change in error.

The purpose of fuzzy self-tuning of controller is to modify the values of the proportional and the integral gain depending on the error and the rate of change in error such that the rise time, the overshoot, the settling time, are reduced and the effects due to unknown non linarites are eliminated finally the controller must achieve an adaptive nature to load variation. X=[NH , NM , NL ,ZE , PL , PM , PH] , represents the term set for the input variables of f_1 and f_2. The set Y= [VL, LO, BM, ME, AME, HI, VHI], X and Y are the collection of Membership functions.

$$\mu_1= [\mu_{NH} , \mu_{NL} , \mu_{NM} , \mu_{ZE} , \mu_{PL} , \mu_{PM} , \mu_{PH}]$$

$$\mu_2 = [\mu_{vl} , \mu_{LO} , \mu_{BM} , \mu_{ME} , \mu_{AME}, \mu_{HI} , \mu_{VHI}]$$

Fig.4.13 shows the rule base for error, change in error for fuzzy logic controller and for PI controller which is used with fuzzy controller also have rule base which actually scheduling the gain for the controller for desired control action in the PMBLDC drive.

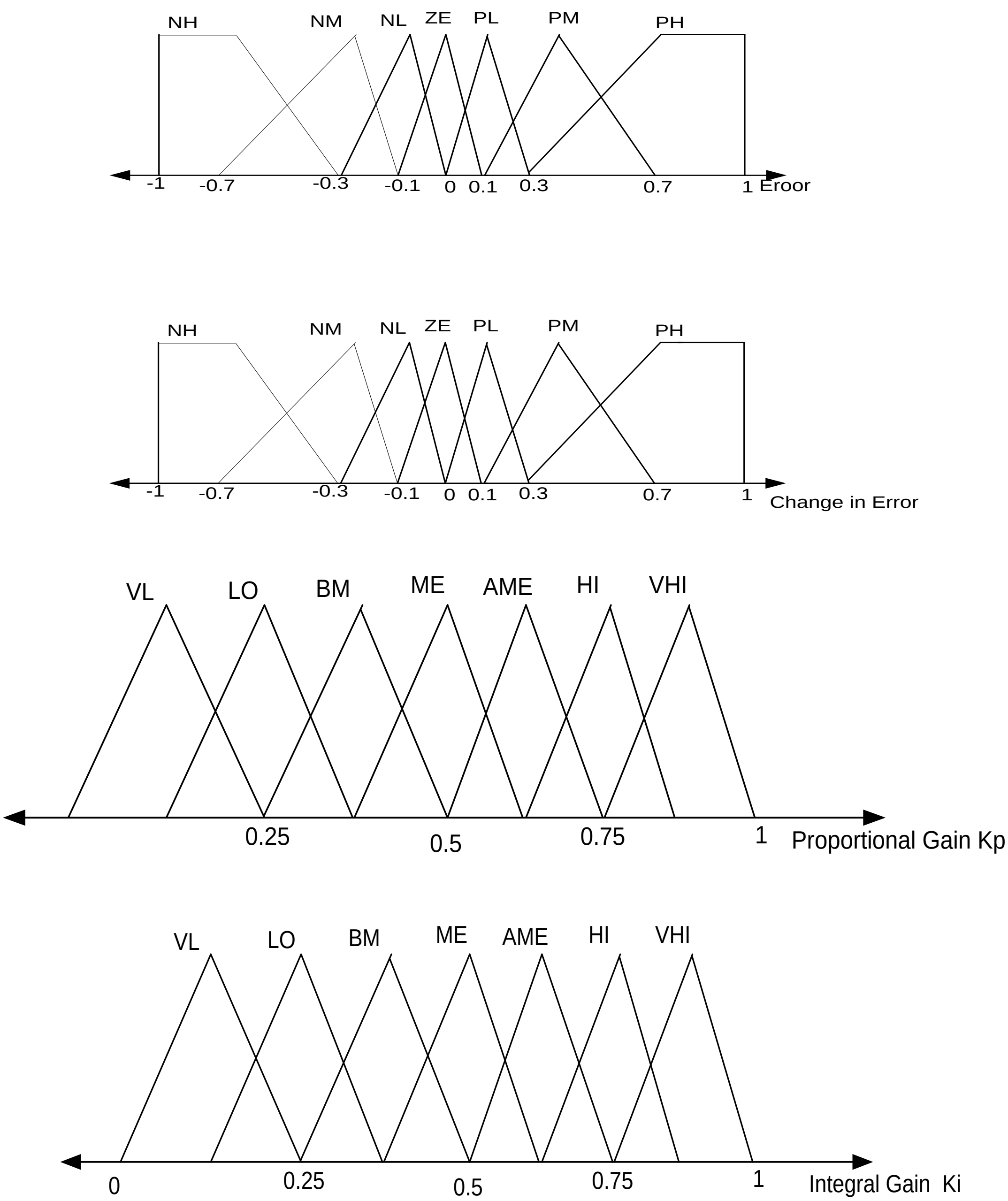

Fig.4.13 Fuzzy membership functions for input and output variables

Table 4.3 Rule base for Proportional gain

E / CE	NH	NM	NL	ZE	PL	PM	PH
NH	VHI	VHI	HI	ME	ME	AME	VHI
NM	VHI	VHI	AME	BM	ME	HI	VHI
NL	VHI	VHI	AME	LO	ME	HI	VHI
ZE	VHI	VHI	AME	VL	AME	VHI	VHI
PL	VHI	HI	ME	LO	AME	VHI	VHI
PM	VHI	HI	ME	BM	AME	VHI	VHI
PH	VHI	AME	ME	ME	HI	VHI	VHI

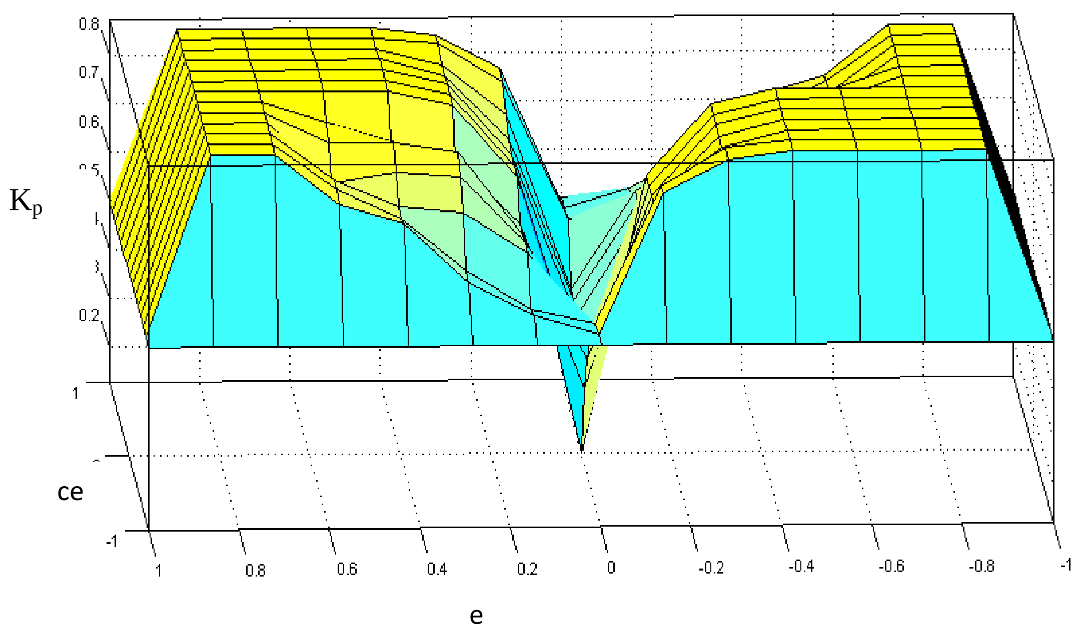

Fig. 4.14 Fuzzy surface for tuning proportional gain(K_P)

Figure 4.14 shows the Fuzzy surface for tuning proportional gain. Proportional gain rule base is designed for controller to take proper control action. The range and rule base table is shown above. While designing the rule base error and change in error are considered.

Table 4.4 Rule base for Integral gain

E / CE	NH	NM	NL	ZE	PL	PM	PH
NH	VL	VL	LO	AME	AME	BM	VL
NM	VL	VL	BM	AME	ME	LO	VL
NL	VL	VL	BM	HI	ME	LO	VL
ZE	VL	VL	BM	VHI	BM	VL	VL
PL	VL	LO	ME	HI	BM	VL	VL
PM	VL	LO	ME	AME	BM	VL	VL
PH	VL	BM	AME	AME	BM	VL	VL

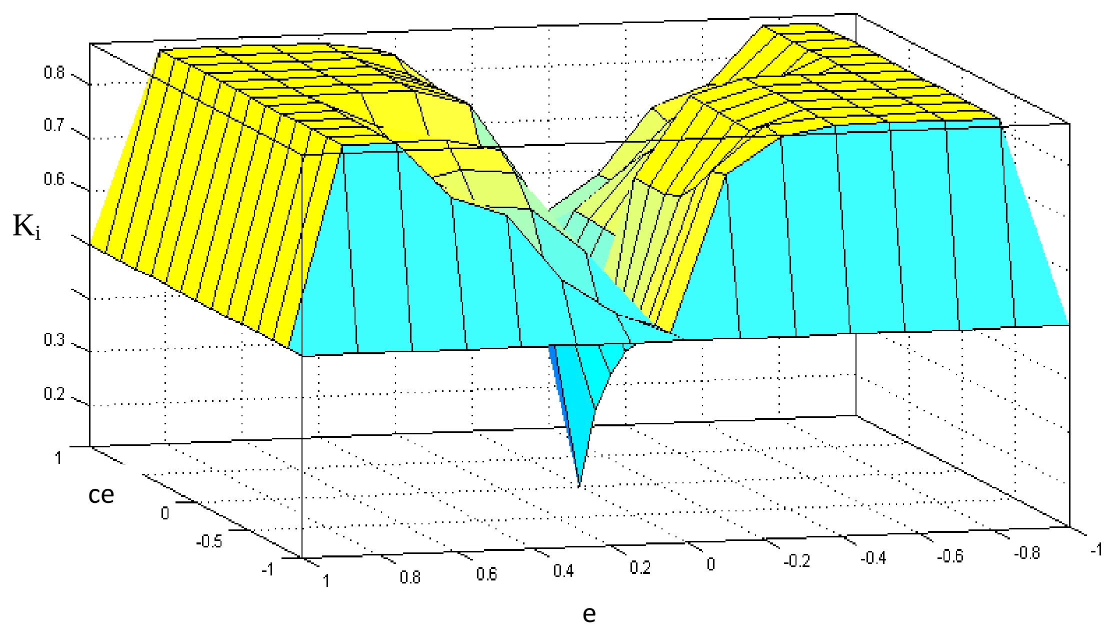

Fig. 4.15 Fuzzy surface for tuning the Integral Gain (K_I)

Figure 4.15 shows the Fuzzy surface for tuning Integral gain. Integral gain rule base is designed for controller to take proper control action. The range and rule base table is shown above. While designing the rule base error and change in error are considered.

There are two sets of rules consisting of 49 rules in each. The rules are designed by the combination of the experience, trial and error and our knowledge of the system behavior. Consider the rule given (ZE , ZE , VL , VHI), which says “if e(n) is Zero and Δe(n) is Zero this shows that the system is operating at the set point as a(n) must be very low and b(n) must be very High” because the Integral gain is responsible to maintain Zero steady state defuzzification process maps the result of the fuzzy logic rule stage to a real number output F_1[e(n),Δe(n)] and F_2[e(n),Δe(n)], we use the Centroid de-fuzzification method. The outputs of the fuzzy controller are error.

4.2.5.2 Simulink Model for the Self-tuning PI Controller

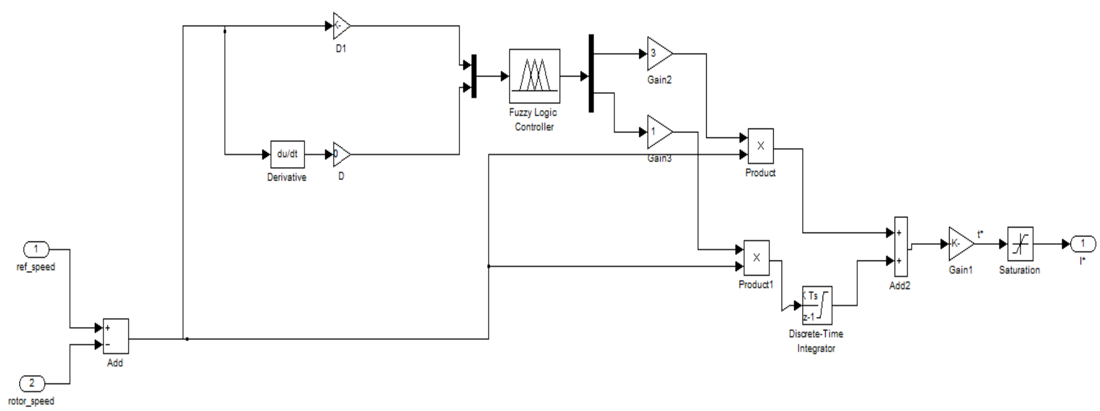

Fig.4.16 Simulink model for the Self-tuning PI Speed Controller

Fig.4.16 shows the MATLAB model diagram for the Self-tuning PI Controller. In this controller the error and the change in error are fed as the input to a Fuzzy logic controller, which generates the corresponding proportional and integral gain values depending on the fuzzy rules fed into FLC. These values are directly used by the PI speed controller to generate the required control torque (T*) signal.

