PERFORMANCE COMPARISON OF BLDC MOTOR WITH DIFFERENT CONTROLLERS FOR EV APPLICATION

PROJECT REPORT

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to

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of

Bachelor of Technology

in

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Declaration

We undersigned hereby declare that the project report **Performance Comparison of BLDC Motor with Different Controllers for EV Application**, submitted for partial fulfillment of the requirements for the award of degree of Bachelor of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by us under supervision of **Dr. N. Mayadevi**. This submission represents the compilation of information gathered from published works in our own words. The original sources reported in this study have been adequately and accurately cited and referenced. We also declare that we have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in our submission. We understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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CERTIFICATE

This is to certify that this report entitled **"Performance Comparison of BLDC Motor with different controllers for EV application"** submitted by **Georgin Jacob - TVE17EE046, Laxmi Nag L. N - TVE17EE067, Nabeel Babu - TVE17EE081, Varghes K. F - TVE17EE125** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Bachelor of Technology in Electrical and Electronics Engineering is a bonafide record of the final year project work carried out by them under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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Abstract

This paper presents the study and comparative analysis of Proportional Integral (PI) controller and Artificial Neural Network(ANN) controller for the speed control of electronically commutated Brushless DC motor (BLDC), with the help of MATLAB/SIMULINK. The conventional PI controllers are one among the most powerful controllers in industries until now. But for non-linear mode and under several operating conditions it gives poor performance.

ANN has excellent self-learning performance and adaptive capability; and has been applied to various applications, such as target detection and industrial control. In this paper, an ANN controller and a PI controller have been proposed for speed control of the system. The simulation and experimental results are to be compared between PI controlled system and ANN controlled system.

The proposed system is designed to improve the performance of motor and other operating conditions such as rise time, settling time, overshoot and stability phenomenon. The response of the system can be observed for the above controllers with the help of MATLAB/SIMULINK.

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Chapter 1

Introduction

1.1 Background

Electric Vehicles(EV) have started gaining importance since people realized the after effects of depletion of natural resources, atmospheric pollution and fuel price hike. Major pros of EVs include low running cost, pollution free operation, long life, controllability, etc. Since EV is a developing technology, it is important to study the parts that are to be integrated in it, especially in the case of motors. Different types of motors are used for EV applications like Induction Motor, Brushless DC(BLDC) Motors, Permanent Magnet Synchronous Motors(PMSM), etc. Among these BLDC motors are popular since they are simple in structure, and they provide high reliability. BLDC has small size and provides high torque. So it is mainly applicable for high performance drives. BLDC electronically commutated with sensor or sensorless system. It has a rotating permanent magnet and stationary armature. There is great demand for efficient variable speed, long term stability and good transient performance of motor drives. Due to uncertain and nonlinear characteristics, the system degrades the performance of controllers. So the best selection of controller makes BLDC most appropriate for EV application and for that a comparison study has to be implemented between several controllers.

1.2 Motivation

The lack of electronic control technology limited the speeds of early electric vehicles to 20 miles per hour. Along with a poor recharging infrastructure, the convenience of gasoline-powered vehicles prompted car owners to abandon the electric vehicle. However, technological advances such as the Brushless DC motor (BLDC motor) have made these energy-efficient automobiles more viable. As the demand for EV increased in the market, the electric vehicle should be highly efficient. There is need for high efficiency and reliable control of BLDC motor. For determining the efficient motor control we have to analyze the performance of controllers, to employ the best controller for the BLDC motor in EV application.

1.3 Problem Statement

Generally the performance of motor is affected by sudden change in unknown load or speed. But as the BLDC motor drive are non linear in nature, they require an improved or modified controller that can adapt a non linear condition and achieve the desired performance. So to encounter this problem, controller is required.

1.4 Objectives

The main objectives of the project are:

- To design and implement PI controller for BLDC based EV
- To design and implement ANN controller for BLDC based EV
- Compare the performance of both controllers, select the best among them and implement it in BLDC motor drive for a three wheeler

1.5 Expected Outcome

After analysing the performance of the controllers PI and ANN in the BLDC motor drive by simulating the system in MATLAB/SIMULINK, the controller which provides better performance, depending on rise time, settling time, cost, etc.. is selected. Then it is to be simulated on a real time simulation platform(dSPACE), analysing the results and then creating hardware model.

1.6 Outline of Report

The organisation of this report is as follows:

Chapter 1 : It contains the introduction to the motor control, background, motivation, objectives and expected outcomes of the project.

Chapter 2 : In this section the literature survey that has been used for planning and execution of this project are described.

Chapter 3 : The proposed system with the block diagram is explained in this chapter.

Chapter 4 : It contains the methodology of the project which is containing the mathematical modelling, open loop simulation, closed loop simulation of PI controller and ANN controller.

Chapter 5 : The system design including vehicle dynamics, selecting the rating of the motor, motor and controller parameters is included in this section.

Chapter 6 : The results obtained from the open loop and closed loop simulation is presented.

Chapter 7 : It contains conclusion and future scope of the project.

Chapter 2

Literature Survey

There are several types of electric motor for electric vehicles application such as, DC motors, induction motors, permanent magnet synchronous motors (PMSM), switched reluctance motors (SRM), and Brushless DC motors (BLDC). Motors with permanent magnetic such as PMSM and BLDC motors have the highest efficiency, power density, and torque density [1]. In [2], it is shown that BLDC motor has higher power density of 15% compared with PMSM. Therefore, BLDC motor is suitable for electric vehicle applications that requires high output power and torque.

BLDC motor is constructed with a permanent magnet rotor and wire wound stator poles. Due to the absence of brush and commutator this motor requires inverter and rotor position sensor. Hall effect sensors are commonly used for sensing rotor position. The inverter uses transistors for low power drives and thyristors for high power drives. The Hall Effect sensor is mounted on the motor shaft [3]. Most of the BLDC motors have three hall sensors. When the rotor magnetic poles pass near the hall sensor, they give a high or low signal, indicating the passing of the north or South Pole near the sensors. Based on the combination of the three hall sensor signals, the exact sequence of commutation can be determined and this signal is sent to the drive circuitry of the inverter circuit [4].In response to these signals, the inverter allows the flow of current to stator phase windings in a controlled sequence so that motor produces the desired torque and speed.

The BLDC Motor selection for Three wheeler is done on the basis of Vehicle dynamics[5].The parameter of the selected motor has to be optimised for accurate analysis[6]. In[7] presents Modelling and Simulation Analysis of the selected BLDC Motor by using MATLAB/SIMULINK. The back EMF generation of the BLDC motor is generated from motor speed and angle of rotation via a MATLAB function[8]. Based on the generated EMF and current inputs from the inverter the hall effect sensor produces gate signal based on logic gates[9]. The gate signal are fed to the inverter which produces the corresponding currents and back EMF which generates the torque and speed.The analysis of torque and speed wave forms are taken for open loop simulation verification[10].

The BLDC motor drive are non linear in nature, they require an improved or modified controller that can adapt a non linear condition and achieve the desired performance [11]. So to encounter this problem controller is required. Because of the simplicity in tuning, the PI controller are until now are mostly useful controller in industries. The PI controller is carried out from the input and feedback signal. And then this error passes through the proportional integrative function one by one, so that the speed error can be reduced and get the desired performance [12].

Artificial neural network is a highly interconnected processing element which processes the information using their dynamic characteristic to the external input[13]. Artificial neural network is most widely used and appreciated control scheme due to their characteristics of high learning trait and nonlinear mapping of various inputs and corresponding outputs of an electric motor drive system[14], [15].

Chapter 3

Proposed System

3.1 System Description

In this study, the three-phase BLDC motor operating in a three-phase, six-state, two-conduction mode is taken. BLDC motor has a wound stator and a permanent magnet rotor assembly. These motors generally use internal or external devices to sense rotor position. The sensing devices provide logic signals for electronically switching the stator winding currents in a proper sequence to maintain rotation of the rotor with magnet assembly. The Hall sensors typically embedded as a part of the motor assembly and gives information on rotor position. The electronic drive is required to control the stator currents to generate rotating magnetic field in a BLDC motor. The electronic drive consists of:

- A power stage with three-phase inverter having the required power capability.
- MCU to implement the motor control algorithm .
- DC-Link current and position feedback from Hall sensors .
- Power supply for the MCU.

According to the characteristics of the electric vehicle drive system and the basic theory of the BLDC motor, this system uses a permanent magnet BLDC motor as the electric vehicle drive motor. Combining the mathematical model of the BLDC

DC motor and the basic theory of motor control, the overall design of the BLDC motor control system for electric vehicles and the establishment of the simulation model are completed, which provides reference for the subsequent hardware design.

According to the performance requirements of the BLDC motor controller, the control scheme is selected next. For electric vehicles, the vehicle speed needs to be changed at any time, and the amplitude of speed change is relatively large. Therefore, the higher requirements on the adjustment of the motor speed are put forwarded by controller; when the electric vehicle carries a heavier object or performs climbing operation, the BLDC motor's operating current will increase accordingly. Therefore, the higher requirements on the adjustment of the motor current are also imposed by controller. Considering the rpm (revolutions per minute) and current regulation functions, a double closed loop control system where the outer ring is the speed loop and the inner loop is the current loop is used in this study.

The speed loop can eliminate the speed deviation and achieve the constant speed function. When the motor is started, the current regulator outputs the maximum current due to the saturation phenomenon of the speed regulator to speed up the transition process and ensure the rapid start of the motor. When the motor is overloaded or even blocked, the output of the excessive current is limited, which plays protective role and ensures the safe operation of electric vehicles. The PI regulator is widely used for the speed and current regulators, which has the advantages of convenient implementation, good control performance and convenient parameter setting, etc., and therefore it is widely used in various control systems.

However, the traditional PI controllers cannot play the biggest advantage in the multi-coupling and nonlinear system like Brushless motor. As a result, the method of ANN control is adopted in the speed control loop of this system and compared with PI control method.

3.1.1 General Block Diagram

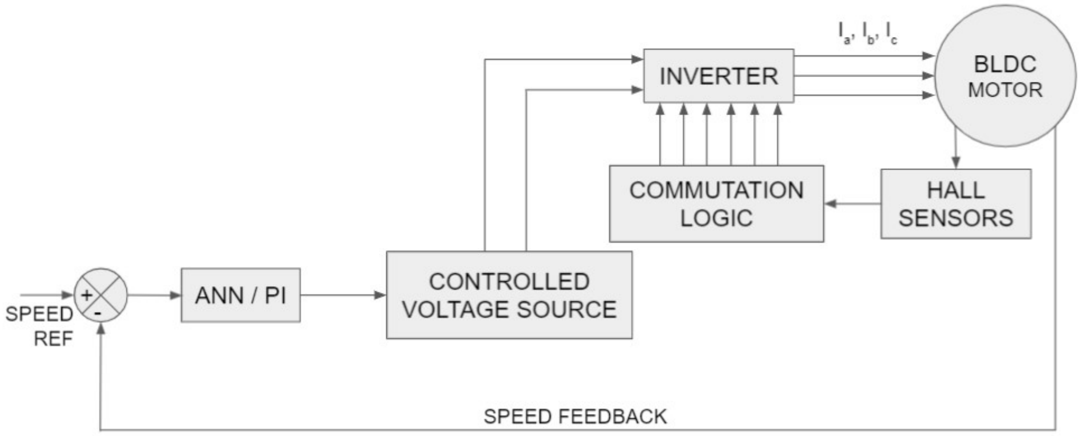

Figure 3.1: Block Diagram

3.1.2 Controlled Voltage Source

For an electric vehicle to be successful largely depends on the voltage source system and it is the lithium-ion batteries that serve the properties that match with a list of specific requirements such as high energy density, decent power capabilities as well as longer life. Lithium-ion batteries, alike any other battery, store energy chemically and release the same electrically. Inside, lithium-ion cells allow large amounts of energy to be squeezed into a very small package that enables faster energy extraction faster than any other battery. It is lithium-ion batteries qualify to be among the top contenders to power electric vehicles. With the lithium-ion battery, DC-DC boost converter is integrated, thus making the voltage source controllable. The current from the PI/ANN controller controls the voltage output of the boost converter powered by lithium-ion battery.

