Performance Comparison of BLDC Motor with different Controllers for EV Application

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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.**

***Index Terms*—ANN, BLDC, EV, GA, PI**

I. INTRODUCTION

Electric Vehicles(EV) have started gaining importance since people realized the aftereffects 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. There are several types of electric motors for electric vehicle 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], it presents modelling and simulation Analysis of the selected BLDC Motor by using MATLAB/SIMULINK. The back EMF generation of the BLDC motor is extracted 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].

A. Problem Statement

Generally the performance of motor is affected by sudden change in unknown load or speed. But as the BLDC motor drives 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, a controller is required.

B. Objectives

The main objectives of the paper are to design and implement PI and ANN controller for BLDC based EV, compare their performance, select the best among them and implement it in BLDC motor drive for a three wheeler.

II. System Description

The three-phase BLDC motor operating in a six-state, two-conduction mode is considered for the study. BLDC motor has a wound stator and a permanent magnet rotor assembly. The Hall sensors typically embedded as a part of the motor assembly and gives information on rotor position. The electronic drive Fig. 1 is required to control the stator currents to generate rotating magnetic field in a BLDC motor. It consists of a power stage with three-phase inverter having the required power capability, a MCU to implement the motor control algorithm, a DC-Link current and position feedback from Hall sensors and Power supply for the MCU. 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 forward by controller. The speed loop can eliminate the speed deviation and achieve the constant speed function. 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.

A. Mathematical Modelling

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

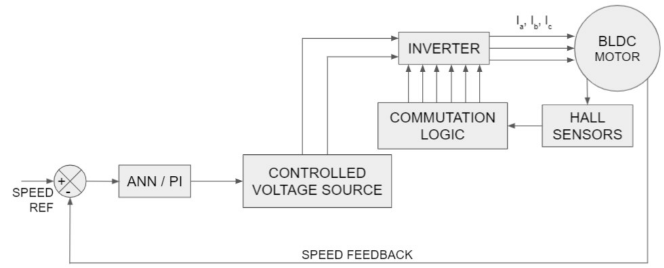


Fig. 1: System Block Diagram

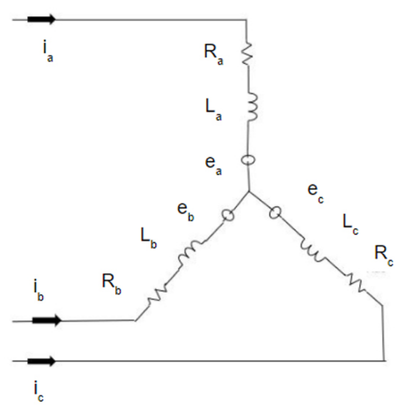


Fig. 2: Equivalent Circuit of BLDC Motor

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. The equivalent circuit representation of BLDC motor drive is shown in Fig. 2. There are three stator winding incorporated with permanent magnet on the rotor. The mathematical modelling of BLDC motor is expressed as :

$$V_{\mathrm{a}} = Ri_{\mathrm{a}} + L\frac{di_{\mathrm{a}}}{dt} + e_{\mathrm{a}} \tag{1}$$

$$V_{\mathrm{b}} = Ri_{\mathrm{b}} + L\frac{di_{\mathrm{b}}}{dt} + e_{\mathrm{b}} \tag{2}$$

$$V_{\mathrm{c}} = Ri_{\mathrm{c}} + L\frac{di_{\mathrm{c}}}{dt} + e_{\mathrm{c}} \tag{3}$$

$R_a = R_b = R_c = R$, 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

$$\begin{bmatrix} V_{\mathrm{a}} \\ V_{\mathrm{b}} \\ V_{\mathrm{c}} \end{bmatrix} = \begin{bmatrix} R+\frac{dL}{dt} & 0 & 0 \\ 0 & R+\frac{dL}{dt} & 0 \\ 0 & 0 & R+\frac{dL}{dt} \end{bmatrix} \begin{bmatrix} i_{\mathrm{a}} \\ i_{\mathrm{b}} \\ i_{\mathrm{c}} \end{bmatrix} + \begin{bmatrix} e_{\mathrm{a}} \\ e_{\mathrm{b}} \\ e_{\mathrm{c}} \end{bmatrix} \tag{4}$$