4.3 MATLAB model of PMBLDC drive using position sensor

Figure 4.17 shows the MATLAB/SIMULINK model of the PMBLDC drive. The “Permanent magnet synchronous machine” block is taken and the trapezoidal back emf mode has been selected to function as a PMBLDM. The parameters of the required machine to be simulated have been entered into the block. The mechanical input is selected as positive torque to make the machine function as a motor; the remaining parameters are assigned the appropriate value. The flux induced by the magnets, moment of inertia, friction factor and the pairs of pole have been entered into the block as per the requirement. The machine is simulated and values of parameters are given in appendix.

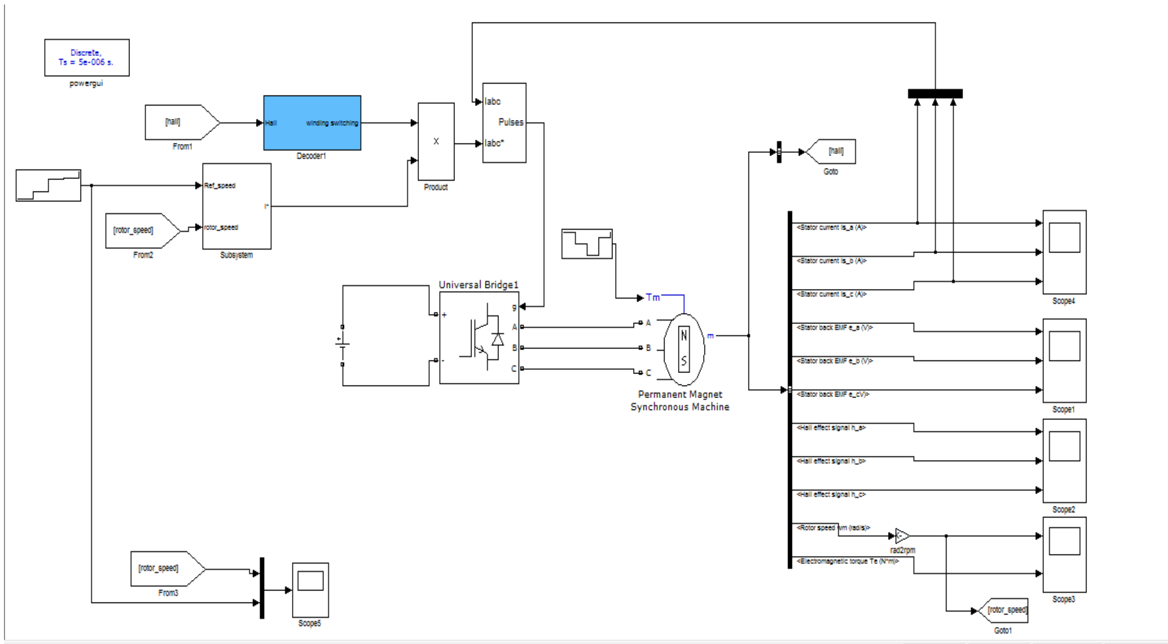

Fig.4.17 Simulink model of the PMBLDCM Drive

The complete Simulink model of the drive is shown in Fig. 4.17. The inputs to the PMBLDC are the three phase voltages and the currents from the inverter block. The speed in revolution per minute (RPM), the torque developed (T_e) and the Hall Effect signals from the sensors are taken as the outputs. In the succeeding chapter, the drive is simulated with the different speed controller under different operating conditions are described.

4.4 Conclusion

The detailed modeling, analysis design and simulation of the PI controller, the fuzzy logic controller, the series hybrid PI controller and the self-tuning PI controller have been described in this chapter. The Fuzzy rules governing the performance were also given in detail. The fuzzy surfaces for the different controllers are also given in the respective section, showing the behavior of individual controllers. The Simulation results of these models are presented in the next chapter.

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

5.1 General

The performance of PMBLDCM in his chapter under various operating conditions such as tracking a reference speed, effect of sudden change of reference speed, sudden application of load, reversal of speed. The PMBLDCM drive performance is evaluated using the four speed controllers, developed in previous chapters are checked in different conditions simulation results are obtained and discussed. Finally the results obtained from the different controllers are compared in terms of performance index i.e. overshoot, undershoot, settling time, rise time and adaptive nature in loading conditions.

5.2 Sensor Based operation of PMBLDCM

The PMBLDCM drive using Hall-sensors for position determination called sensor BLDCM. The performance of drive with different controller is discussed below.

5.2.1 Response of the drive with a PI Speed Controller

The simulation model of a 2 hp, 7.4A, 500rpm PMBLDC drive is simulated using PI speed controller and the response is observed for different operating conditions such as the starting response, load perturbation and speed direction reversal. The rotor speed is presented in revolution per minute (RPM), electromagnetic torque (T_e) developed by the motor in (N-m), stator currents of phase are in Ampere, the back emf developed in phase is in (V).

5.2.1.1 Starting response of the drive for Constant Speed and Constant Load operation

The Fig. 5.1 shows the starting response of the PMBLDC drive for a set point speed of 500 RPM with a PI speed controller. The developed model is simulated for t=2 sec. In this simulation with PI controller a constant torque of 3 N-m is applied on the drive. It has an overshoot of 1.364%and finally settles at the set point at the time instant 0.9 sec.

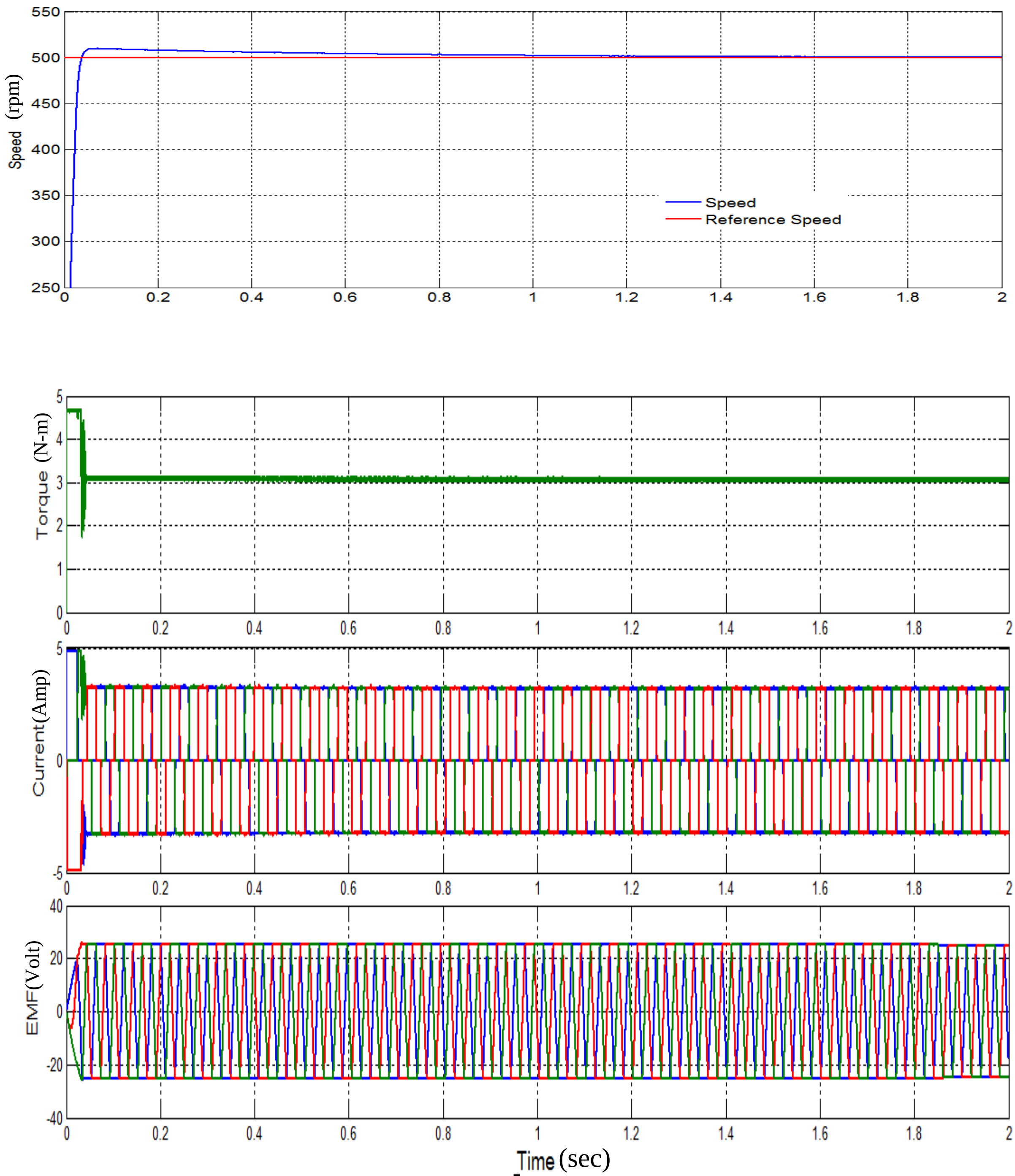

Fig. 5.1 Starting response of a the drive with PI controller for constant speed and constant load operation

Figure 5.2 shows the current waveform of the drive during constant load of 3 N-m and constant speed of 500 rpm using PI controller. The shape of current is rectangular in nature. To limit the current values, the current limiter is used, which limit the magnitude of the current.

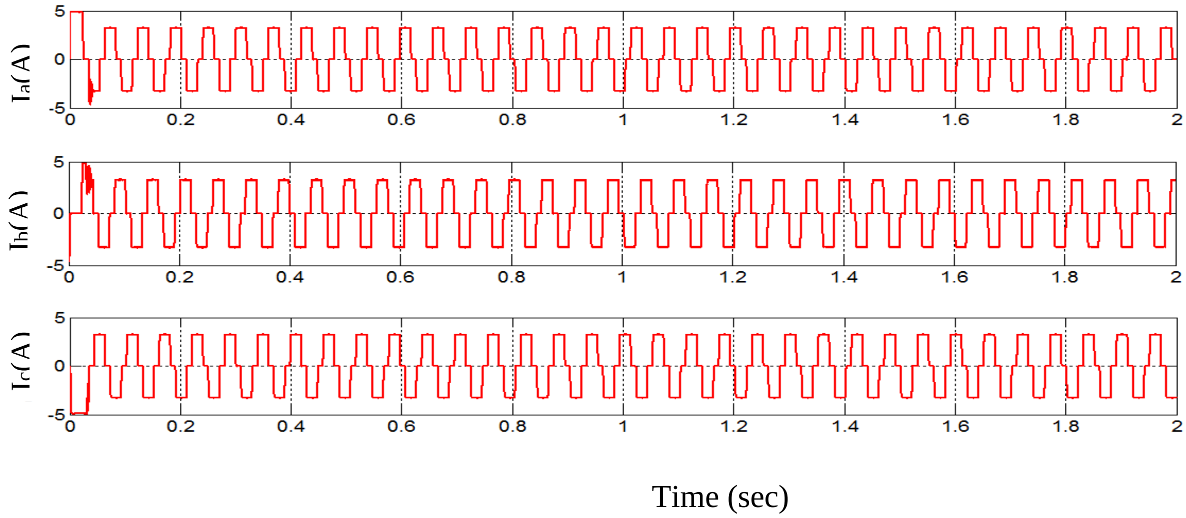

Figure 5.2 Current waveform of drive with constant speed constant load.

Figure 5.3 shows the Back- EMF waveform of the drive during constant load of 3 N-m and constant speed of 500 rpm using PI controller. BACK-EMF have trapezoidal shape for BLDCM drive.