3.1.3 BLDC Motor

All of today's hybrid vehicles use a BLDC motor. Green car manufacturers often prefer BLDC motors over the alternatives because the peak point efficiency is higher and rotor cooling is simpler. The BLDC motor has a permanent-magnet rotor surrounded by a wound stator. The winding in the stator get commutated electronically, instead of with brushes. This makes the the BLDC motor:

- Simpler to maintain,
- More durable,
- Smaller,
- 85%–90% more efficient,
- Able to respond faster and at higher operating speeds,
- Simpler to control in regard to speed control and reversing,
- Lighter,
- Less prone to the failures that brushed motors experience, and
- Able to self-start.

The composition of the BLDC motor also keeps the machinery inside a vehicle cooler and thermally resistant. Plus, because the motor is brushless, there is no dangerous brush sparking.

3.1.4 Controller (PI/ANN)

The conventional PI type controller is still used in industries because of their relative simple implementation. It is used to control and maintain the process. Basically PI type control algorithm is a simple mathematical equation based controller use to obtain the controlled variables. It is working on the principle that, if the speed is controlled variable, then it is measured and fed back to the controller. Then based on reference value and current value, an error is generated. Then this error is passed through the Proportional Integrative Derivative algorithm to examine it. The P controller utilizes the gain $\mathrm{K_p}$ and produces the output which is proportional to the current error value. If the proportional gain is high then the system becomes unstable.

In order to make the system performance stable, integral action is to be taken. This integral mode is used to accumulate steady state error which is caused by proportional action and providing slow response. The derivative mode response to the rate at which error is changing. But due to the derivative action noise will be formed. Hence in this project we will control the speed of BLDC motor by using only Proportional Integrative (PI) Controller.

In this project we prefer two methods. One is Ziegler Nichols tuning method and the other is Genetic Algorithm tuning method.

Artificial Neural Networks are famous learning models for their ability to cope with the demands of a changing environment. In this study, we analyze the application of Artificial Neural Network (ANN) controller in BLDC motor control as a replacement of PI control to control the angular position of a DC motor. This network works with supervised learning where data set is presented to train the network before simulation is run to get output results.

3.1.5 Inverter

Three phase inverters, driving various types of motors have been widely used due to their fast dynamic response, absence of commutation failure, and independent control. The voltage and current ratings of MOSFETs have been significantly improved, so that the use of three-phase inverters has been extended to high-power rated motors. However, in spite of its popularity, the significant power loss in a three-phase inverter has become problematic, particularly for motor drives requiring high power and high efficiency. The power efficiency of three-phase inverters using conventional six-step and inverted pulse width modulation (PWM) driving schemes have low power efficiency.

Inverters are used to convert Direct Currents (DC) to Alternating Currents (AC) in which we can control the output voltage and output frequency as per our requirement. The output waveforms of inverter rely on the gate signals of the inverter. Research is carried out for meeting the requirement of inverters such as to reduce harmonics in the output, switching frequency of the inverter and better consumption of the available dc voltage and the maximum modulator index. The inverter switches are controlled by manipulating the hall effect sensor signals, finding the back emfs using decoder and retrieving gate signals from them. This method is easy to implement, less complicated and gives good results.

Chapter 4

Methodology

4.1 Mathematical Modelling of BLDC motor

The BLDC motor is working as same as the traditional DC motor, but it is construction wise different from it. It is a self rotating synchronous machine whose stator is similar to that of an induction motor and the rotor has permanent magnet which is rotating part. BLDC has no brushes and commuters, instead of this it is replaced by electronically commutated system.

Current polarity can be reversed by switches like MOSFET or IGBT for the three phase inverter circuit in synchronisation with rotor position. This rotor position can be sensed using Hall Effect sensor encapsulated in the stator. The drive can be controlled in sensor or sensor-less mode. The schematic representation of equivalent BLDC motor dive is as shown in fig 4.1. There are three stator winding incorporated with permanent magnet on the rotor. Hence the circuit equation for the stator windings are in phase variable is as follows:

The mathematical modelling of BLDC motor is expressed as:

$$V_{\mathrm{a}} = Ri_{\mathrm{a}} + L\frac{di_{\mathrm{a}}}{dt} + e_{\mathrm{a}} \tag{4.1}$$

$$V_{\mathrm{b}} = Ri_{\mathrm{b}} + L\frac{di_{\mathrm{b}}}{dt} + e_{\mathrm{b}} \tag{4.2}$$

$$V_{\mathrm{c}} = Ri_{\mathrm{c}} + L\frac{di_{\mathrm{c}}}{dt} + e_{\mathrm{c}} \tag{4.3}$$

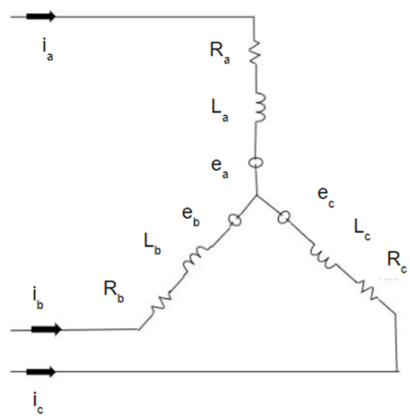

Figure 4.1: Equivalent Circuit of BLDC Motor

$R_a = R_b = R_c = R$, motor phase resistance - Ω

$L_a = L_b = L_c = L$, motor phase inductance - H

V_a, V_b, V_c - stator phase voltages - Volt

i_a, i_b, i_c - stator phase currents - Ampere

$$\begin{bmatrix} V_{\mathrm{a}} \\ V_{\mathrm{b}} \\ V_{\mathrm{c}} \end{bmatrix} = \begin{bmatrix} R + \frac{dL}{dt} & 0 & 0 \\ 0 & R + \frac{dL}{dt} & 0 \\ 0 & 0 & R + \frac{dL}{dt} \end{bmatrix} \begin{bmatrix} i_{\mathrm{a}} \\ i_{\mathrm{b}} \\ i_{\mathrm{c}} \end{bmatrix} + \begin{bmatrix} e_{\mathrm{a}} \\ e_{\mathrm{b}} \\ e_{\mathrm{c}} \end{bmatrix} \tag{4.4}$$

The back-emfs are :

$$e_{\mathrm{a}} = k_{\mathrm{e}}.\omega.f(\theta) \tag{4.5}$$

$$e_{\mathrm{b}} = k_{\mathrm{e}}.\omega.f(\theta - \frac{2\pi}{3}) \tag{4.6}$$

$$e_{\mathrm{c}} = k_{\mathrm{e}}.\omega.f(\theta + \frac{2\pi}{3}) \tag{4.7}$$

The electrical angle and velocity are given by :

$$\theta_{\mathrm{e}} = \frac{P}{2}.\theta_{\mathrm{m}} \tag{4.8}$$

$$\omega_{\mathrm{m}} = \frac{d\theta_{\mathrm{m}}}{dt} \tag{4.9}$$

The torque equations are :

$$T_\mathrm{a} = k_\mathrm{e}.i_\mathrm{a}.f(\theta) \tag{4.10}$$

$$T_\mathrm{b} = k_\mathrm{e}.i_\mathrm{b}.f(\theta - \frac{2\pi}{3}) \tag{4.11}$$

$$T_\mathrm{c} = k_\mathrm{e}.i_\mathrm{c}.f(\theta + \frac{2\pi}{3}) \tag{4.12}$$

$$T_\mathrm{e} = T_\mathrm{a} + T_\mathrm{b} + T_\mathrm{c} \tag{4.13}$$

$$T_\mathrm{e} - T_\mathrm{l} = J.\frac{d^2\theta_\mathrm{m}}{dt^2} + B.\frac{d\theta_\mathrm{m}}{dt} \tag{4.14}$$

Considering the Laplace transform of equation [4.1] :

$$V_\mathrm{a}(s) - e_\mathrm{a}(s) = RI_\mathrm{a}(s) + LsI_\mathrm{a}(s) \tag{4.15}$$

Rearranging equation [4.15] we get :

$$\frac{I_\mathrm{a}(s)}{V_\mathrm{a}(s) - e_\mathrm{a}(s)} = \frac{1}{R + Ls} \tag{4.16}$$

Similarly we can write

$$\frac{I_\mathrm{b}(s)}{V_\mathrm{b}(s) - e_\mathrm{b}(s)} = \frac{1}{R + Ls} \tag{4.17}$$

$$\frac{I_\mathrm{c}(s)}{V_\mathrm{c}(s) - e_\mathrm{c}(s)} = \frac{1}{R + Ls} \tag{4.18}$$

The total torque equation can be derived from previous torque equations :

$$T_\mathrm{e} = \frac{i_\mathrm{a}e_\mathrm{a} + i_\mathrm{b}e_\mathrm{b} + i_\mathrm{c}e_\mathrm{c}}{\omega} = k_\mathrm{e}.i_\mathrm{a}.f(\theta) + k_\mathrm{e}.i_\mathrm{b}.f(\theta - \frac{2\pi}{3}) + k_\mathrm{e}.i_\mathrm{c}.f(\theta + \frac{2\pi}{3}) \tag{4.19}$$

$$T_\mathrm{e} = J.\frac{d^2\theta_\mathrm{m}}{dt^2} + T_\mathrm{l} + B.\frac{d\theta_\mathrm{m}}{dt} \tag{4.20}$$

Therefore :

$$V_\mathrm{a} = \frac{L}{K}.J.\frac{d^2\omega}{dt^2} + \frac{RJ + LB}{K}.\frac{d\omega}{dt} + \frac{RJ + K^2}{K}.\omega \tag{4.21}$$

Taking Laplace transform, we get :

$$\frac{\omega(s)}{V_{\mathrm{a}}(s)} = \frac{K}{LJs^2 + (RJ + LB)s + (RB + K^2)} \tag{4.22}$$

4.2 Open Loop Simulation of BLDC Motor

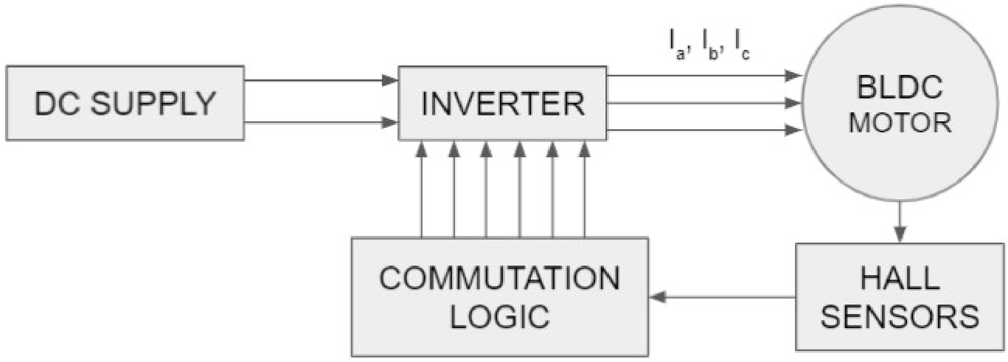

Figure 4.2: Open loop BLDC motor drive

A BLDC motor consist of a rotor and a stator. But in BLDC motors the rotor is a permanent magnet and the stator is winding distributed, in most cases, in three phases. BLDC motors are six steps electrically commutated, in each step, one phase is positive energized, and one is negative energized, and the third phase is floating.

This commutation can be done using Hall sensors or without using them, which is called sensorless commutation. This sensorless commutation depends on detecting the back EMF in each phase of the stator winding, and so detects the zero crossing point (ZCP) of these back EMF. When a ZCP is detected the motor shall be commutated to the next step, so a smooth continues motion can be achieved.

Most of the cases motor starter is monitoring by using three hall sensor devices. The hall sensors provide the information to the decoder block for producing the sign of reference current signal vector to the back electromotive force (BEMF). To operate the motor in the opposite direction, the current is changed in reverse direction or the switching order of the controller is changed.

The MATLAB simulation block diagram for generating the back EMF of the decoder is shown in Fig 4.3 and Table 4.1 shows the decoder sequences.