The back-emfs are :

$$e_{\mathrm{a}} = k_{\mathrm{e}}.\omega.f(\theta) \tag{5}$$

$$e_{\mathrm{b}} = k_{\mathrm{e}}.\omega.f(\theta - \frac{2\pi}{3}) \tag{6}$$

$$e_{\mathrm{c}} = k_{\mathrm{e}}.\omega.f(\theta + \frac{2\pi}{3}) \tag{7}$$

The electrical angle and velocity are given by :

$$\theta_{\mathrm{e}} = \frac{P}{2}.\theta_{\mathrm{m}} \tag{8}$$

$$\omega_{\mathrm{m}} = \frac{d\theta_{\mathrm{m}}}{dt} \tag{9}$$

The torque equations are :

$$T_{\mathrm{a}} = k_{\mathrm{e}}.i_{\mathrm{a}}.f(\theta) \tag{10}$$

$$T_{\mathrm{b}} = k_{\mathrm{e}}.i_{\mathrm{b}}.f(\theta - \frac{2\pi}{3}) \tag{11}$$

$$T_{\mathrm{c}} = k_{\mathrm{e}}.i_{\mathrm{c}}.f(\theta + \frac{2\pi}{3}) \tag{12}$$

$$T_{\mathrm{e}} = T_{\mathrm{a}} + T_{\mathrm{b}} + T_{\mathrm{c}} \tag{13}$$

$$T_{\mathrm{e}} - T_{\mathrm{l}} = J.\frac{d^2\theta_{\mathrm{m}}}{dt^2} + B.\frac{d\theta_{\mathrm{m}}}{dt} \tag{14}$$

Considering the Laplace transform of equation [1] :

$$V_{\mathrm{a}}(s) - e_{\mathrm{a}}(s) = RI_{\mathrm{a}}(s) + LsI_{\mathrm{a}}(s) \tag{15}$$

Rearranging equation [15] we get :

$$\frac{I_{\mathrm{a}}(s)}{V_{\mathrm{a}}(s) - e_{\mathrm{a}}(s)} = \frac{1}{R + Ls} \tag{16}$$

Similarly we can write

$$\frac{I_{\mathrm{b}}(s)}{V_{\mathrm{b}}(s) - e_{\mathrm{b}}(s)} = \frac{1}{R + Ls} \tag{17}$$

$$\frac{I_{\mathrm{c}}(s)}{V_{\mathrm{c}}(s) - e_{\mathrm{c}}(s)} = \frac{1}{R + Ls} \tag{18}$$

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

$$T_{\mathrm{e}} = \frac{i_{\mathrm{a}}e_{\mathrm{a}} + i_{\mathrm{b}}e_{\mathrm{b}} + i_{\mathrm{c}}e_{\mathrm{c}}}{\omega} \tag{19}$$

$$T_{\mathrm{e}} = k_{\mathrm{e}}.i_{\mathrm{a}}.f(\theta) + k_{\mathrm{e}}.i_{\mathrm{b}}.f(\theta - \frac{2\pi}{3}) + k_{\mathrm{e}}.i_{\mathrm{c}}.f(\theta + \frac{2\pi}{3}) \tag{20}$$

$$T_{\mathrm{e}} = J.\frac{d^2\theta_{\mathrm{m}}}{dt^2} + T_{\mathrm{l}} + B.\frac{d\theta_{\mathrm{m}}}{dt} \tag{21}$$

Therefore :

$$V_{\mathrm{a}} = \frac{L}{K}.J.\frac{d^2\omega}{dt^2} + \frac{RJ + LB}{K}.\frac{d\omega}{dt} + \frac{RJ + K^2}{K}.\omega \tag{22}$$

Taking Laplace transform, we get :

$$\frac{\omega(s)}{V_{\mathrm{a}}(s)} = \frac{K}{LJs^2 + (RJ + LB)s + (RB + K^2)} \tag{23}$$

The equation [23] gives the transfer function of the BLDC motor.