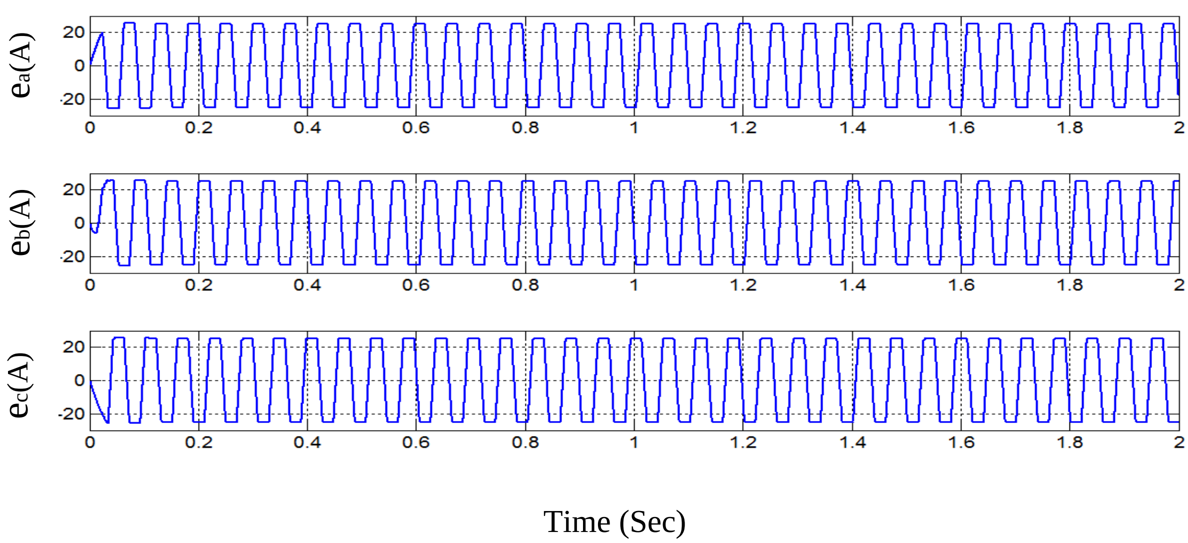

Fig.5.3 Back-EMF wave form of drive with constant speed and constant load

5.2.1.2 Tracking response of the drive in Variable Speed operation and Variable Load

The Fig. 5.4 shows the tacking response of the PMBLDC drive in variable speed operation of [300 500 200 250 150] RPM with a PI speed controller. The developed model is simulated for t=2 sec. In this simulation with PI controller a variable torque of [2 1.8 2.2 2.5 2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive As the speed changes current and back-EMF also changes The change in drive parameter are shown below in figure..

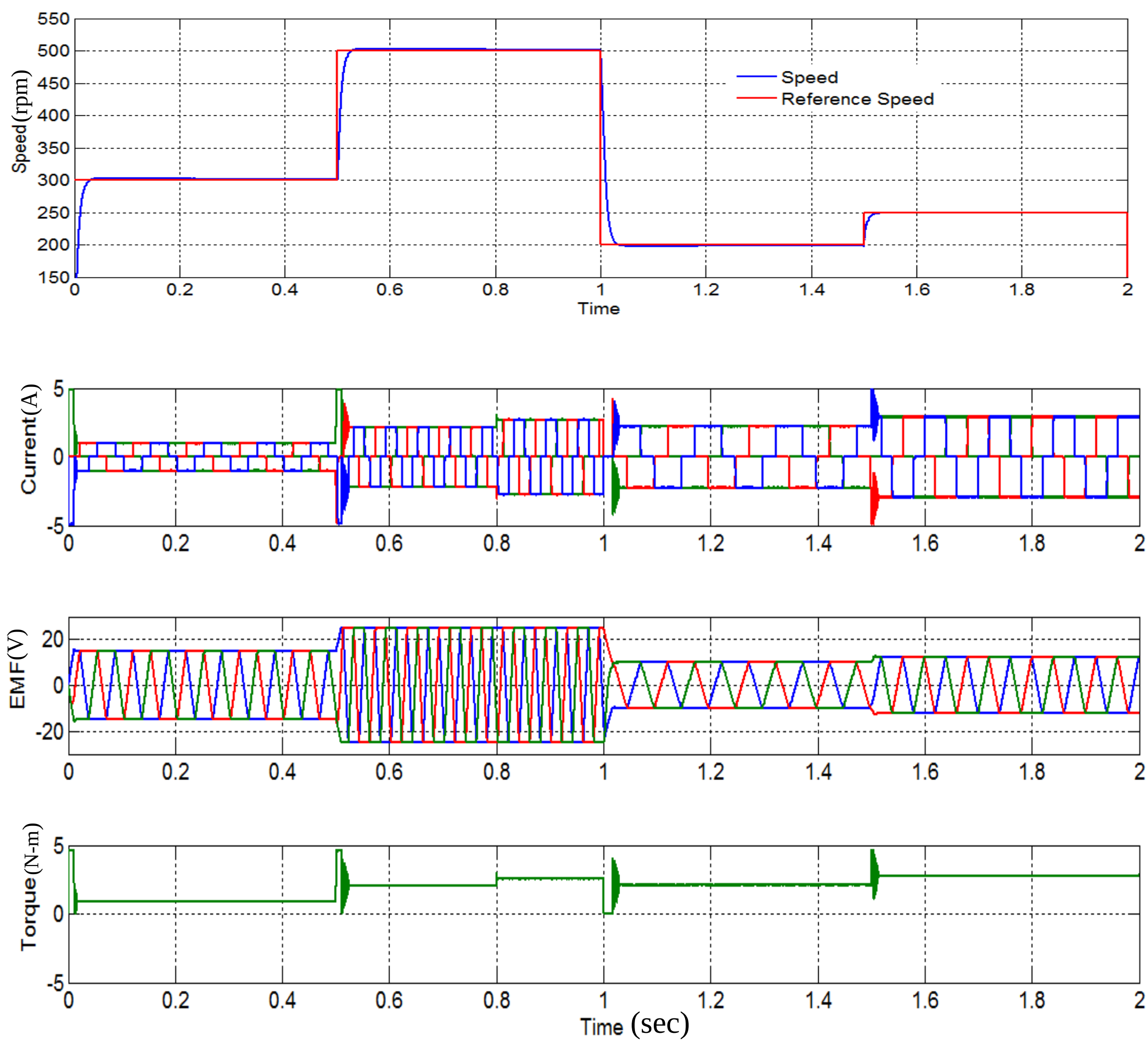

Fig. 5.4 Tracking response of a the drive with PI controller in variable speed operation and variable load

5.2.1.3 Response of the drive on reversal of speed with variable load

The fig. 5.5 shows the response of the PMBLDC drive on speed reversal using PI controller. The PMBLDC drive on starting a variable speed of [500 300 -250 -200 150] RPM with a PI speed controller. The developed model is simulated for t=2 sec. In this simulation with PI controller a variable torque of [1.8 1.7 2 1.4 1.6] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive.. The speed of the drive is changes from 300 RPM to -250 RPM and again changes from -200 RPM to 150 RPM. It is observed that motor currents (i_a, i_b, i_c) changes their profilesduring speed reversal and increase in load torque increases the amplitude of motor current

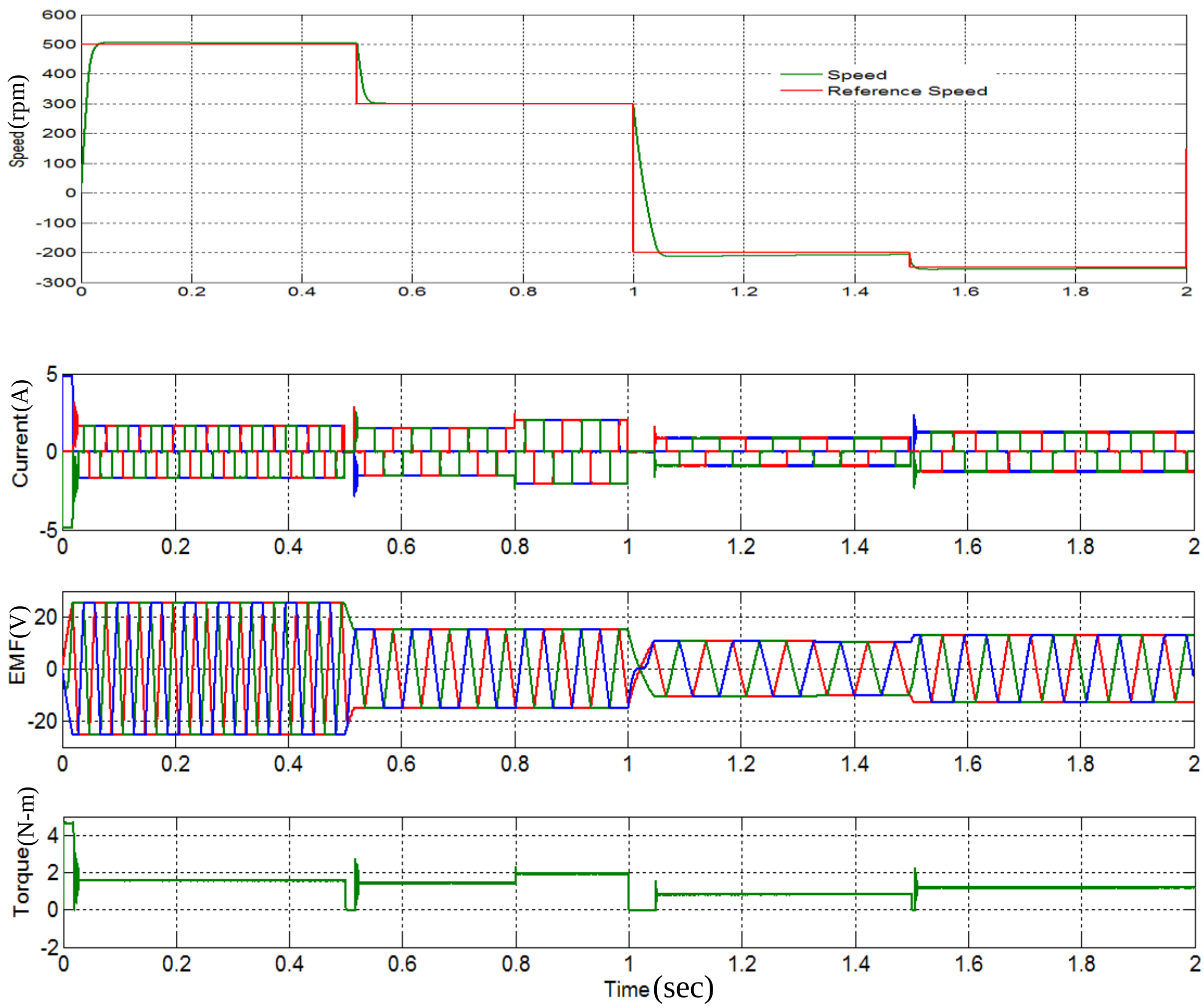

Fig. 5.5 Response of a the drive with PI controller on reversal of speed direction

5.2.2 Response of the drive with Fuzzy logic Speed Controller

The simulation model of a 2hp, 7.4A, 500rpm PMBLDC drive is simulated using developed Fuzzy logic speed controller and the response is observed for different operating conditions such as the starting response, load perturbation and speed direction reversal.