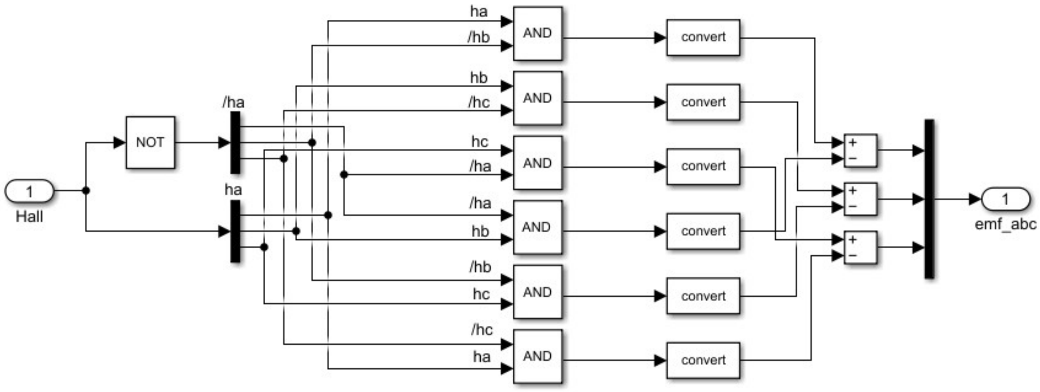

Figure 4.3: Back EMF Decoder

h_a	h_b	h_c	emf_a	emf_b	emf_c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

Table 4.1: Truth Table for Decoder

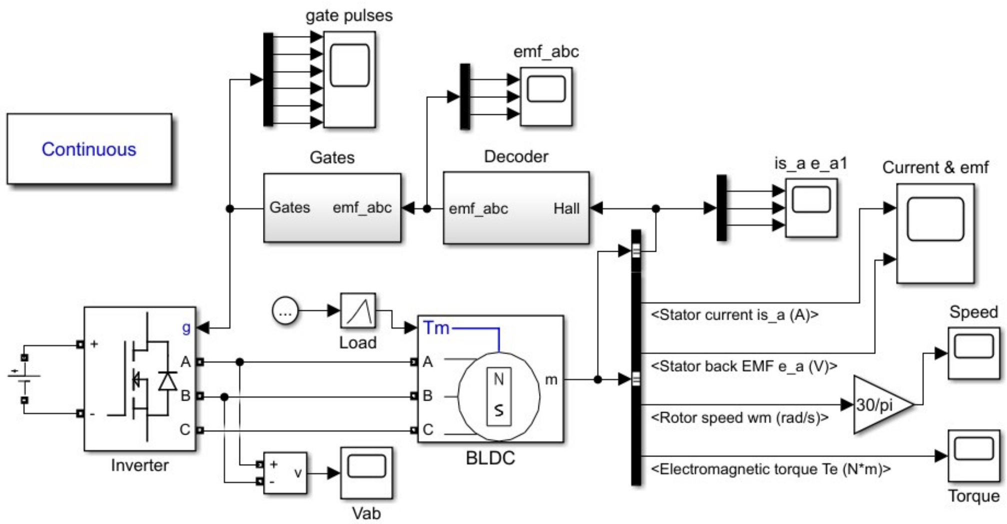

Figure 4.4: Open Loop Simulation (Referred)

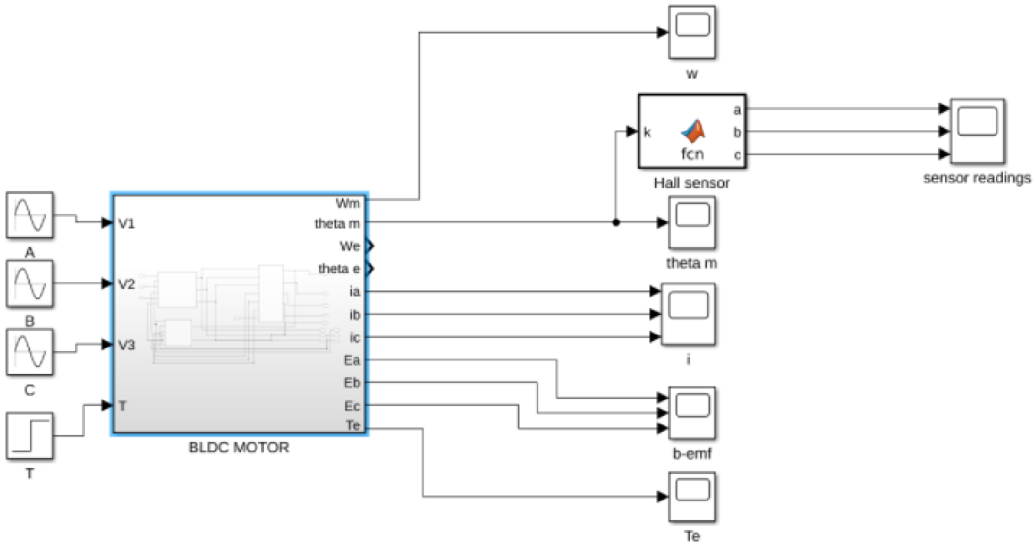

Figure 4.5: Open Loop Simulation Model

4.3 Closed Loop Simulation of BLDC Motor

Closed-loop controls are used in applications that require more accurate and adaptive control of the system. These controls use feedback to direct the output states of a dynamic system. Closed-loop controls overcome the drawbacks of open-loop control to provide compensation for disturbances in the system, stability in unstable processes, and reduced sensitivity to parameter variations (dynamic load variation). The commutation is similar to the open loop control.

4.3.1 PI Controller

The target from any controller is to minimize the error between the actual output, which needed to be controlled, and the desired output, which is called the set point. In the case of speed control this error can be expressed by the following equation:

$$e(t) = \omega_{\text{sp}}(t) - \omega_{\text{pv}}(t) \tag{4.23}$$

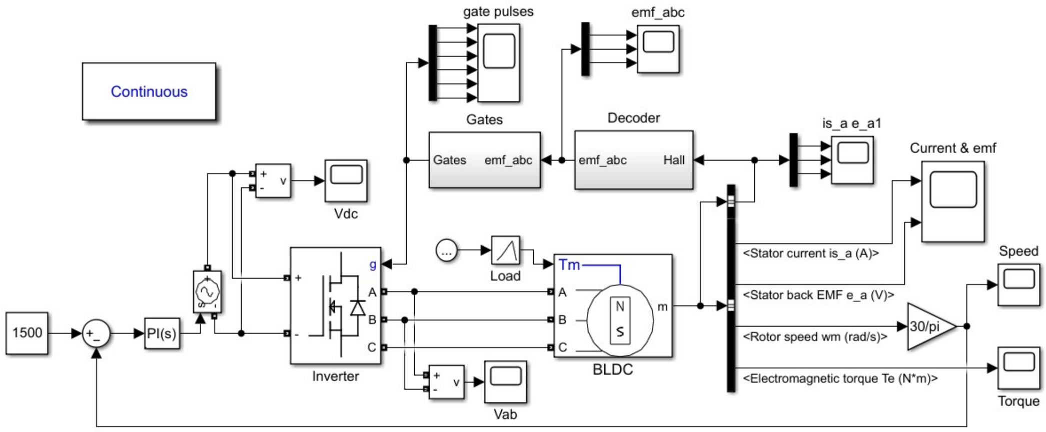

Figure 4.6: PI Closed Loop Simulation Model

where e(t) is the error function of time, ω_{sp} the reference speed or the speed set point as function of time, and ω_{pv} the actual motor speed as function of time. The PI term stands for Proportional Integral, so any PI controller can be divided into 2 parts where each part has its Gain. The first part is the proportional part which is the error multiplied by a constant gain which is $\mathrm{K_P}$. The second part is the integral part, which is the integration of error with time multiplied by a constant gain, which is $\mathrm{K_I}$. The PI controller equation can be expressed as the following.

$$u(t) = K_{\mathrm{P}} e(t) + K_{\mathrm{I}} \int e(t)dt \tag{4.24}$$

where u(t) is the PI output, $\mathrm{K_P}$ is the proportional gain, $\mathrm{K_I}$ is the integral gain and e(t) is the error function shown in equation (4.23). The following function block, in figure 4.7, shows the operation of the PI controller.

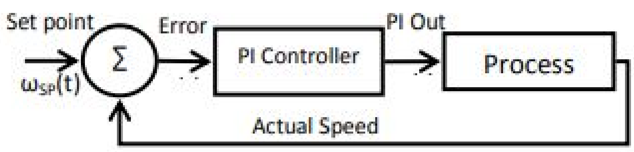

Figure 4.7: PI Controller Block Diagram

There are four main parameters which should be minimized by the control system:

- Rise time (Tr): defined as the time taken to go from 10% to 90% of the targeted set point value.
- Settling time (Ts): defined as the time required for the response curve to reach and stay within a range of certain percentage (usually 5% or 2%) of the final value.
- Steady state error: defined as the difference between the steady state output and the desired output.
- Overshooting: defined as the maximum peak value of the response curve measured from the desired response of the system .Overshooting is the maximum value in the response curve minus the targeted value divided by the targeted value.

There are more parameters which should be taken into account in case of motor speed control, like start up current, start up torque, and speed variation percentage.

Ziegler Nichols Tuning Method

The Ziegler–Nichols tuning method is a PID tuning method which is more of a practical method which may or may not give an optimal solution. It is performed by setting the I (integral) and D (derivative) gains to zero. The proportional gain $\mathrm{K_p}$ is then increased from zero until it reaches the ultimate gain, at which the output of the control loop has stable and consistent oscillations. This ultimate gain $\mathrm{K_u}$ and oscillation period $\mathrm{T_u}$ are used to are then used to set the P, I, and D gains (in this paper only P and I gains) depending on the type of controller used and behaviour desired.

The ultimate gain and oscillation period values are found by running simulation in MATLAB/SIMULINK and converted to required $\mathrm{K_p}$, $\mathrm{K_i}$ values using the table 4.2. The transfer function relationship between error and controller output is given by :

$$u(s) = K_{\mathrm{p}}.(1 + \frac{1}{T_{\mathrm{i}}s} + T_{\mathrm{d}}s) \tag{4.25}$$

Controller Type	$\mathbf{K_p}$	$\mathbf{T_i}$	$\mathbf{T_d}$
P	0.5 K_u	∞	0
PI	0.45 K_u	$T_u/1.2$	0
PID	0.6 K_u	$T_u/2$	$T_u/8$

Table 4.2: Ziegler Nichols Tuning method

From this equation, we can find the value of K_i :

$$K_i = \frac{K_p}{T_i} \tag{4.26}$$

By utilizing the relationships given in the table 4.2, the final values of K_p and K_i are found for the PI controller.

Genetic Algorithm Method

Genetic Algorithm(GA) is a search-based optimization technique based on the principles of Genetics and Natural selection. Optimization refers to finding the best values of inputs by maximizing or minimizing one or more objective functions, by varying the input parameters. In GA, we have a pool or a population of possible solutions to the given problem. These solutions then undergo recombination and mutation, producing new children, and the process is repeated over various generations. Each individual is assigned a fitness value(based on its objective function value) and the fitter individuals are given a higher chance to mate and yield more fitter individuals. The initial randomly chosen parameter space is called the chromosome. In each generation a new population is created.

The cost function represents the problem that is to be solved. The complete response of the system for each PID parameter value and its initial fitness value is computed using individual cost functions like Integral Square Error(ISE), Integral Absolute Error(IAE), and Integral Time Absolute Error(ITAE) a weighted combination of these three cost functions.

$$ITAE = \int_0^\infty t|e(t)|dt \tag{4.27}$$

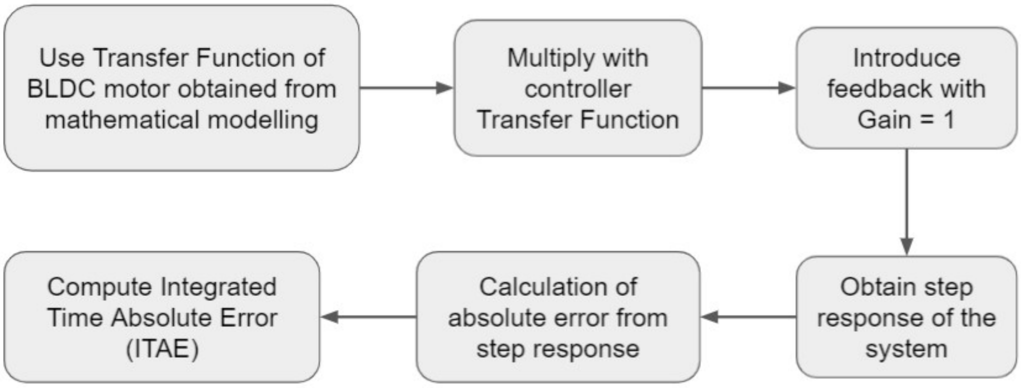

Figure 4.8: Fitness Function - Genetic Algorithm

This process will go through above steps until the end of the generations where the best fitness value is achieved. The ultimate aim of GA is to seek global PI values with minimum fitness value to operate the system in the entire range.