B. Vehicle Dynamics

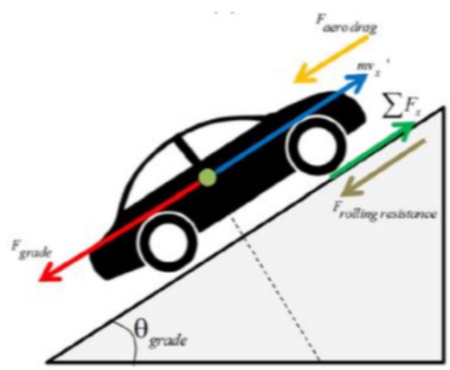


Fig. 3: Resistive Forces on a Vehicle

The BLDC motor rating is decided based on the vehicle dynamics of the three wheeler. There are mainly three resistive forces while a vehicle moves on a plane Rolling Resistance, Aerodynamic Drag, Grade Resistance, Fig. 3.

$$RollingResistance = Cr.M.g.cos\theta \tag{24}$$

$$AerodynamicDrag = 0.5.\rho.v^2.A.Cd \tag{25}$$

$$GradeResistance = M.g.sin\theta \tag{26}$$

The Three Wheeler considered is in reference of Kinetic Safar DX which one of the three wheelers available in the market. As vehicle dynamics have many factors which decides the final performance of the vehicle, series of iterations has to be done and the best performance resulting iteration has to be selected. According to the government norms the maximum speed that a three wheeler can have is 25 km/hr. Two iterations are conducted by considering the vehicle with a gradability of 17.5% (10° slope) and 12.27% (7° slope) for velocity of 5 km/hr. Based on the iterations performed and the availability of the motors, the BLDC Motor of 2 kW is selected with specifications given in Table I.

C. Open Loop Simulation

BLDC motors are six steps electrically commutated. In each step, one phase is positively energized, and one is negatively energized, and the third phase is floating. This commutation can be done using Hall sensors. The hall sensors provide the information to the decoder block for producing the sign of reference current signal vector to the back electromotive force

Parameter	Value
Power	2 kW Continuous
Torque (Continuous Range)	12.5 Nm
Torque (Peak Range)	16.25 Nm
Rated rpm	1500 rpm
Maximum rpm	3000 rpm
Maximum Speed	23.75 km/hr
Maximum Acceleration	1.19 m/s^2
Acceleration (Continuous Range)	0.87 m/s^2
Maximum Slope Angle	9.2°
Maximum Gradability	16.27%
Stator Inductance	9.4 x 10^{-3} H
Stator Resistance	1.43 Ω
Rotor Inertia	0.008 $kg.m^2$
Damping Coeeficient	0.2 Nms/rad
Back EMF Constant	0.513 volt/rad/sec
Poles	4

TABLE I. Motor Parameters

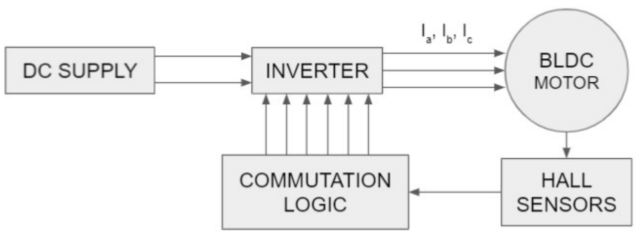


Fig. 4: Open Loop BLDC Motor Drive

(BEMF) Fig. 4. 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. 5 and Table II shows the decoder sequences. The open loop simulation model built using MATLAB with the help of mathematical modelling is shown in Fig. 6.

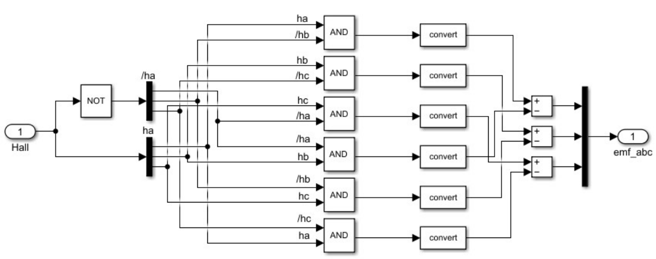


Fig. 5: Back EMF Decoder

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 II. Truth Table for Decoder