5.2.2.1 Starting response of the drive for constant Speed and constant load operation

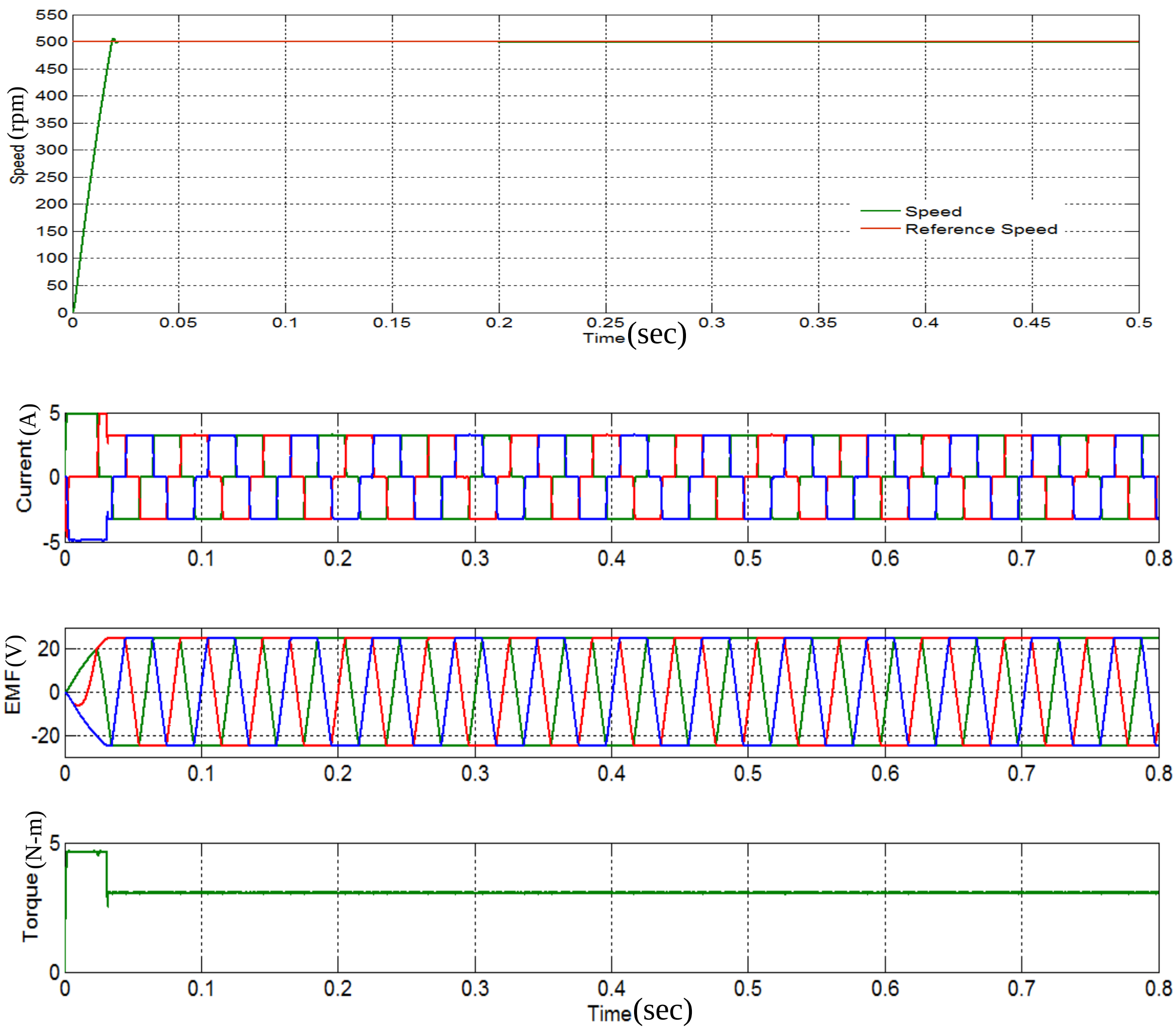

Fig. 5.6 Starting response of a the drive with Fuzzy logic controller with constant speed and constant load

The Fig. 5.6 shows the starting response of the PMBLDC drive for starting a set point speed of 500 RPM with a Fuzzy logic speed controller. The developed model is simulated for t=0.8 sec. In this simulation the motor is started with a constant load torque of 3 N-m. It has an overshoot of 1.242% with settling time 0.2 sec.

5.2.2.2 Tracking response of the drive in variable Speed and variable load operation

The Fig. 5.7 shows the response of the PMBLDC drive on starting a variable speed of [500 250 200 300 150] RPM with a Fuzzy logic speed controller. The developed model is simulated for t=5 sec. In this simulation with Fuzzy logic controller a variable torque of [2 1.8 2.2 2.5 2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive. It is observed that current and back- emf profile changes as the speed changes. When torque is applied on the motor, amplitude of current and back-emf changes.

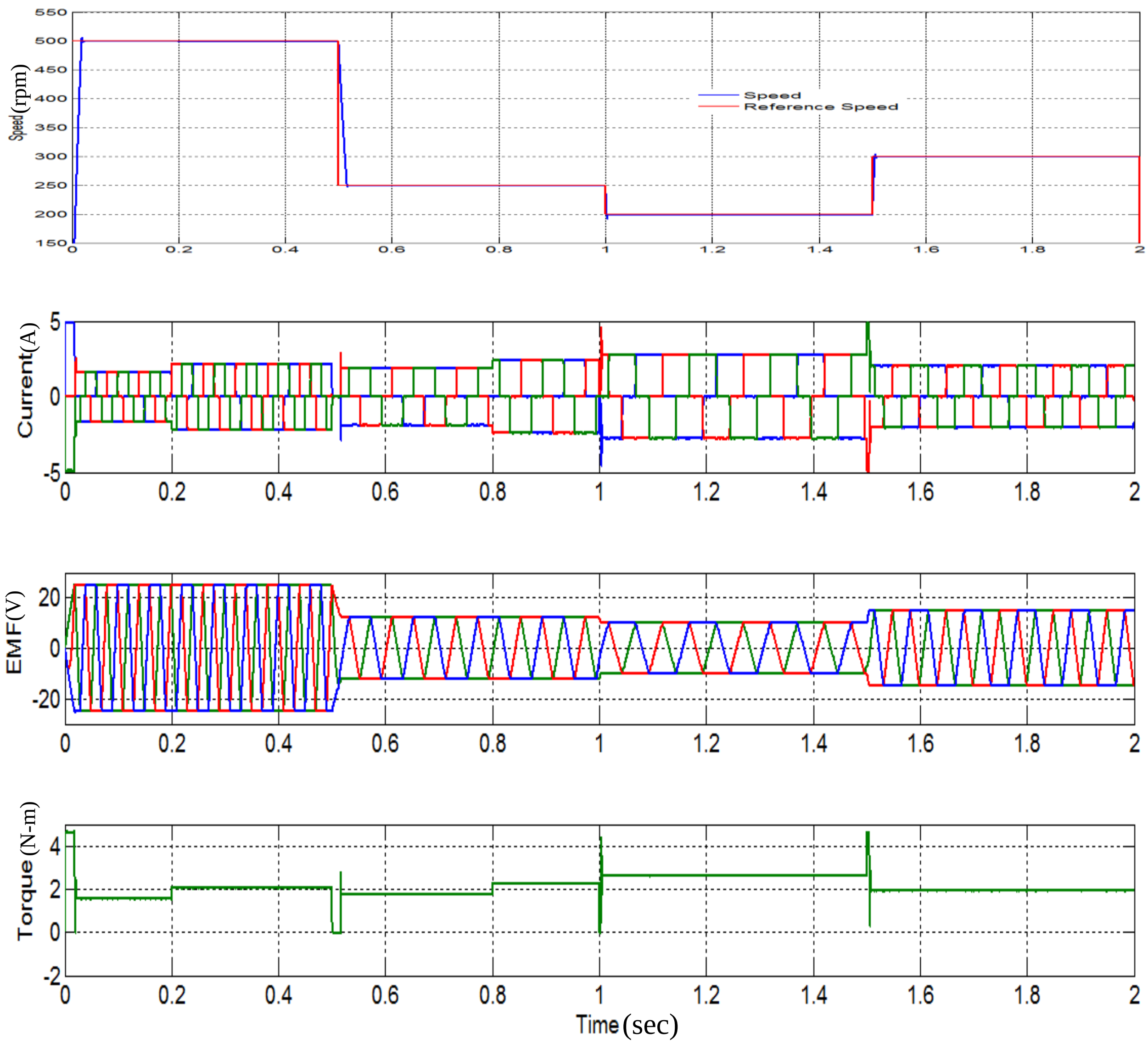

Fig. 5.7 Response of a the drive with Fuzzy logic controller with variable speed and variable load

5.2.2.3 Response of the drive on reversal of speed with variable load

The fig. 5.8 shows the response of the PMBLDC drive on speed reversal using Fuzzy logic controller. The PMBLDC drive on starting a variable speed of [500 300 -200 -250 150] RPM with a Fuzzy logic speed controller. The developed model is simulated for t=2sec. In this simulation with fuzzy logic controller a variable torque of [1.8 2 2.2 1.7 1.2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive. The speed of the drive is changes from 300 rpm to -200 rpm and again changes from -250 rpm to 150 rpm. It is observed that motor currents (i_a, i_b, i_c) changes their profilesduring speed reversal and increase in load torque increases the amplitude of motor current

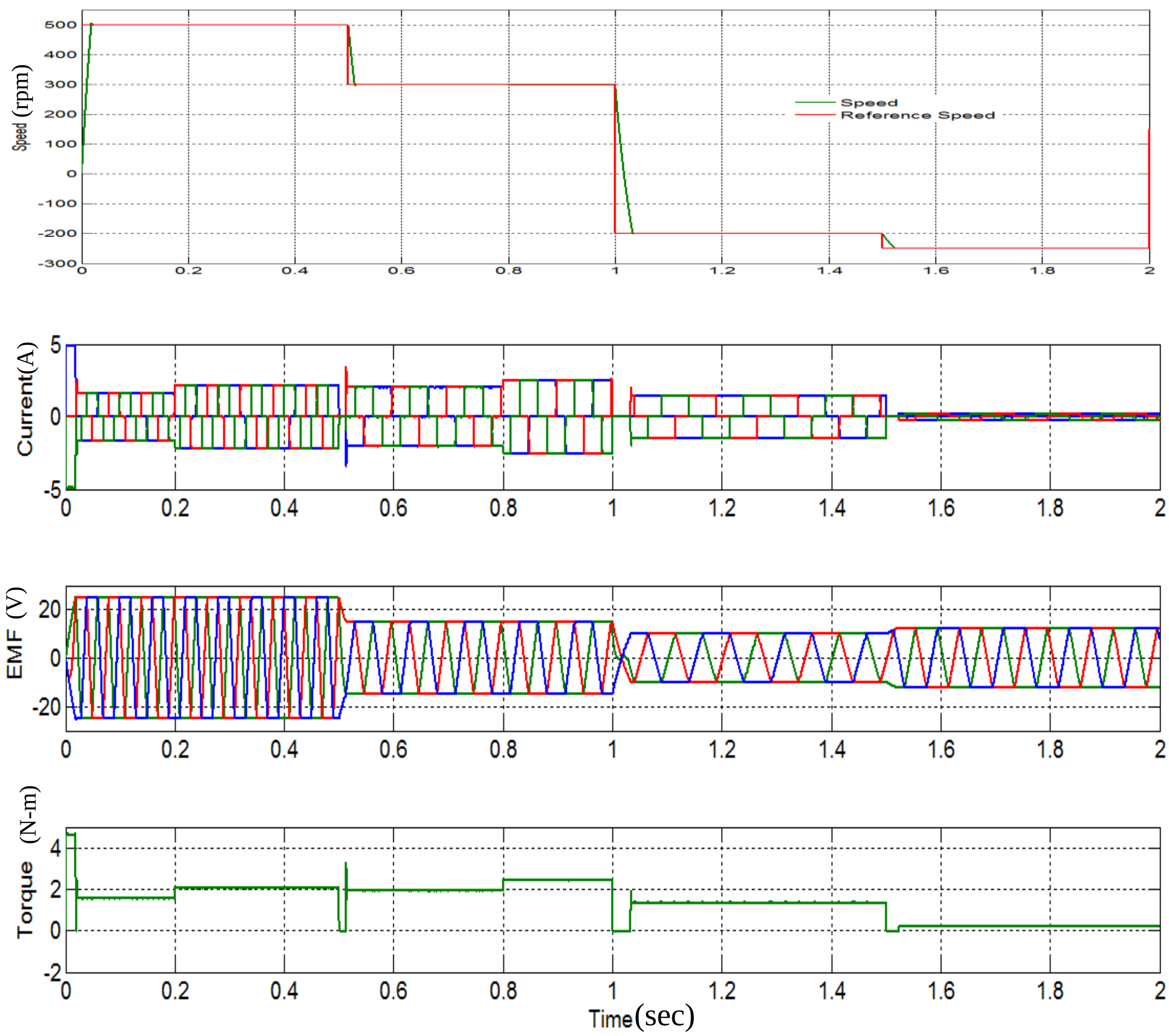

Fig. 5.8 Response of a the drive with Fuzzy logic controller on reversal of speed direction

5.2.3 Starting response of the drive with Adaptive-Neuro Fuzzy logic Speed Controller (ANFIS)

The simulation model of the PMBLDC drive is simulated using developed ANFIS speed controller and the response is observed for different operating conditions such as the starting response, load perturbation and speed direction reversal.