4.3.2 ANN Controller

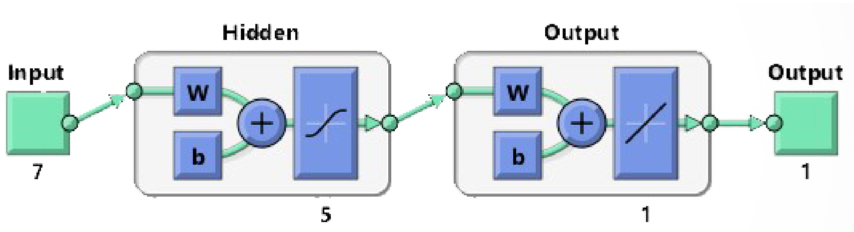

Figure 4.9: Neural Network

The artificial neural network is like human brains which receives process and transmit the information in terms of computer science. The structure of artificial neural network has mainly three layers. Input layer consisting of set of input values (X_j) and associated weights (W_{ij}). Input layers consisting of the information we are trying to classify. The middle layer is neither input nor output layer. It is called hidden layer. Hidden layer includes summation of product of earlier input and its associated weight and the activation function. In hidden layer number of layers and number of neurons is a bit arbitrary and it is usually an experiment to decide what works best for particular model.

The summation function is given by :

$$Z_{\mathrm{j}} = \Sigma_{j=1}^{n} X_{\mathrm{i}} W_{\mathrm{ij}} \tag{4.28}$$

The function fitting neural network is built using the **nntraintool** in MATLAB/SIMULINK. The data for training is taken from the PI-GA controller model. The variables chosen for training are Speed Error, Actual Speed, Electromagnetic Torque, Reference Speed, Load Torque, Stator Current and Back EMF values; and they are mapped to the PI-output. The collected data is divided and used for training, validating and testing of the ANN model.

Levenberg Marquardt Algorithm(LMA) is employed for training the neural network. Even though it consumes a lot of memory, it is the fastest and better algorithm for training purposes.

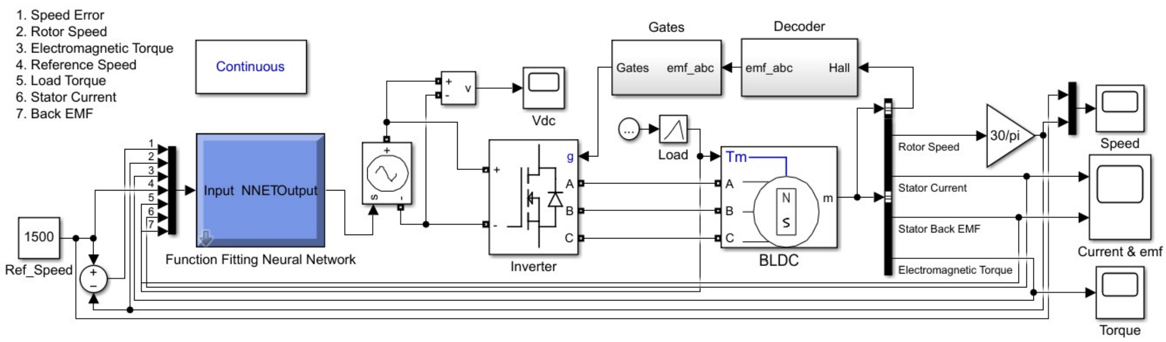

Figure 4.10: ANN Closed Loop Simulation Model

As a result a two-layer feed-forward network with sigmoid hidden neurons and linear output neurons (fitnet), is built, with consistent data and enough neurons in its hidden layer.

Chapter 5

System Design

5.1 Vehicle Dynamics

The BLDC motor rating is decided based on the vehicle dynamics of the three wheeler. Vehicle dynamics is study of vehicle performance based on the set of required constraints. There are mainly three resistive forces while a vehicle moves on a plane Rolling Resistance, Aerodynamic Drag, Grade Resistance.

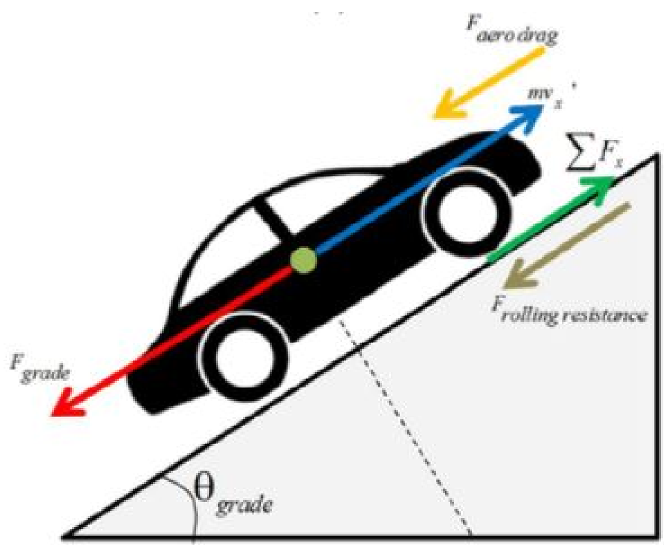

Figure 5.1: Resistive forces on a vehicle

Rolling resistance is the combination of forces that work against the forward motion of your vehicle. The weight of the vehicle, gravity and inertia, the amount of friction between the tires and the road surface, and air drag all play a part. Which is given by (**??**)

$$RollingResistance = Cr * M * g * cos\theta \tag{5.1}$$

Aerodynamic Drag is a force which the oncoming air applies on a moving body. It is the resistance offered by the air to the movement of the body. So, when a car is moving; it displaces the air. However, it affects the car's speed and performance. Which is given by (**??**)

$$AerodynamicDrag = 0.5 * \rho * v^2 * A * Cd \tag{5.2}$$

Grading resistance is when a vehicle goes up or down a slope, its weight produces a component of force that is always directed downwards. This force component opposes the forward motion, i.e. the grade climbing. When the vehicle goes down the grade, this force component aids the vehicle motion. The grading resistance can be expressed as (**??**)

$$GradeResistance = M * g * sin\theta \tag{5.3}$$

based on these Resistances the required Torque and speed is calculated which gives the idea about the rating of the motor to be selected. Since the set of constraints cannot be set the selection is done by a series of iterations.

5.1.1 Vehicle Specifications

The Three Wheeler considered is in reference of Kinetic Safar DX which one of the three wheeler available in the market.

- Kerb Mass of the vehicle = 324 Kg
- Configuration = 1 Driver+3 Passengers
- Total weight of the vehicle = 628 Kg(average weight=76 Kg)

- Radius of Tyre = 0.21 m(approx)
- Coefficient of Rolling Resistance = 0.014
- low Gear Ratio = 10:1
- High Gear Ratio = 13:1
- Gear Box Efficiency = 85%
- Coefficient of Air Resistance = 0.44
- Length = 2.718 m
- Width = 0.995 m
- Height = 1.799 m
- Frontal area = 1.79 m^2

5.1.2 Vehicle Dynamics Iterations

The BLDC motor for the three wheeler has to be selected based on the vehicle dynamics.as vehicle dynamics have many factors which decides the final performance of the vehicle, series of iteration has to be done and the best performance resulting iteration has to be selected. According to the government norms the maximum speed that the three wheeler can have is 25 km/h. Hence we have the following conclusions.

- Maximum speed required = 25 km/h
- Lowest gear ratio = 10:1
- Maximum Rpm required = 3157
- Nominal Rpm required = 1579

Iteration 1

When the vehicle is considered with a Gradability= 17.5% (10 °slope) and velocity of 5km/h. we have the following conclusions.

- Rolling Resistance= 121.25N
- Air Drag= 0.85N
- Grade Resistance= 1058.12N
- Total Road Load= 1180.22N
- Torque required at the wheel= 247.85Nm
- High Gear Ratio= 13:1
- Torque of the BLDC Motor at peak region= 21Nm
- Torque of the BLDC Motor at continuous region = 16.15
- BLDC Motor Power required= 3KW

Hence the BLDC motor requires a power of 3.5KW

Iteration 2

When the vehicle is considered with a Gradability= 12.27% (7 °slope) and velocity of 5km/h. we have the following conclusions.

- Rolling Resistance= 122.17 N
- Air Drag= 0.85N
- Grade Resistance= 750N
- Total Road Load=873.02 N
- Torque required at the wheel= 183.33 Nm
- High Gear Ratio= 13:1
- Torque of the BLDC Motor at peak region= 12.76 Nm
- Torque of the BLDC Motor at continuous region = 9.8 Nm
- BLDC Motor Power required= 1620 W

Hence the BLDC motor requires a power of 2 KW.

5.1.3 Selection of Rating of the BLDC Motor

Based on the iterations performed and the availability of the motors, the BLDC Motor of 2KW is selected with following specification.

- Motor power = 2 kW continuous
- Motor Torque at continuous range = 12.5 Nm
- Torque at peak range = 16.25 Nm
- Rated Rpm = 1500 rpm
- Maximum Rpm = 3000 rpm

5.1.4 Performance of the Vehicle based on selected BLDC Motor

Based on the selected BLDC Motor the three wheeler have following performance specification.

- Maximum speed = 23.75 km/h
- Maximum Acceleration = 1.19 m/s^2
- Acceleration in continuous region = 0.87 m/s^2
- Maximum slope angle = 9.2°
- Maximum Gradability = 16.27%

5.2 Motor Parameters

Sl.no	Parameter	Value
1	L	9.4 x 10^{-3} H
2	R	1.43 Ω
3	J	0.008 kg.m^2
4	B	0.2 Nms
5	K	0.513 volt/rad/sec
6	T	12.5 Nm
7	P	4

Table 5.1: Motor Parameters

5.3 Controller Parameters

5.3.1 PI - Ziegler Nichols Tuning

Sl.no	Parameter	Value
1	K_P	0.000000001
2	K_I	33.4987439489544

Table 5.2: Ziegler Nichols Controller Parameters

5.3.2 PI - Genetic Algorithm Tuning

Sl.no	Parameter	Value
1	Number of Variables	2
2	Lower and Upper Bound	[0, 0] and [50, 50]
3	Population Size	50
4	Plot Functions	Best fitness, Best individual

Table 5.3: Optimtool Parameters

Sl.no	Parameter	Value
1	K_P	0.2507
2	K_I	49.4967

Table 5.4: Genetic Algorithm Controller Parameters

5.3.3 ANN - Function Fitting

Sl.no	Parameter	Value
1	Input Layers	7
2	Hidden Layers	1
3	Hidden Neurons	5
4	Training Epochs	1000
5	Training Algorithm	trainlm
6	Training Samples	653848
7	Valdation Samples	140110
8	Testing Samples	140110

Table 5.5: ANN Controller Parameters

5.4 Bill of Materials

Sl.no	Item	Quantity	Cost(₹)
1	BLDC Motor (48V, 2kW)	1	90,000
2	Inverter	1	12,000
3	FPGA based development board	1	15,000
4	Current Sensor	3	1000
5	Battery (48V, 110Ah)	1	1,00,000
	Total		2,18,000

Table 5.6: Bill of Materials

5.5 Conclusion

The BLDC Motor for the Three Wheeler is selected based on the Vehicle Dynamics. The selected motor is having specifications of 2KW, 12.5 Nm continuous torque, 16.25 Peak Torque, 1500 rpm. The BLDC Motor is so efficient such that the Three Wheeler can provide a maximum Gradability of 16.27% and speed of 23.75 km/h. The Motor Parameters are selected based on the specifications of the motor. The PI controller parameters are selected by Ziegler Nichols AND Genetic Algorithm methods and ANN controller parameters are selected as to provide an accurate closed loop response. The overall system hardware includes BLDC Motor, Inverter, FPGA based development board, Current sensors, Battery, Charger which is having an estimate of 2,18,000 /-.

Chapter 6

Results and Discussions

6.1 Introduction

An open loop model of BLDC motor is designed based on its mathematical model and simulated in MATLAB/SIMULINK. The results obtained from this simulation is verified with a open loop motor drive system with inbuilt BLDC motor block available in MATLAB/SIMULINK. Further the a closed loop model with PI controller and ANN controller integrated in motor drive system is simulated. The results thus obtained are shown.