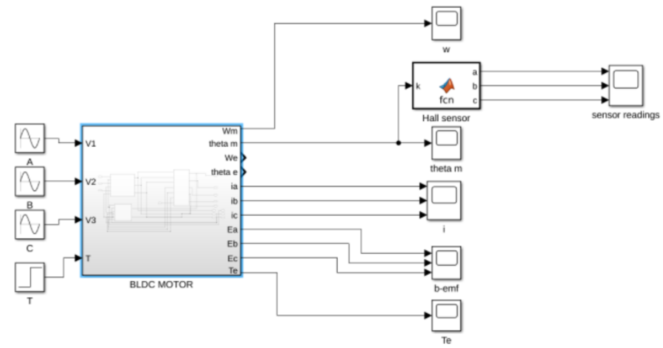


Fig. 6: Open Loop Simulation Model

III. Controller Design

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 employed while controller is in action, is similar to the open loop control. The target of any controller is to minimize the error between the actual output, which is 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 :

$$e(t) = \omega_{\mathrm{sp}}(t) - \omega_{\mathrm{pv}}(t) \tag{27}$$

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.

A. PI - Closed Loop Simulation

The aim of PI controller is to reduce the error between the actual output and the desired output, Fig. 7. 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 K_p. The second part is the integral part, which is the integration of error with time multiplied by a constant gain, which is K_i. The PI controller equation can be expressed as the following :

$$u(t) = K_{\mathrm{p}}e(t) + K_{\mathrm{i}}\int e(t)dt \tag{28}$$

There are four main parameters which should be minimized by the control system, which are rise time, settling time, steady state error and overshoot. 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.

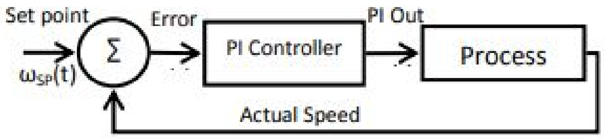


Fig. 7: PI - Closed Loop Control

1) Ziegler Nichols Tuning: 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 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 K_u and oscillation period 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 K_p, K_i values using the Table III. The transfer function relationship between error and controller output is given by :

$$u(s) = K_{\mathrm{p}}(1 + \frac{1}{T_{\mathrm{i}}s} + T_{\mathrm{d}}s) \tag{29}$$

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

$$K_{\mathrm{i}} = \frac{K_{\mathrm{p}}}{T_{\mathrm{i}}} \tag{30}$$

By utilizing the relationships given in the Table III, the final values of K_p and K_i are found for the PI controller, given in Table IV.

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 III. Ziegler Nichols Tuning method

Parameter	**Value**
K_p	0.000000001
K_i	33.4987439489544

TABLE IV. Ziegler Nichols Controller Parameters

2) Genetic Algorithm Tuning: Genetic Algorithm(GA) is a search-based optimization technique based on the principles of Genetics and Natural selection. 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 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.

$$ITAE = \int_0^\infty t|e(t)|dt \tag{31}$$

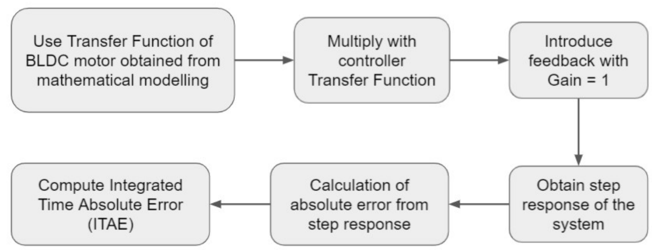


Fig. 8: Fitness Function - Genetic Algorithm

Parameter	**Value**
Solver	ga - Genetic Algorithm
Number of Variables	2
Lower Bound	[0, 0]
Upper Bound	[50, 50]
Population Size	50
Plot Functions	Best fitness, Best individual

TABLE V. Optimtool Parameters

The program written according to Fig. 8 is executed with the help of optimization toolbox with the parameters given in the Table V. The obtained values of K_p and K_i from this process is given in Table VI. The fitness values of population plotted against each generation is shown in Fig. 9 and the step response produced as a result of new PI controller parameters are shown in Fig. 10.