5.2.3.1 Starting response of the drive for constant Speed and constant load operation

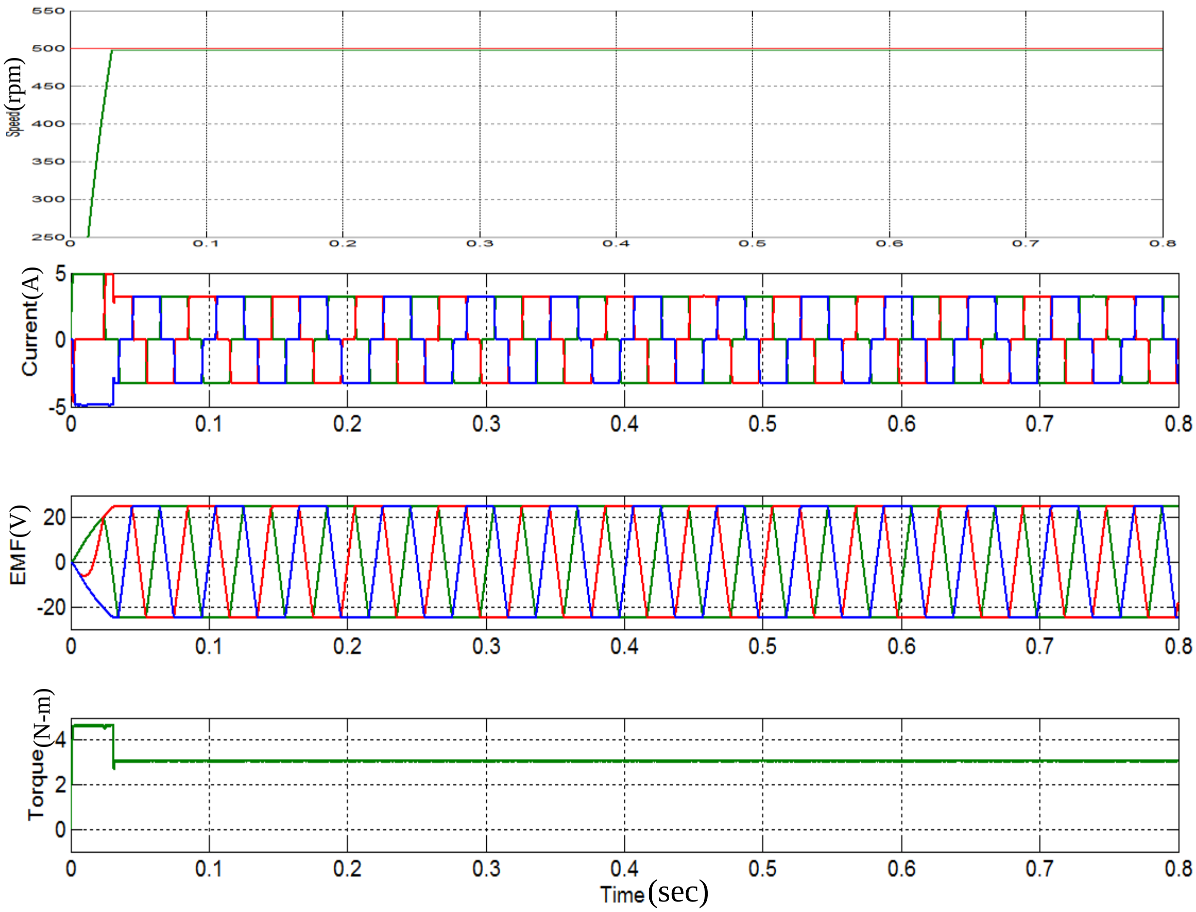

Fig. 5.9 Response of a the drive with ANFIS controller with constant speed and constant load

The Fig. 5.9 shows the response of the PMBLDC drive on starting a set point speed of 500 RPM with a ANFIS speed controller. The developed model is simulated for t=2 sec. In this simulation with ANFIS controller the motor is started with an initial constant torque of 3 N-m is applied on the drive. It is observed the speed response has an undershoot of 0.4% with settling time in 0.15 sec.

5.2.3.2 Tracking response of the drive in variable Speed and variable load operation

The Fig. 5.10 shows the response of the PMBLDC drive in variable speed operation of [500 250 200 300 150] RPM with a ANFIS speed controller. The developed model is simulated for t=2 sec. In this simulation with ANFIS controller a variable torque of [2 1.8 2.2 2.5 2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive. As the speed changes current and back-EMF profile also changes. When load torque is applied on drive magnitude of current and back-EMF changes.

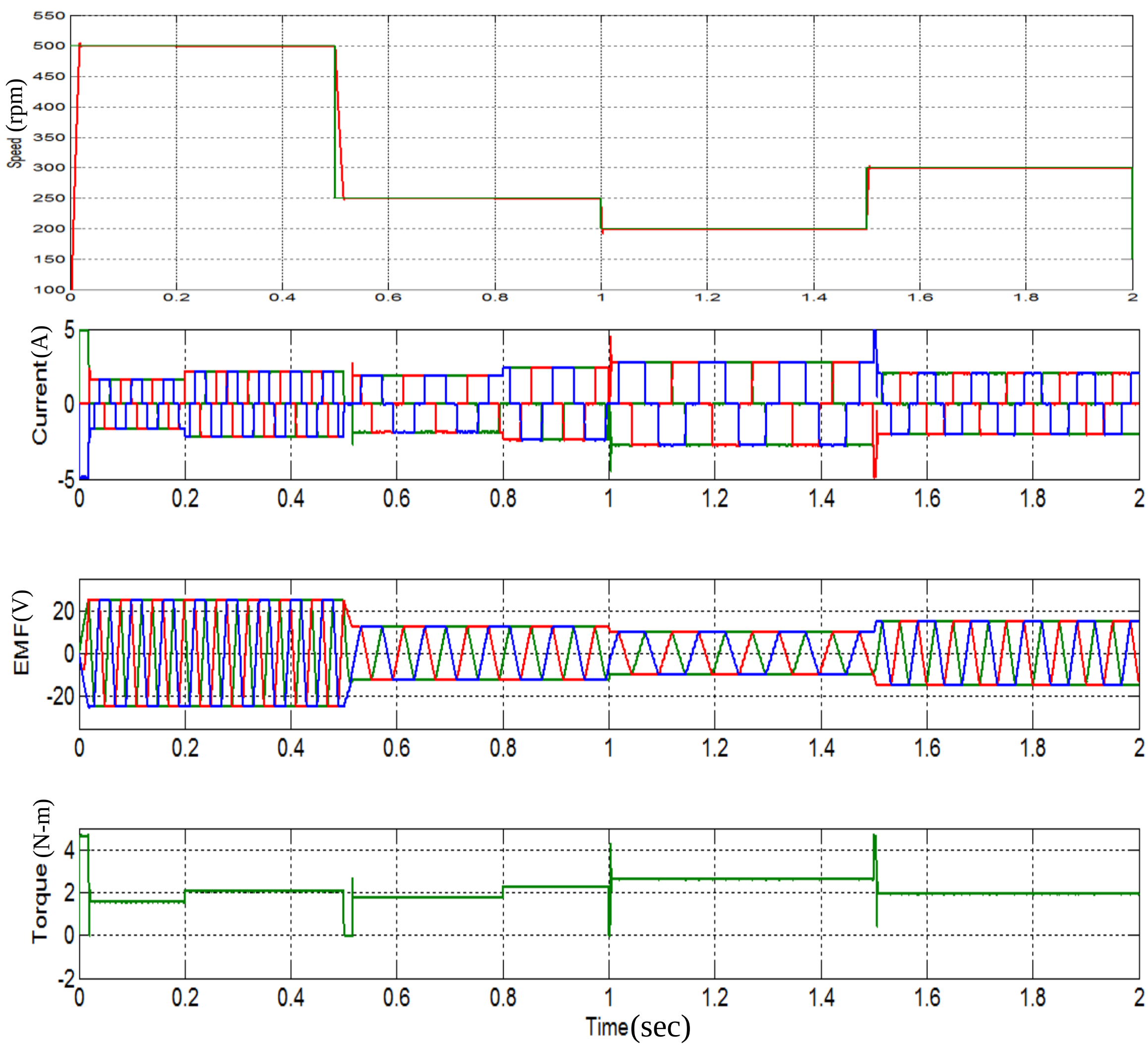

Fig. 5.10 Tracking response of a the drive with ANFIS controller in variable speed and variable load operation

5.2.3.3 Response of the drive on reversal of speed with variable load

The fig. 5.11 shows the response of the PMBLDC drive on speed reversal using ANFIS controller. The PMBLDC drive on starting a variable speed of [500 300 -200 -250 150] rpm with a ANFIS controller. The developed model is simulated for t=5 sec. In this simulation with fuzzy logic controller a variable torque of [1.8 2 2.2 1.7 1.2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive. The speed of the drive is changes from 300 rpm to -200 rpm and again changes from -250 rpm to 150 rpm. It is observed that motor currents (i_a, i_b, i_c) changes their profilesduring speed reversal and increase in load torque increases the amplitude of motor current

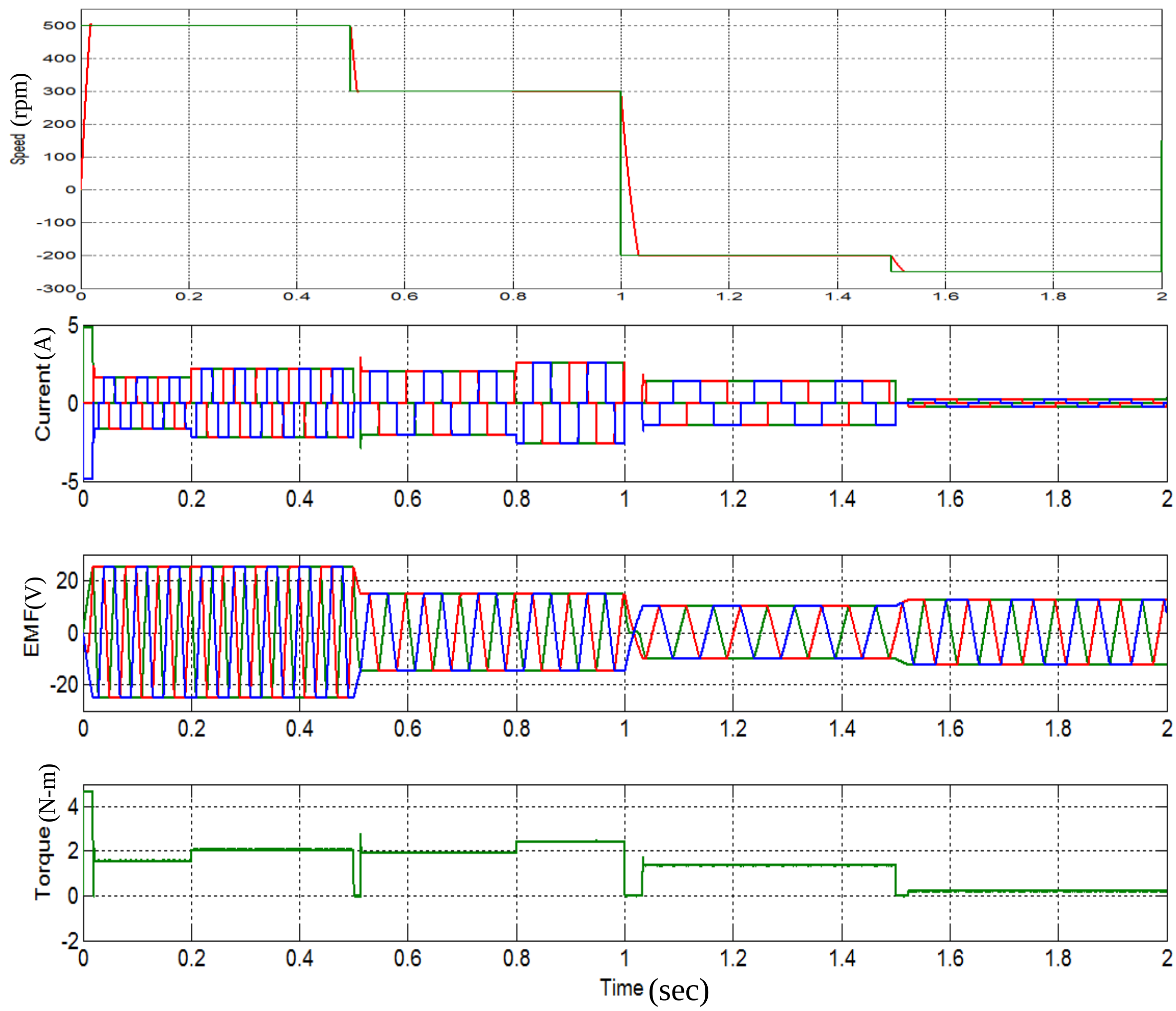

Fig. 5.11 Response of a the drive with ANFIS controller on reversal of speed

5.2.4 Response of the drive with Series Hybrid (Fuzzy- precompensated) Speed Controller

The simulation model of 2 hp, 7.4 A, 500rpm PMBLDC drive is simulated using developed Series Hybrid speed controller and the response is observed for different operating conditions such as the starting response, load perturbation and speed direction reversal.