6.2 Results and Discussions

6.2.1 Open loop Simulation Results(Referred)

An open loop model of BLDC motor drive with inbuilt motor block from MATLAB/ SIMULINK is simulated for the reference of the created mathematical model. Results obtained from the reference model are shown below.

The results shown are stator current of the BLDC motor in open loop simulation and the back EMF thus obtained in Fig 6.1 for different loads applied. For each second, load is increased by 1/4 times the full load from no load to full load.

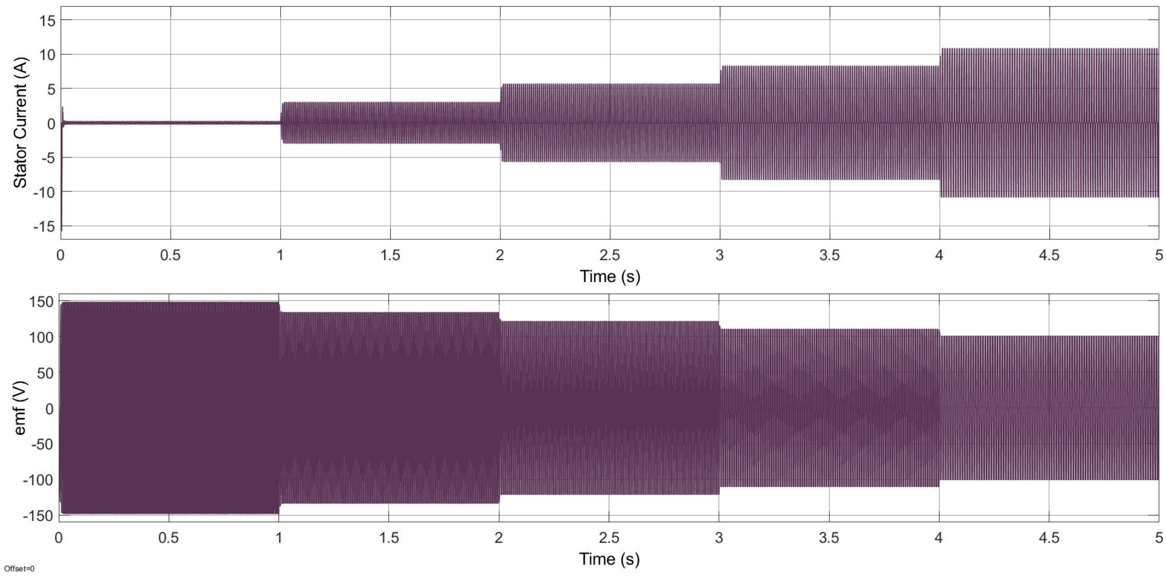

Figure 6.1: Stator Current(A) Vs Time(s) and EMF(V) Vs Time(s)

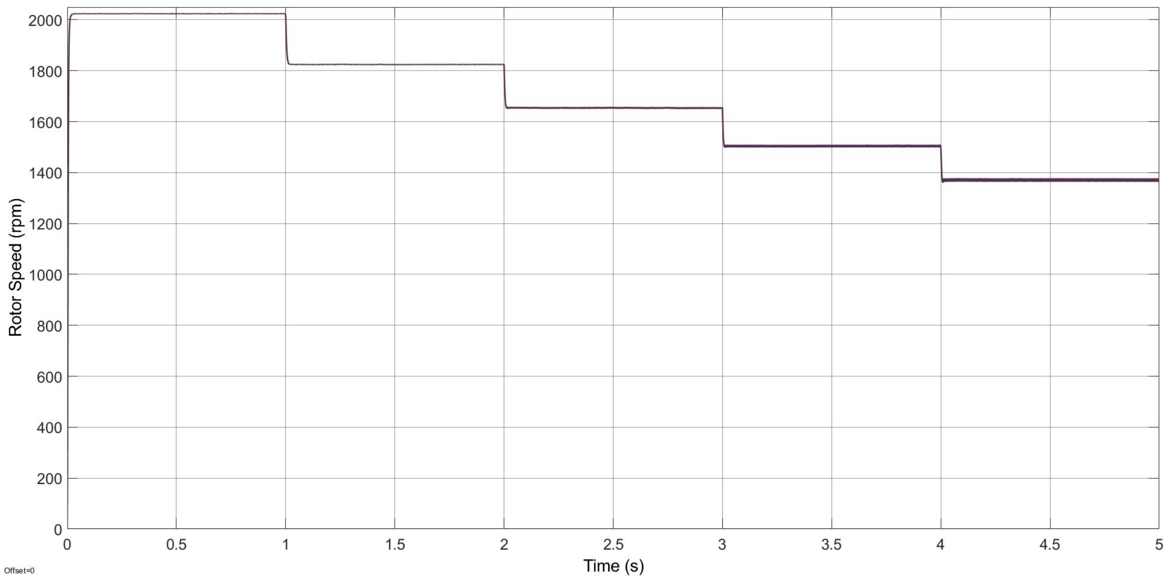

Figure 6.2: Rotor Speed(rpm) Vs Time(s)

The obtained speed, gate pulses and torque is shown in the figures 6.2-6.4 respectively .

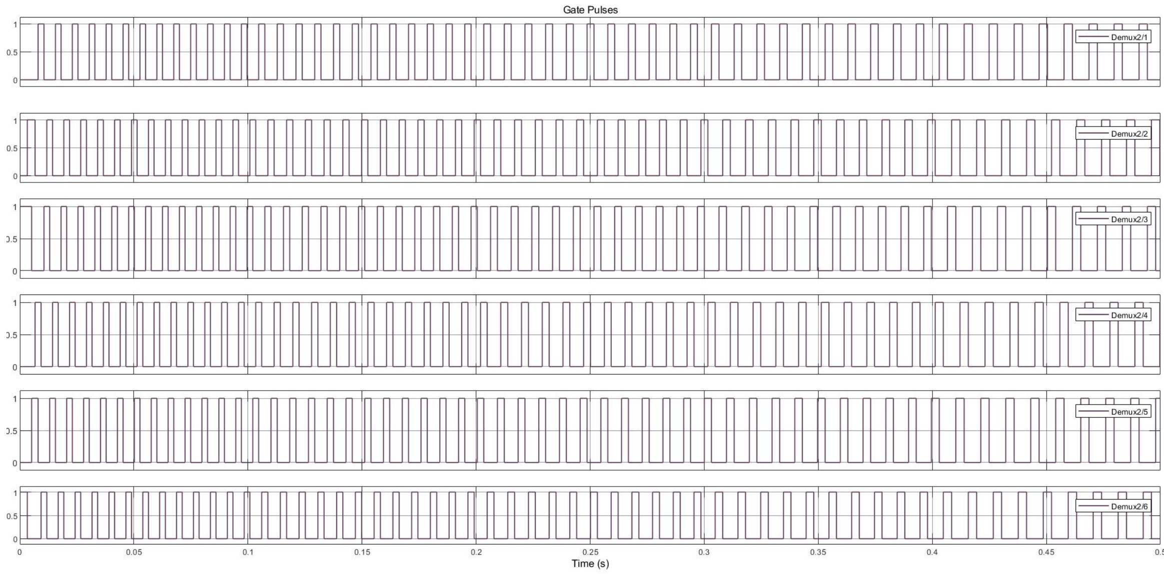

Figure 6.3: Gate Pulses

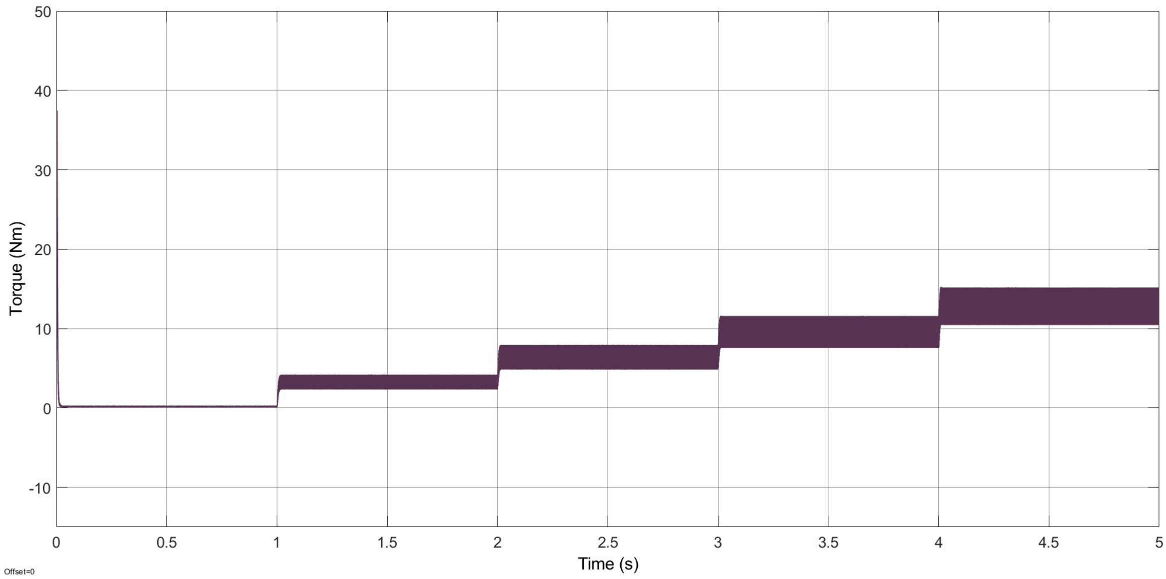

Figure 6.4: Torque(Nm) Vs Time(s)

6.2.2 Open loop Simulation Results

An open loop model of BLDC motor drive with motor block obtained by mathematical equations is simulated in MATLAB/ SIMULINK. Results obtained from the model are shown below.

The waveform of back emf obtained from mathematical model and the stator current are shown in Fig 6.5.

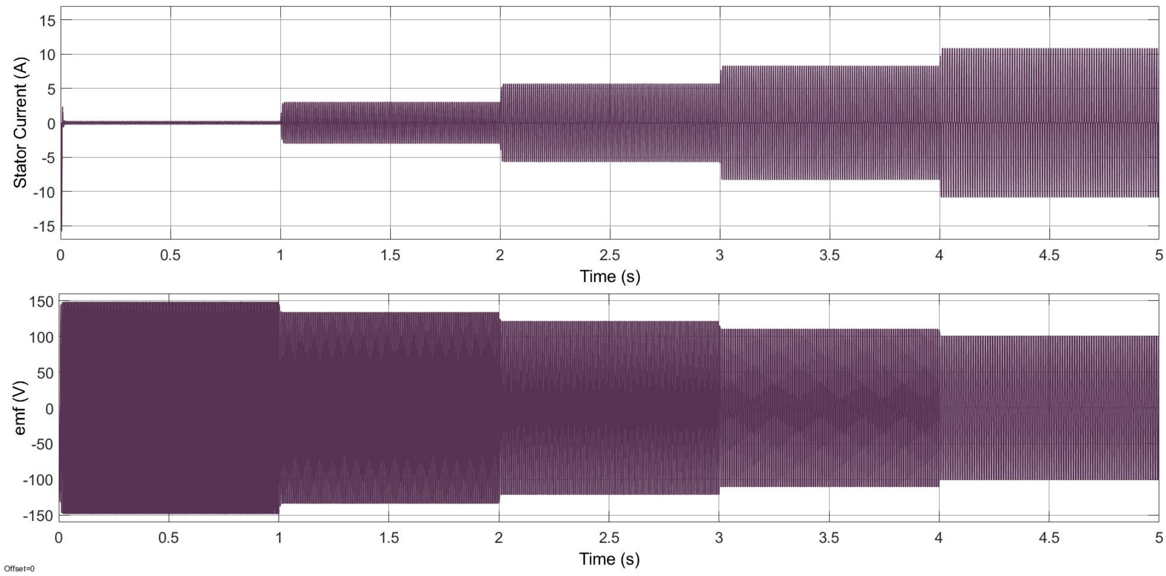

Figure 6.5: Stator Current(A) Vs Time(s) and EMF(V) Vs Time(s)

For each second, load is increased by 1/4 times the full load from no load to full load.

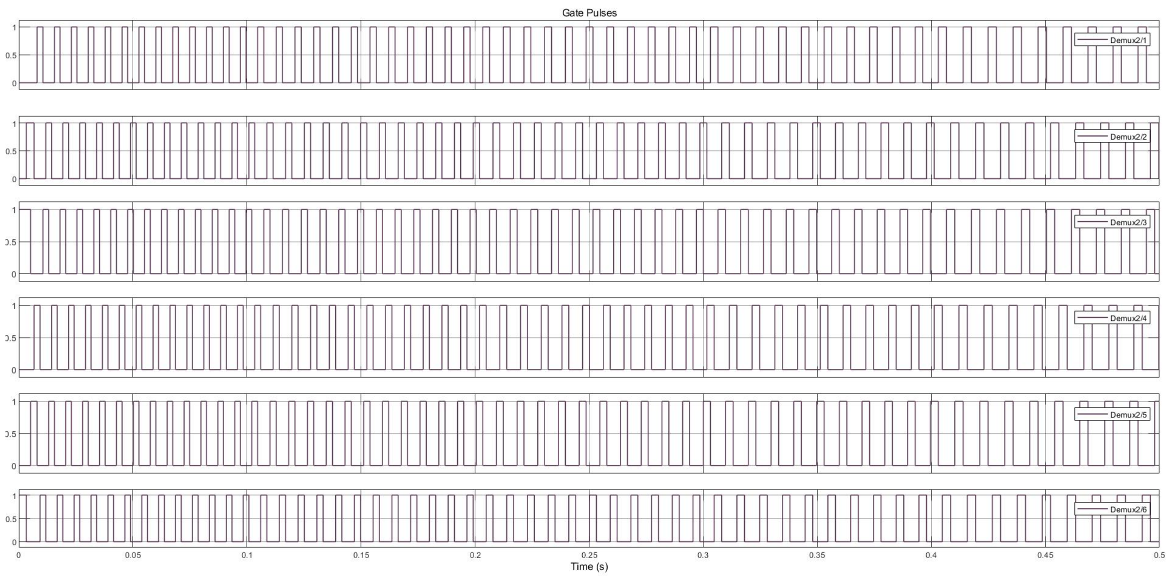

Figure 6.6: Gate Pulses

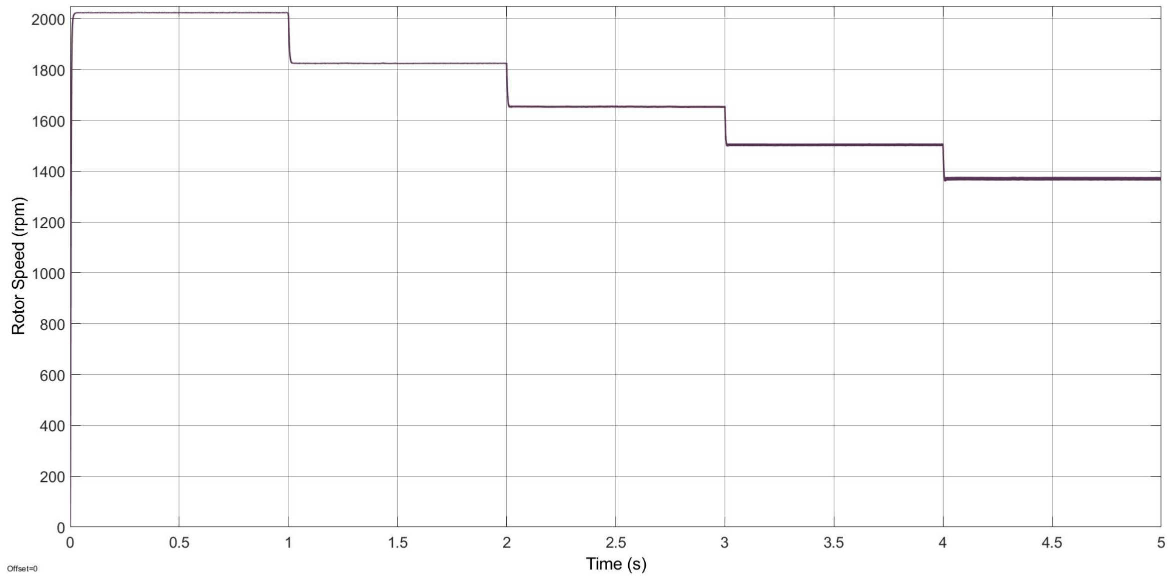

Figure 6.7: Speed(rpm) Vs Time(s)

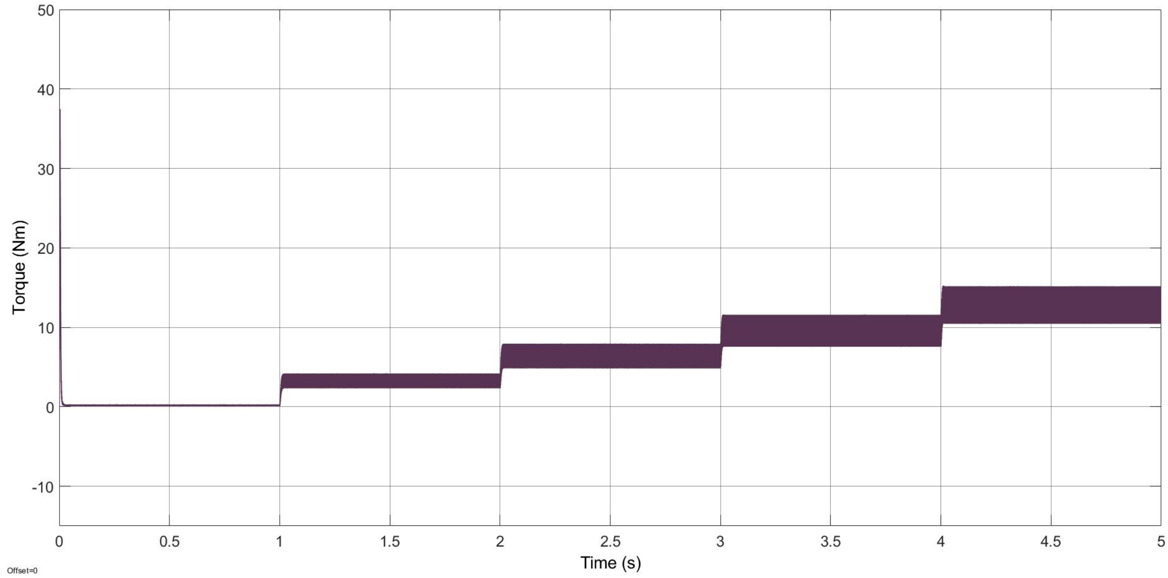

Figure 6.8: Torque(Nm) Vs Time(s)

Fig 6.6-6.8 represents the Gate pulses, speed and the torque of the BLDC Motor respectively

6.2.3 Closed loop Simulation Results

PI - Ziegler Nichols

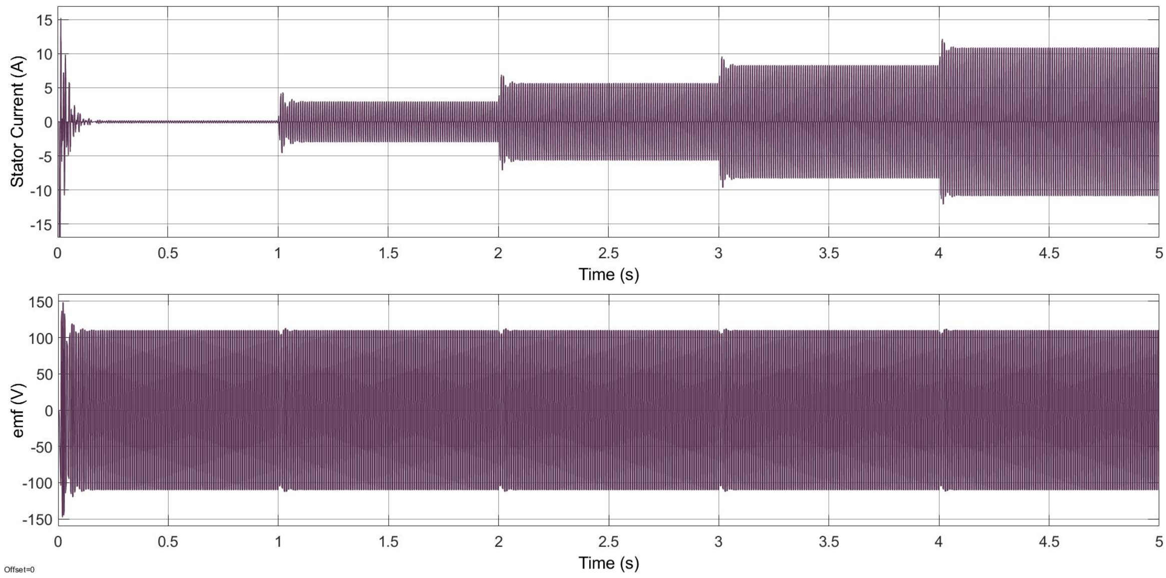

Figure 6.9: Stator Current(A) Vs Time(s) and EMF(V) Vs Time(s)

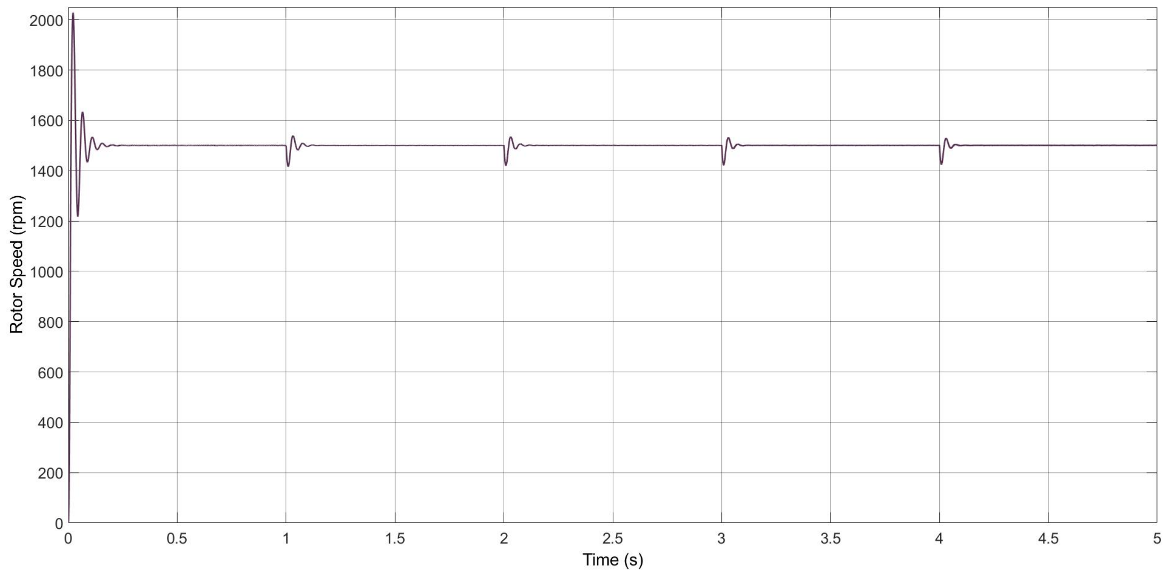

Figure 6.10: Speed(rpm) Vs Time(s)

Fig 6.9-6.11 represents the stator current, speed and the torque obtained from the closed loop simulation. For each second, load is increased by 1/4 times the full load from no load to full load.