5.2.4.1 Starting response of the drive for constant Speed and constant load operation

The Fig. 5.12 shows the response of the PMBLDC drive on starting a set point speed of 500 RPM with a Series Hybrid speed controller. The developed model is simulated for t=2 sec. In this simulation with Series Hybrid controller a constant torque of 3 N-m is applied on the drive. It has an overshoot of 1.36% and finally settles at the set point at the time instant 0.2 sec.

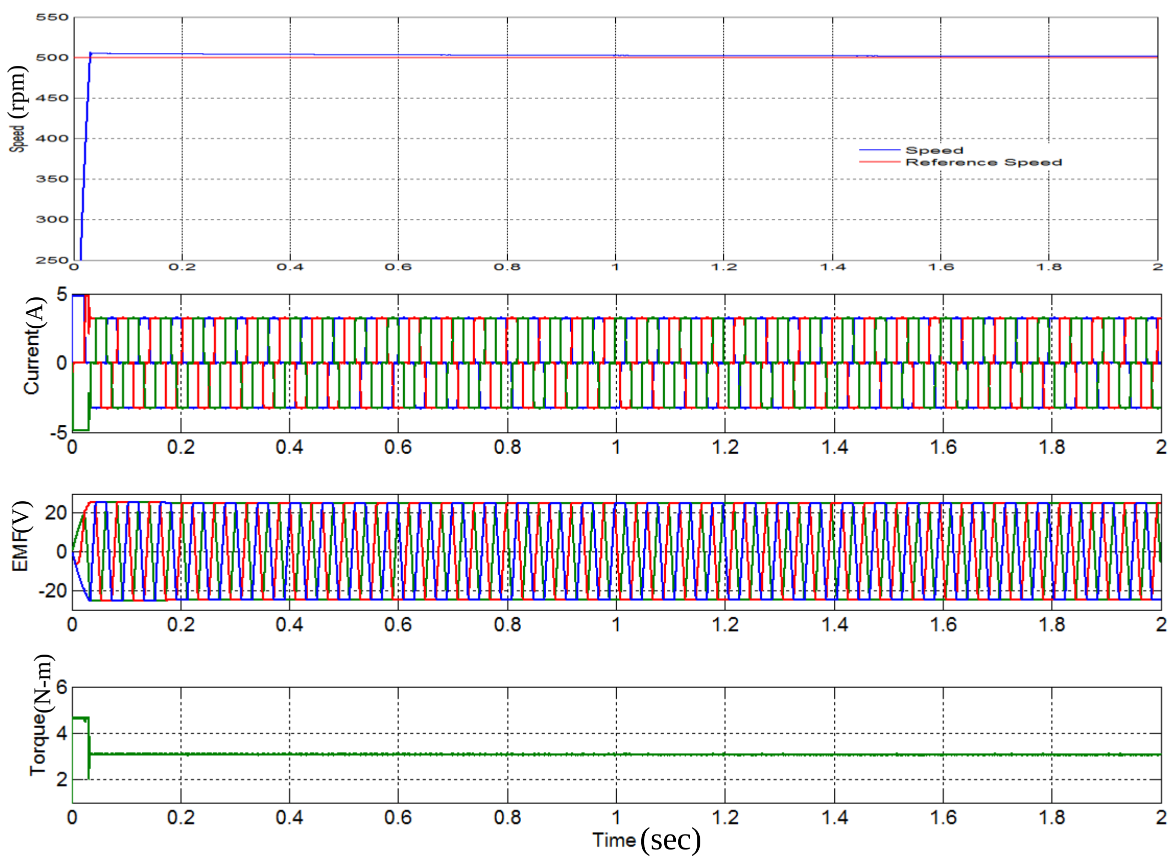

Fig. 5.12 Response of a the drive with Series Hybrid controller with constant speed and constant load

5.2.4.2 Tacking response of the drive in variable Speed and variable load operation

The Fig. 5.13 shows the response of 2 hp,7.4 A, 500 rpm PMBLDC drive on starting a variable speed of [500 250 200 300 150] RPM with a Series Hybrid speed controller. The developed model is simulated for t=5 sec. In this simulation with Series Hybrid controller a variable torque of [2 1.8 2.2 2.5 2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive. As the speed changes current and back-EMF also changes Controller trying to track the desired speed. As the speed changes current and back emf profile changes and when load torque changes the amplitude of motor parameter also changes.

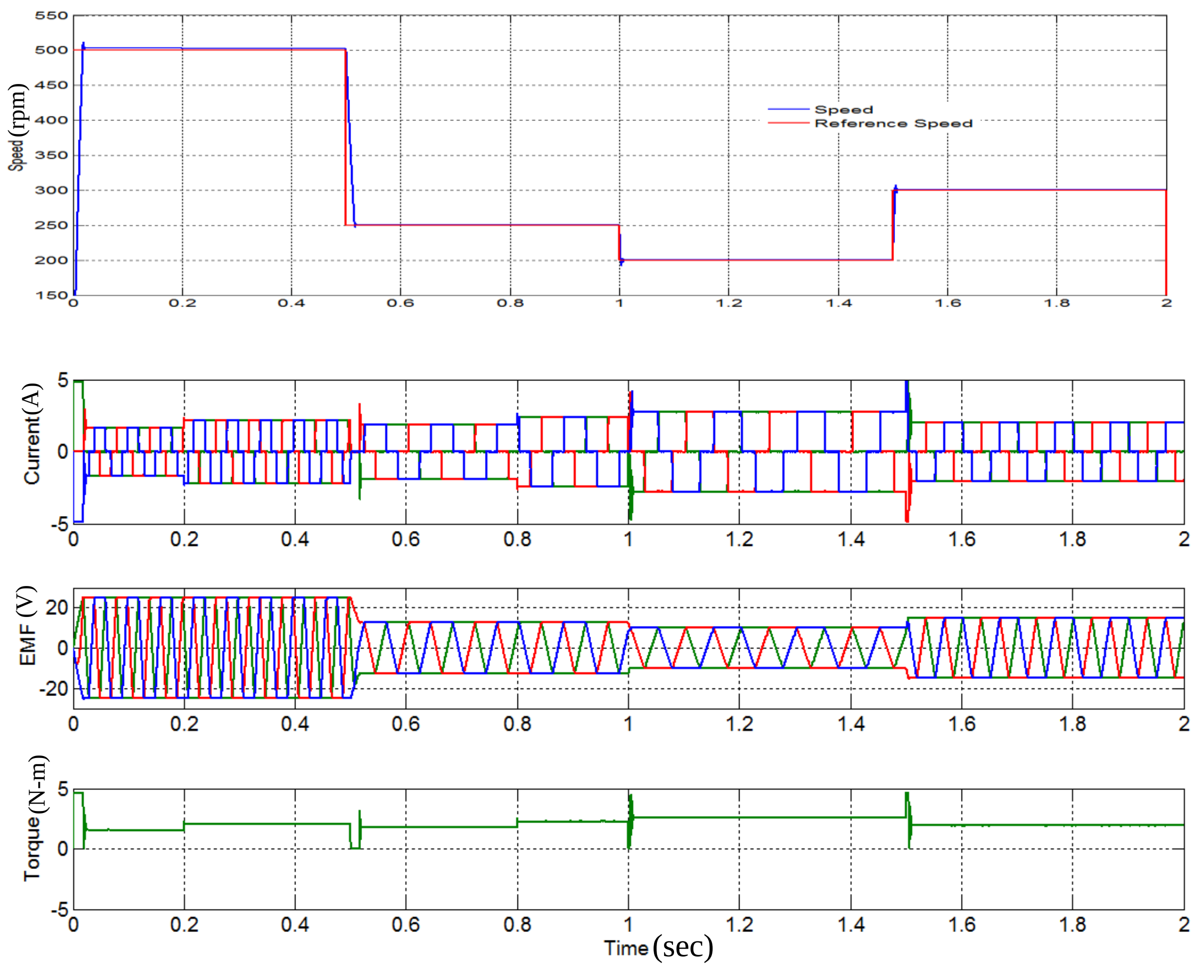

Fig. 5.13 Response of a the drive with Series Hybrid controller with variable speed and variable load

5.2.4.3 Response of the drive on reversal of speed with variable load

The fig. 5.14 shows the response of the PMBLDC drive on speed reversal using Series Hybrid controller. The PMBLDC drive on starting a variable speed of [500 300 -200 -250 150] RPM with a Series Hybrid controller. The developed model is simulated for t=2 sec. In this simulation with fuzzy logic controller a variable torque of [1.8 2 2.2 1.7 1.2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive.. The speed of the drive is changes from 300 rpm to -200 rpm and again changes from -250 rpm to 150 rpm. It is observed that motor currents (i_a, i_b, i_c) changes their profilesduring speed reversal and increase in load torque increases the amplitude of motor current

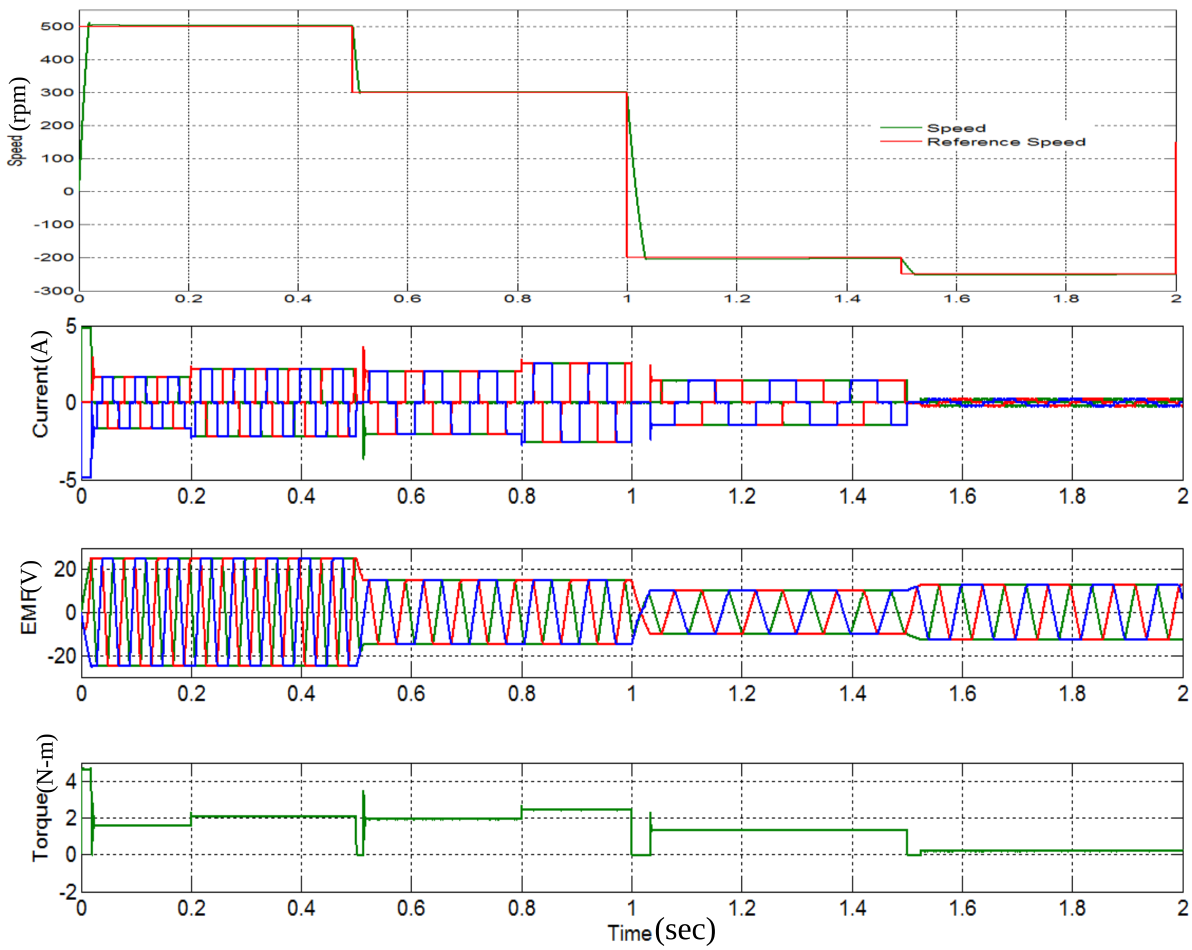

Fig. 5.14 Response of a the drive with Series Hybrid controller on reversal of speed

5.2.5 Response of the drive with Self-tuning PI Speed Controller

The simulation model of 2hp, 7.4A, 500 rpm PMBLDC drive is simulated using Self-tuning PI speed controller and the response is observed for different operating conditions such as the starting response, load perturbation and speed direction reversal.