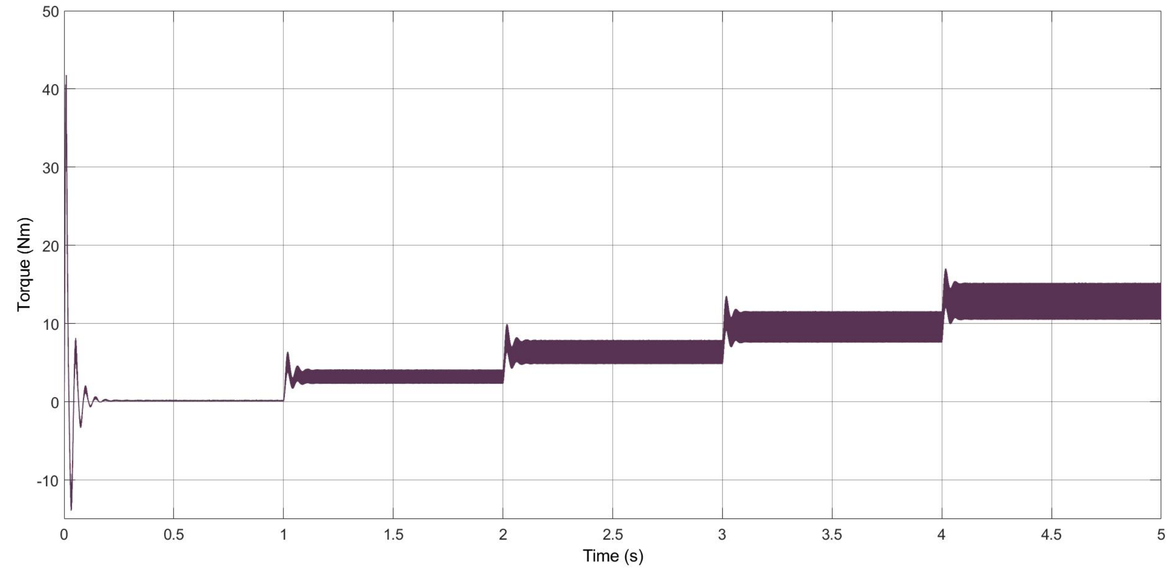

Figure 6.11: Torque(Nm) Vs Time(s)

PI - Genetic Algorithm

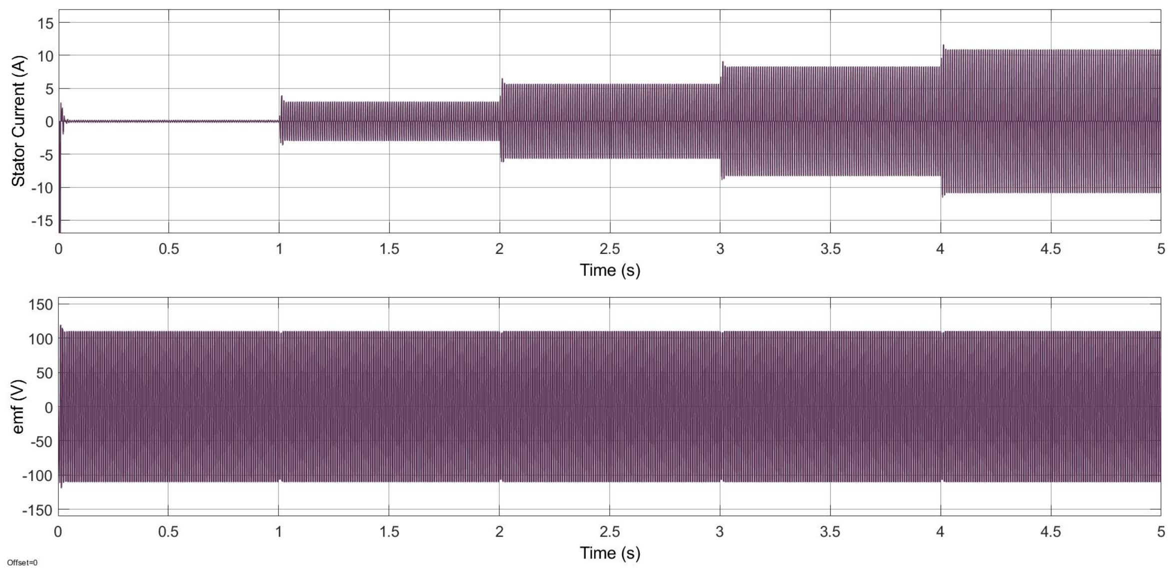

Figure 6.12: Stator Current(A) Vs Time(s) and EMF(V) Vs Time(s)

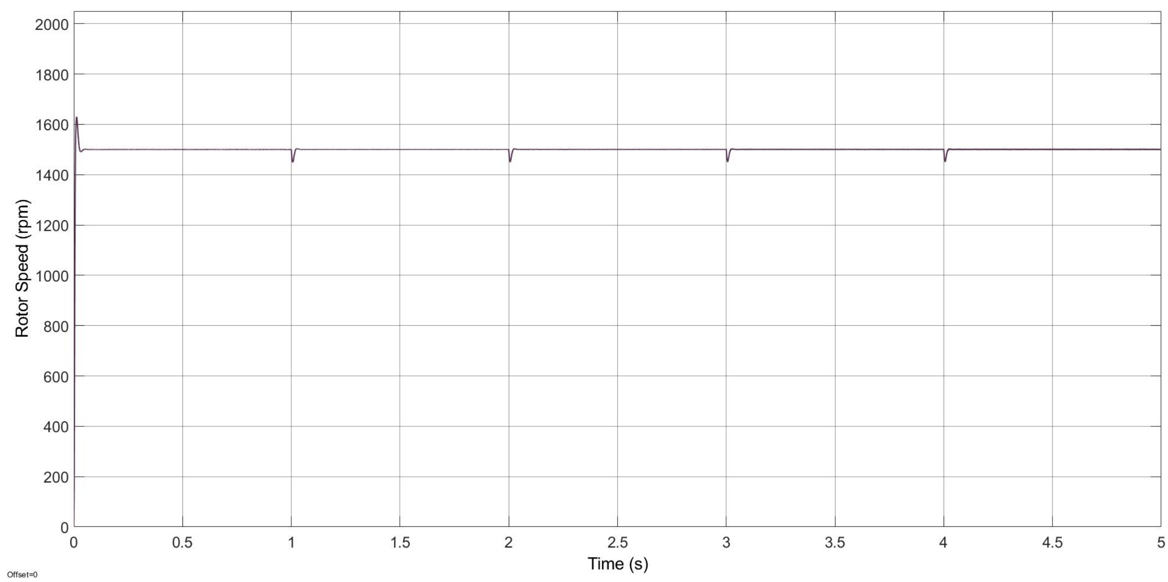

Figure 6.13: Speed(rpm) Vs Time(s)

Fig 6.12-6.14 represents the stator current, speed and the torque obtained from the closed loop simulation. For each second, load is increased by 1/4 times the full load from no load to full load.

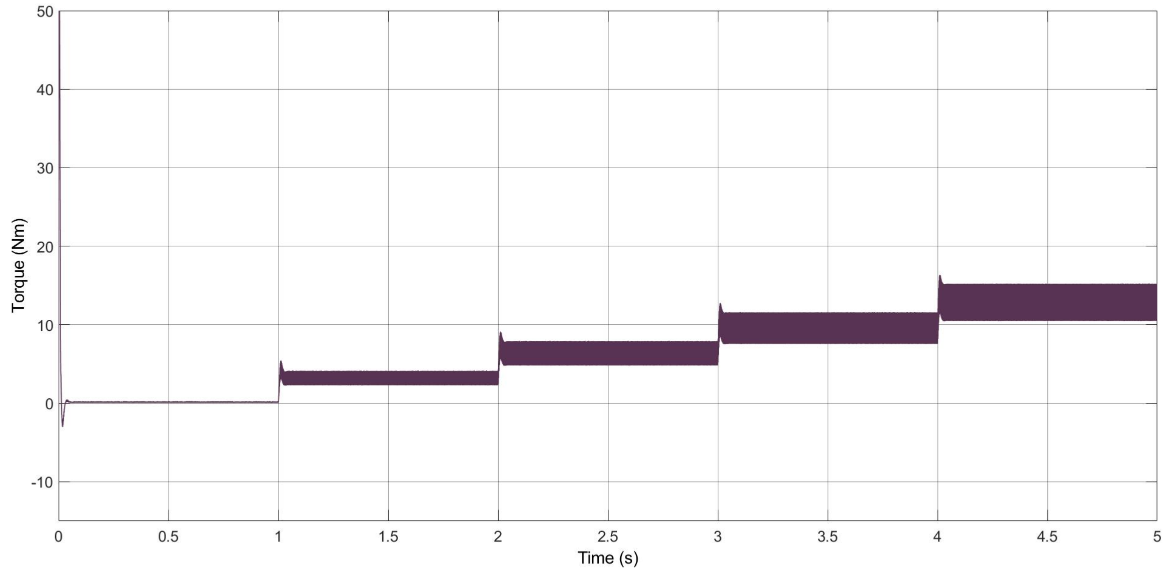

Figure 6.14: Torque(Nm) Vs Time(s)

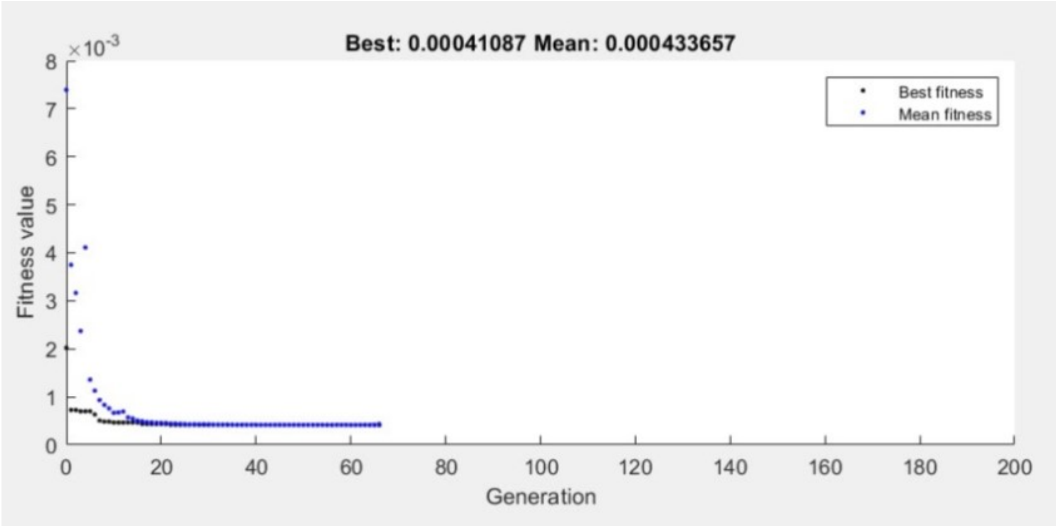

Figure 6.15: Fitness Value Vs Generation

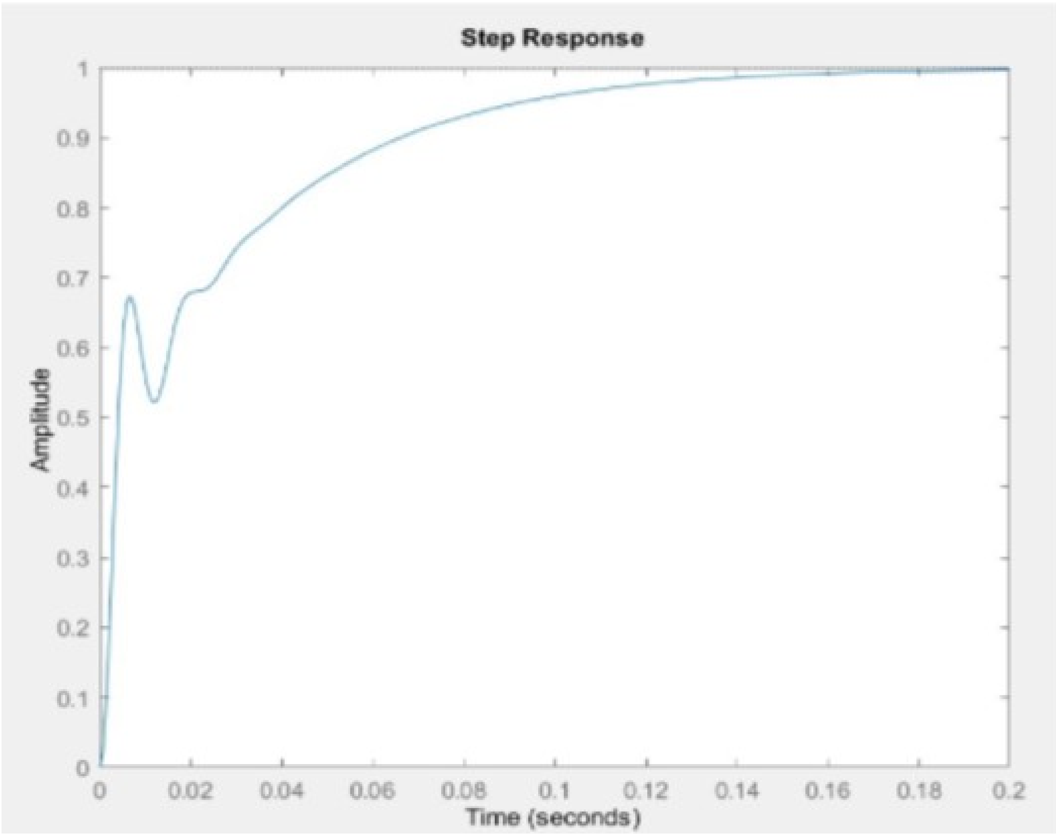

Figure 6.16: Step Response Vs Time(s)

Fig 6.15-6.16 shows the best fitness value and step response produced by the optimization tool in MATLAB/SIMULINK for the genetic algorithm tuning of PI controller.