5.2.5.1 Starting response of the drive for constant Speed and constant load operation

The Fig. 5.15 shows the response of the PMBLDC drive on starting a set point speed of 500 RPM with a Self-tuning PI controller. The developed model is simulated for t=2 sec. In this simulation with Series Hybrid controller a constant torque of 3 N-m is applied on the drive. It has an overshoot of 1.6% and finally settles at the set point at the time instant 0.18 sec.

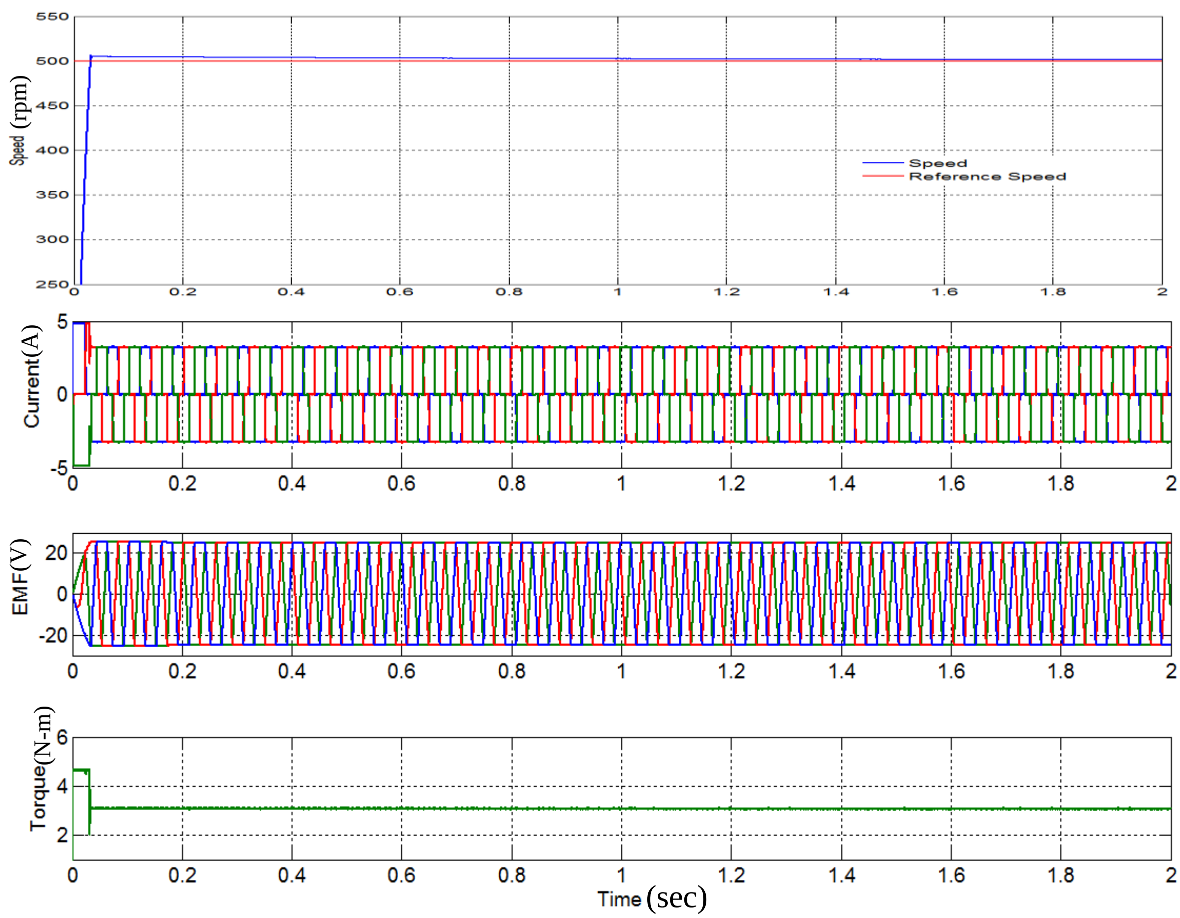

Fig. 5.15 Tacking response of a the drive with Self-tuning PI controller with constant speed and constant load

5.2.5.2 Tracking response of the drive in variable Speed and variable load operation

The Fig. 5.16 shows the response of the PMBLDC drive on starting a variable speed of [500 250 200 300 150] RPM with a Self-tuning PI speed controller. The developed model is simulated for t=5 sec. In this simulation with Series Hybrid controller a variable torque of [2 1.8 2.2 2.5 2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive. As the speed changes current and back-EMF also changes As the speed changes current and back emf profile changes and when load torque changes the amplitude of motor parameter also changes

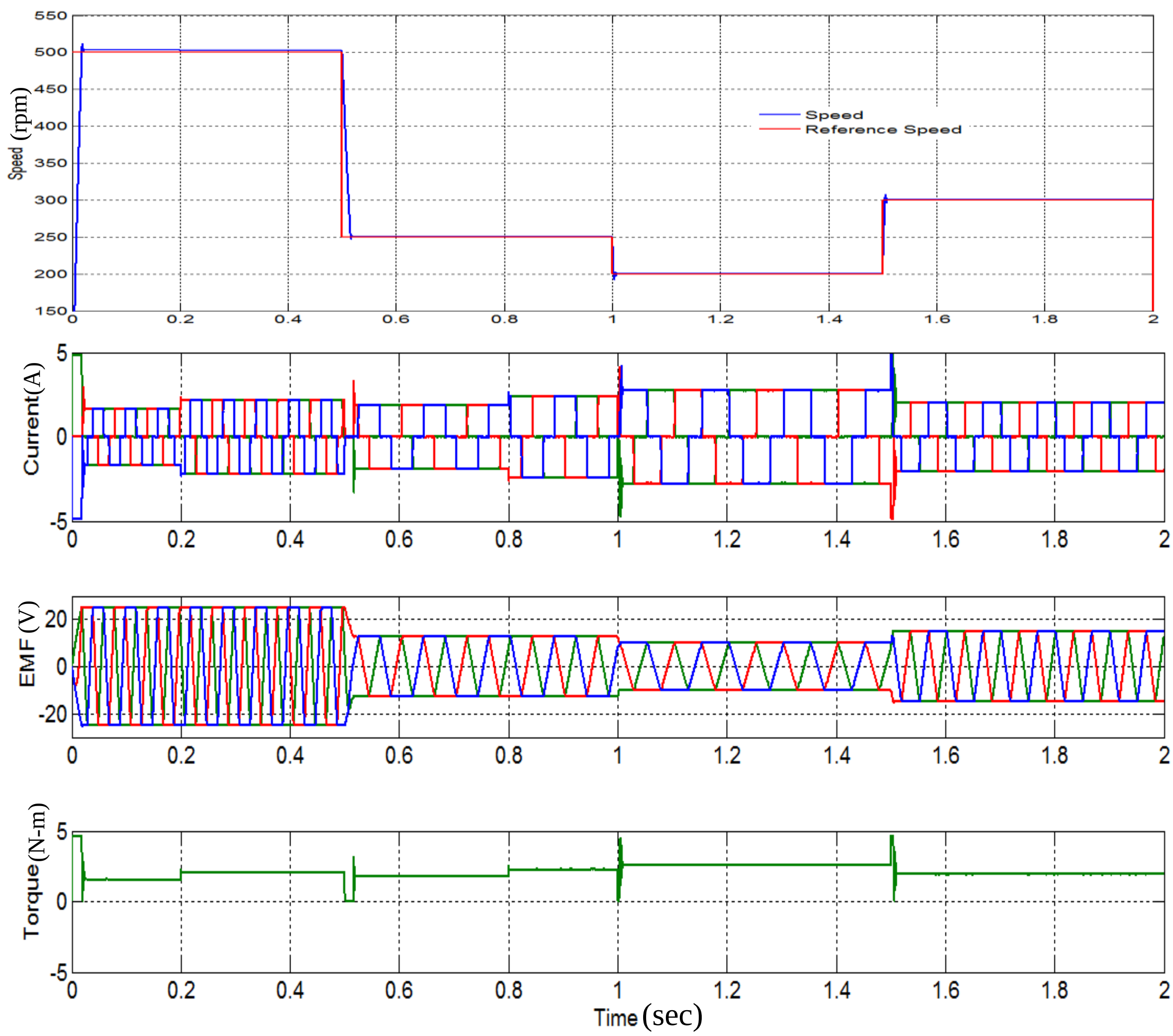

Fig. 5.16 Tacking response of a the drive with Self-tuning PI controller with variable speed and variable load

5.2.5.3 Response of the drive on reversal of speed with variable load

The fig. 5.17 shows the response of the PMBLDC drive on speed reversal using Self-tuning PI controller. The PMBLDC drive given to variable speed of [500 300 -200 -250 150] RPM with a Self-tuning PI controller. The developed model is simulated for t=2 sec. In this simulation with fuzzy logic controller a variable torque of [1.8 2 2.2 1.7 1.2] N-m at time [0.2 0.5 0.8 1 1.5] respectively, is applied on the drive.. The speed of the drive is changes from 300 rpm to -250 rpm and again changes from -250 rpm to 150 rpm. It is observed that motor currents (i_a, i_b, i_c) changes their profilesduring speed reversal and increase in load torque increases the amplitude of motor current

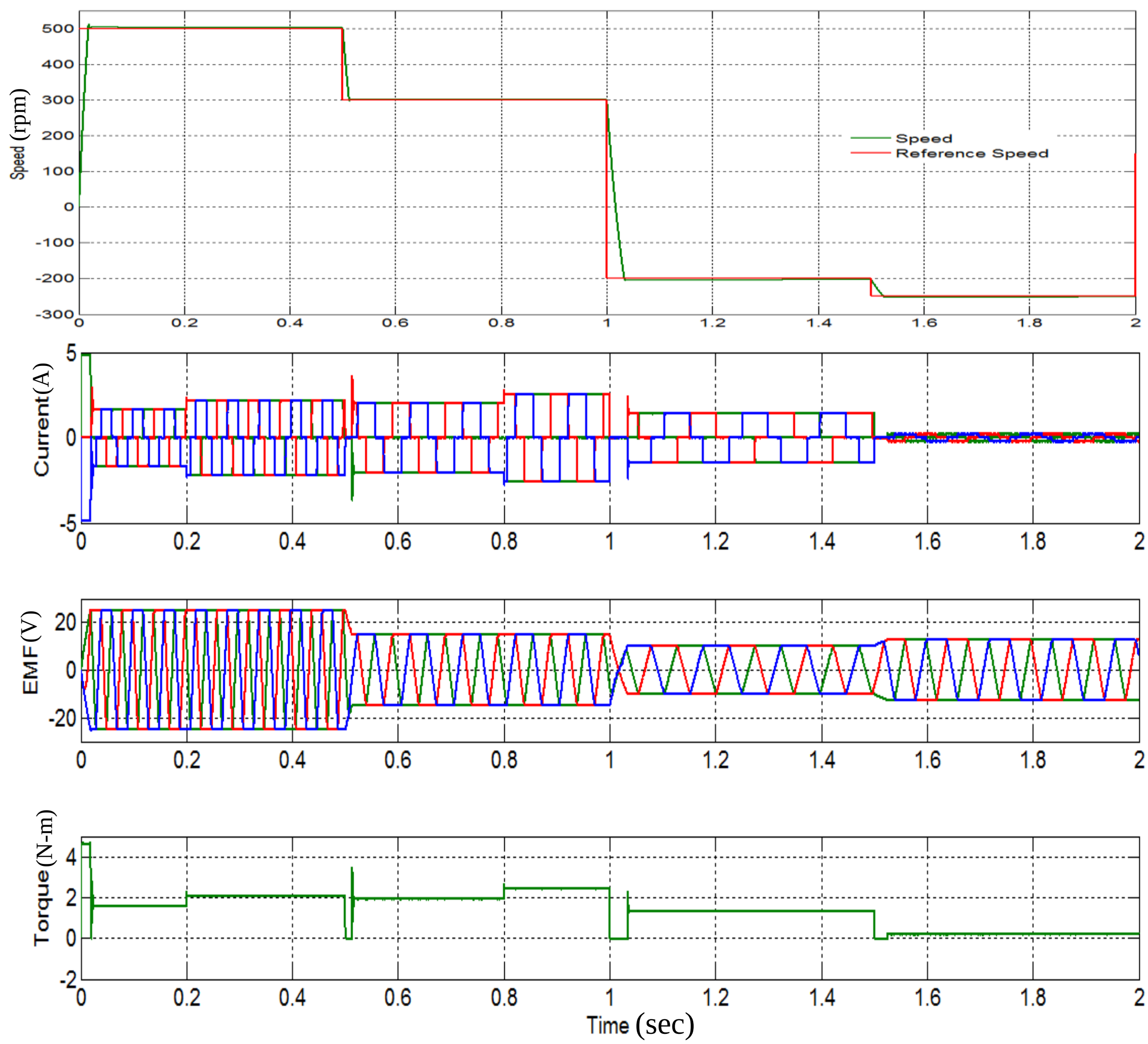

Fig. 5.17 Response of a the drive with Self-tuning PI speed controller on reversal of speed

5.3 Comparative analysis of the dynamic response of BLDC drive with different controllers

Figure 5.18 shows the responses of the drive on starting and load perturbation for a speed set point of 500 RPM while using the controllers, PI, FUZZY,ANFIS, Series Hybrid, self-tuning PI controllers.

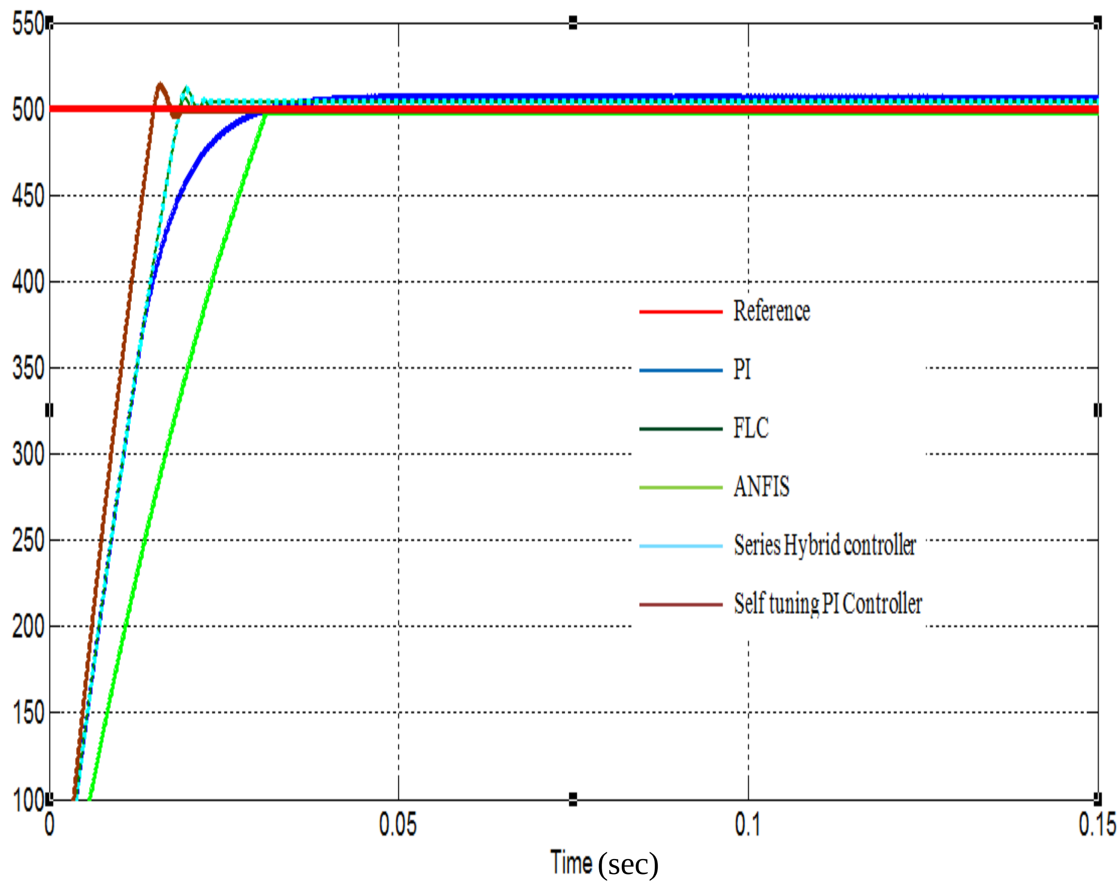

Fig.5.18 Response of drive on starting and load perturbation for all the controllers at 500 rpm

The responses of the drive with different controller are compared in the conditions of starting and of load perturbation. The comparison for the starting response is done in terms of rise time, settling time, peak time, overshoot It can observed from the table 5.1 , the PI controller gives the moderate overshoot and takes the longest time to settle making the response slower.

Table 5.1 A comparison of starting behavior of the drive

Type of controller	Rise time (sec)	Peak time (sec)	Settling time (sec)	Overshoot (%)
PI Controller	0.015	0.06	0.9	1.364
FLC controller	0.014	0.02	0.2	1.242
ANFIS controller	0.023	--------	0.15	0.4(undershoot)
Series Hybrid Controller	0.0145	0.0197	0.2	1.36
Self-tuning PI Controller	0.011	0.016	0.18	1.6

The Fuzzy logic controller has 0.2 sec and ANFIS controller has least settling time. controller have undershoot of 0.4 %.The response with the series hybrid controller and Self-tuning PI controller is excellent in terms of reducing peak time, settling time but it have overshoots slightly greater than FLC and ANFIS. The choice of controller is depend upon our requirement. The Self-tuning PI controller is very slow. The comparison between the responses is also done for load a perturbation which is shown in table 5.2. It can be observed from table 5.2 that the PI controller has the highest overshoot in the present case with longer settling time. The FLC shows an overshoot of 1.842 and settling time of 0.4 sec.

The ANFIS controller has undershoot of 0.64% and settling time of 0.22 sec. The series hybrid controller could efficiently reduce the overshoot and having 0.7 sec of settling time. The Self-tuning controller exhibited a quite lesser overshoot and have 0.3 sec of settling time.

Table 5.2 Comparison of dynamic responses on load perturbation

Type of controller	Rise time (sec)	Peak time (sec)	Settling time (sec)	Overshoot (%)
PI Controller	0.028	0.075	1.2	2.4
FLC controller	0.025	0.042	0.4	1.842
ANFIS controller	0.023	--------	0.22	0.64(undershoot)
Series Hybrid Controller	0.025	0.0417	0.7	1.36
Self-tuning PI Controller	0.019	0.026	0.3	0.2

5.4 A Comparative analysis of main features of different controllers in operation of BLDC drive

5.4.1 Proportional Integral Speed Controller

The response of the PMBLDCM drive using the PI speed controller for starting response, load perturbation and reversal of speed direction are shown in the Fig. 5.1 to 5.5. PI controller completely eliminates the steady state error, but it brings an overshoot into the system response and also increasing the settling time for the speed. It is simple and easy to implement.

5.4.2 Fuzzy logic Speed Controller

The response of the PMBLDCM drive with PI controller starting, load perturbation and speed reversal is shown inFig.5.6 to 5.8. Fuzzy logic controller gives an excellent transient state performance The advantage of fuzzy logic controller is that it requires no exact mathematical model of the plant, a simple knowledge of the plant behavior is sufficient to construct the FLC. Hence when only fuzzy logic controller is used, it cannot improve the performance of the drive in all terms.

5.4.3 Adaptive-Neuro Fuzzy logic Speed Controller (ANFIS)

The response of the PMBLDCM drive with the ANFIS controller on starting, load perturbation and speed reversal is shown in the fig.5.9 to 5.11. ANFIS controller gives an excellent transient performance. It has also not displayed any overshoot unlike the remaining controllers. The advantage of ANFIS controller is that we need not make rule base like FLC, ANFIS controller make rules according to the values and conditions of the model and gives superior performance than other controllers.

5.4.4 Hybrid (Fuzzy precompensated PI) Speed Controller

The response of the PMBLDCM drive with the series hybrid controller on starting, load perturbation and speed reversal is shown in the fig.5.12 to 5.14. Series hybrid controller gives the best performance than conventional PI controller. The construction of the series hybrid is such that PI controller is connected in series with FLC. The FLC will be modifying the reference command signal, which is further supplied to the PI controller. Hence the FLC will be continuously modifying the control reference and the PI will be delivering the required performance. Series hybrid controller eliminates the problem of overshoots and undershoots which is normally occurring in PI controller.

5.4.5 Self-tuning PI Speed Controller

The response of the PMBLDCM drive with the Self-tuning PI controller on starting, load perturbation and speed reversal is shown in the fig.5.15 to 5.17. In this control technique the basic fact that in a PI controller, the proportional gain is responsible for the transient response and the integral term is responsible for steady state performance is used. The controller employs a FLC to continuously modify the proportional and integral gain values of the PI Controller base on the operating point of the drive. This control strategy can work well even is the presence of severe and unknown non linearity in drive model.

5.5 Conclusion

The modeling, analysis and the simulation of the PMBLDC drive system has been done in the MATLAB/ SIMLINK environment. A comparative study has been carried out on the drive performance with different speed controllers. It has shown that the individual controllers have their own merits and demerits. Selection of controller is based on system requirement. When the requirements are simple and ease of application, a PI Controller is of a good choice. When the need is of intelligent and fast dynamic response then ANFIS control technique can be selected. When the requirement is of both intelligent response and good steady state performance with minimum overshoot, the series hybrid controller is the best choice. The self-tuning PI controller uses an efficient method of continuously tuning the gains of a PI controller to suitable values depending on the operating point of the system.

CHAPTER 6

MAIN CONCLUSION AND FUTURE SCOPE OF WORK

6.1 Main Conclusion

The present work is motivated to evaluate the performance of the Permanent Magnet Brushless DC motor in different modes and different operating conditions with different controllers using MATLAB/SIMULINK environment. The detailed study of Permanent Magnet Brushless DC motor, advantages, working are carried out. A detailed literature survey and summary of important development in the area of PM machines are discussed.

In this dissertation the performance of Permanent Magnet Brushless DC motor is evaluated under the various modes like open loop and closed loop mode.. Performance evaluation of PMBLDC motor in terms of different controllers is discussed. Some schemes are modeled and simulated for the speed and current control of PMBLDCM .The mathematical model of the PMBLDCM drive with PI controller, Fuzzy logic controller, ANFIS controller, Series hybrid controller, Self-tuning PI controller have been developed in the SIMULINK environment using the SimpowerSystem toolbox and Fuzzy Logic toolbox. The drive is also simulated with the developed controllers in MATLAB/SIMULINK environment. The Speed response of the drive with different controllers has been compared and analyzed. The comparative study has shown that individual controllers have their own merits and demerits. The choice of choosing a speed controller for particular applications depends on application.

The PI speed controller would be a good choice for simplicity and ease of application. PI controllers are observed to have no steady state error but are slow in response. The Fuzzy Logic Controller offer good performance even in the presence of unknown nonlinearity and an exact mathematical model of plant in not required to develop this controller for the plant. FLC has offset at steady state, FLC provides excellent transient response in terms of quickness of the response. ANFIS Speed controller gives good performance with different conditions of the PMBLDC drive. ANFIS controller automatically learns the plant and according to that learning gives the response.

ANFIS controller provides excellent response in transient and in steady state conditions. The Series hybrid PI controller helps to reduce overshoots and undershoots present in a normal PI controller response. The controller eliminates the disadvantages of PI and FLC. Controller delivers a smooth transient and steady state response. The controller can work efficiently and effectively in the presence of non-linearities.

In the self-tuning PI controller configuration, the gain values of the PI controller are modified continuously depending on the operating point of the speed response. The controller works efficiently in reducing the overshoot and making the drive more adaptive to load variations. Since all the control action taken by the PI controller directly the response is smooth and due to gain tuning it exhibits an adaptive performance during load variations. A complete study of the BLDCM drive and control strategies with different modes has been implemented and imparted a fairly good knowledge in the PM machines in terms of performance.

6.2 Future Scope of the present work

The Hybrid and ANFIS controllers' configuration displayed excellent simulation results and can be implemented on existing PI control system simply by adding the auto tuning techniques. With the availability of so advanced and powerful computing equipment like controller can be verified for control of the PMBLDCM drive. The Hybrid controller scheme, the PI controller gains are varied in their respective predetermined ranges to make the controller adaptive. The compatibility of other available controller techniques like self-tuning FPID controller, Sliding mode controller, and Model reference adaptive controllers with the PMBLDCM drive can also be verified through simulation and implementation.

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APPENDIX

PMBLDC Motor Specification

1. Rating- 2.0 HP, Type of connections- Star, Speed- 500 rpm

Sr. No.	Parameter	Value
1	Poles number	4
2	Voltage constant (V/Krpm)	136.1357
3	Torque Constant(Nm/A)	1.3
4	Stall current(A)	4 A
5	Peak Current(A)	7.4 A
6	Peak Torque(Nm)	8.6
7	Resistance/phase(Ώ)	2.8
8	Inductance/ phase(mH)	0.00521
9	Moment of Inertia (Kgm^2)	0.013

2. Controller Gain Values

The gain values for PI controller are

K_p = 3.256 Ki = 8.8396