ANN - Function Fitting

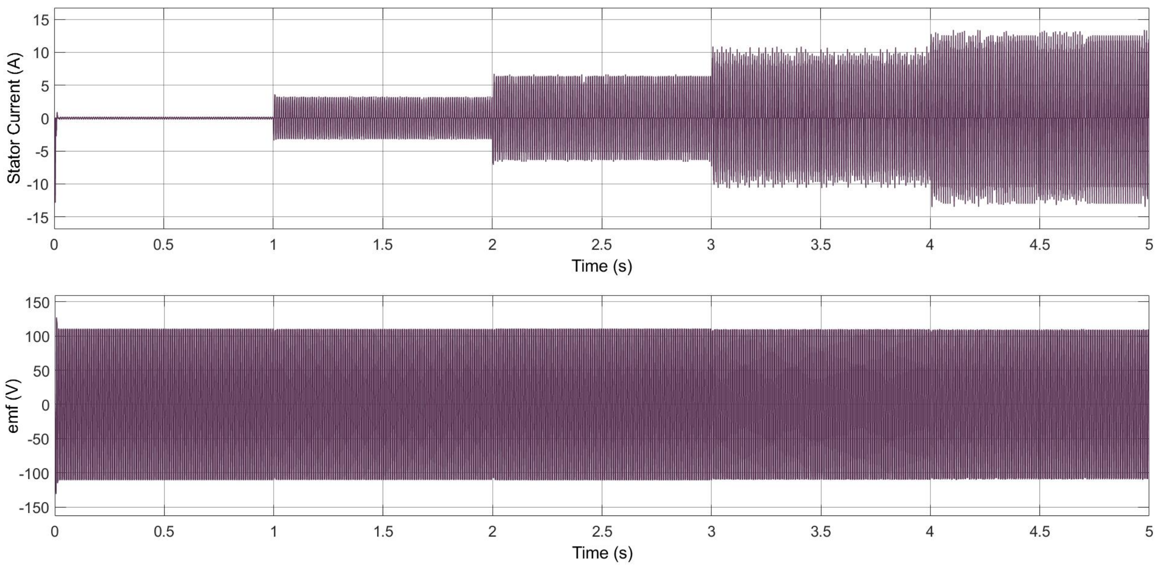

Figure 6.17: Stator Current(A) Vs Time(s) and EMF(V) Vs Time(s)

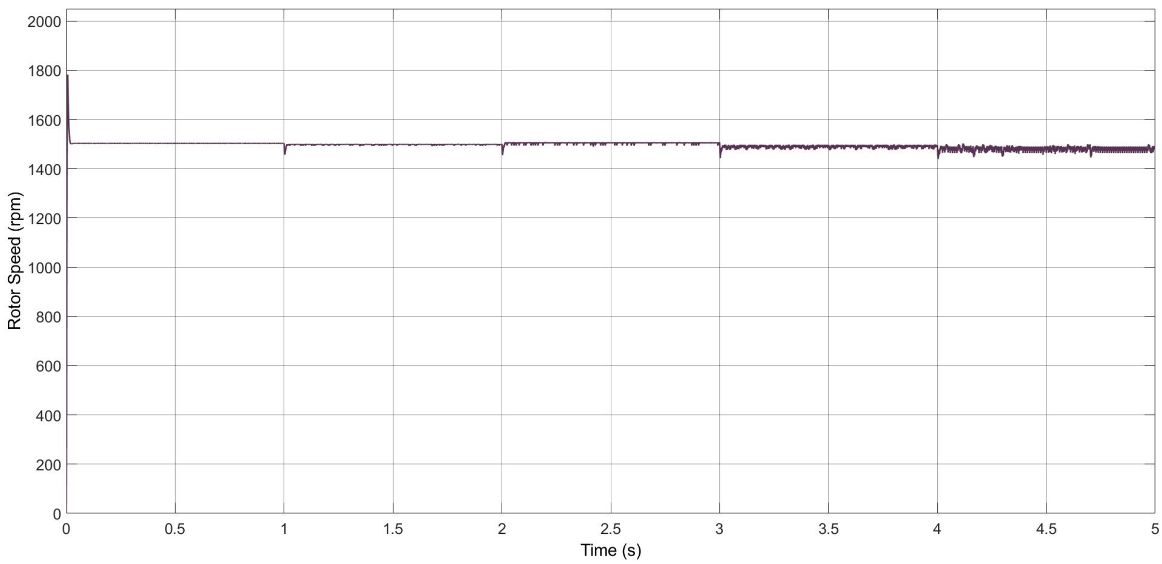

Figure 6.18: Speed(rpm) Vs Time(s)

Fig 6.17-6.19 represents the stator current, speed and the torque obtained from the closed loop simulation. For each second, load is increased by 1/4 times the full load from no load to full load.

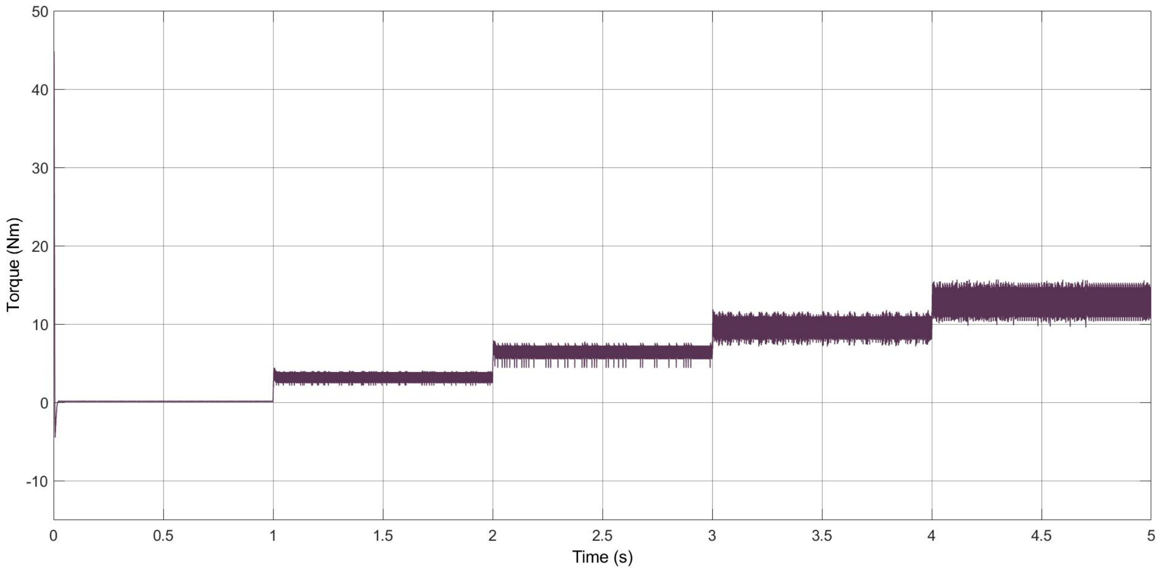

Figure 6.19: Torque(Nm) Vs Time(s)

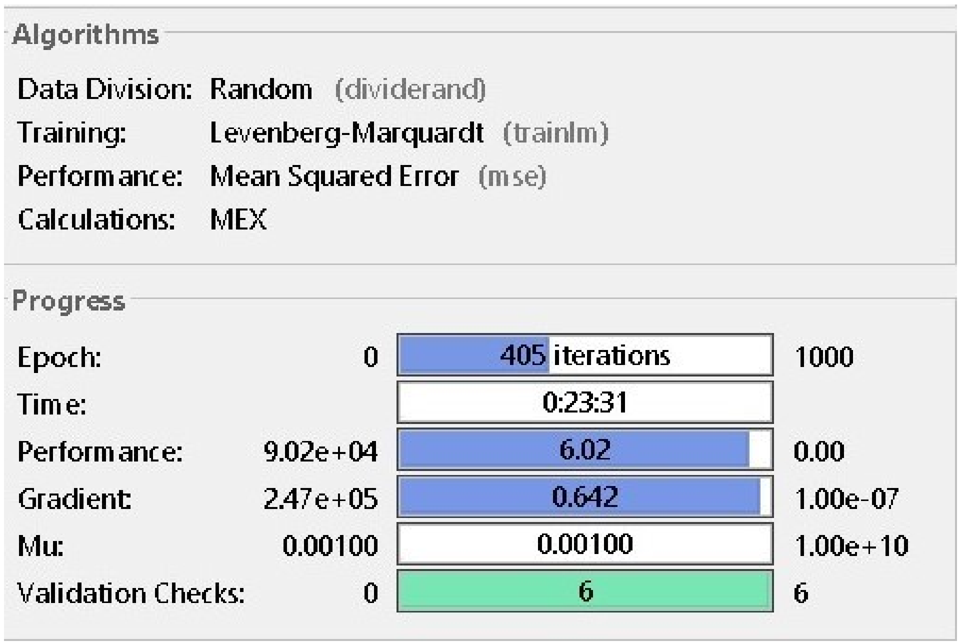

Figure 6.20: ANN Training Performance

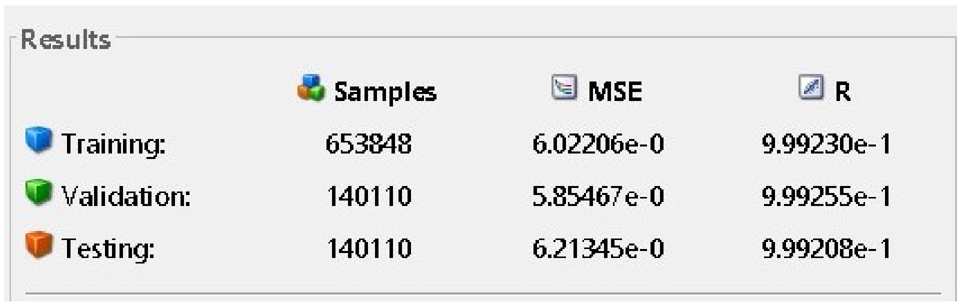

Figure 6.21: Function Fitting Results

6.3 Comparison

Parameter	Ziegler Nichols	Genetic Algorithm	ANN
Speed Overshoot	528rpm	130rpm	166rpm
Speed Rise Time	7.392ms	4.917ms	4.413ms
Speed Settling Time	18.431ms	17.739ms	13.018ms
Speed Ripples	Less	Least	More
Torque Overshoot	39.29Nm	44.25Nm	38.75Nm
Torque Rise Time	2.717ms	2.502ms	2.419ms
Torque Settling Time	18.652ms	17.581ms	13.337ms
Torque Ripples	Less	Least	More
Transience	Moderate	Best	Good

Table 6.1: Comparison of Controllers - 6.25Nm

6.4 Conclusion

The performance parameters are extracted from the speed and torque response curves of the PI and ANN controllers. It is clear from the comparison that in the first step (0 RPM to 1500 RPM), the proposed PI-GA Controller has a very small rise time, overshoot, ripples and transience compared to PI-Ziegler Nichols. And it has least amount of ripples compared to ANN controller; also other parameters are really close in magnitude. Genetic Algorithm tuning method has increased the stability by reducing oscillations. For EV application torque should be steady and such a response is produced by PI-GA controller.

Chapter 7

Conclusions and Future Scope

7.1 Conclusions

A BLDC motor speed controller is presented in this paper, using PI controller tuned by two methods and an ANN controller. The performance of these controllers are analysed and a comparative study has been conducted between them to find the most suitable controller of EV application. It has been understood that the PI controller tuned using Genetic Algorithm is the best among the other implemented controllers.

7.2 Future Scope

The comparison between the presented controllers showed that ANN controller slightly improves the response except in the case of speed and torque ripples. A future work could be done to add current control function to the proposed speed controller, so the current can be kept within a certain range for a given speed, which will help in enhancing the motor startup current, reducing the motor current ripples, and enhancing the motor torque characteristics. Also by current control, the speed and torque variations can be reduced to minimum, by avoiding any sudden changes in the motor current value.

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