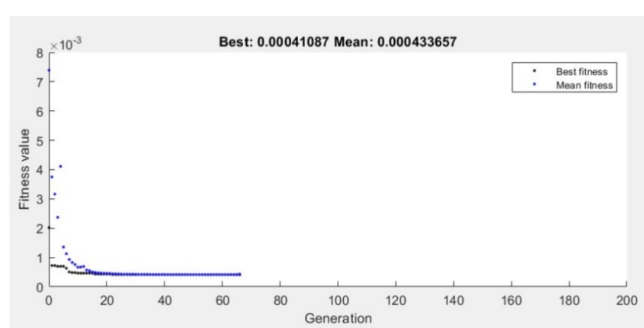


Fig. 9: Fitness Function - Genetic Algorithm

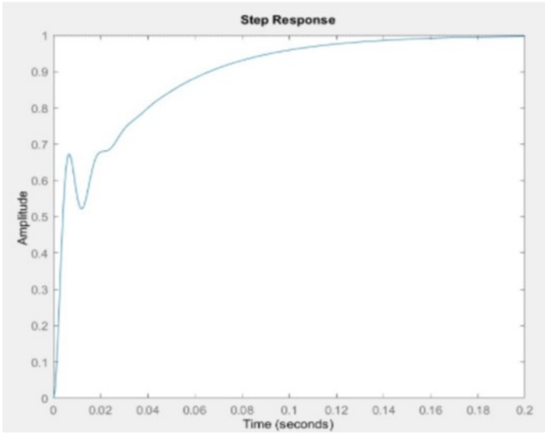


Fig. 10: Fitness Function - Genetic Algorithm

Parameter	Value
K_P	0.2507
K_I	49.4967

TABLE VI. Genetic Algorithm Controller Parameters

The PI closed loop control simulation model built using MATLAB/SIMULINK is shown in Fig. 11.

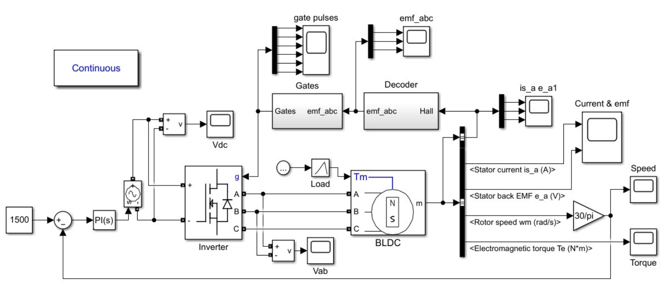


Fig. 11: PI Closed Loop Simulation Model

B. ANN - Closed Loop Simulation

The ANN is like human brain which receives, processes and transmits the information. The structure of ANN has mainly three layers, Fig. 12. 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 it's 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 :

$$Z_j = \Sigma_{j=1}^{n} X_i W_{ij} \tag{32}$$

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.

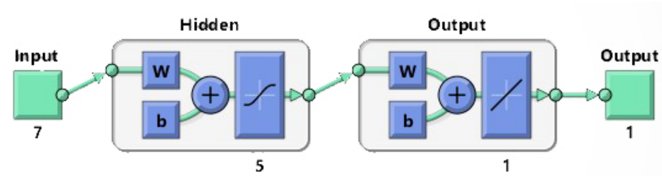


Fig. 12: Neural Network

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.

The parameters related to the training of Artificial Neural Network is given Table VII. The ANN training performance is given in Fig. 13 and the function fitting results are shown in Fig. 14.

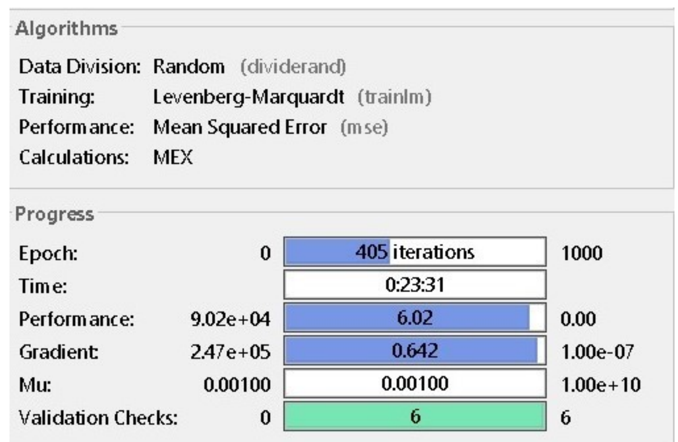
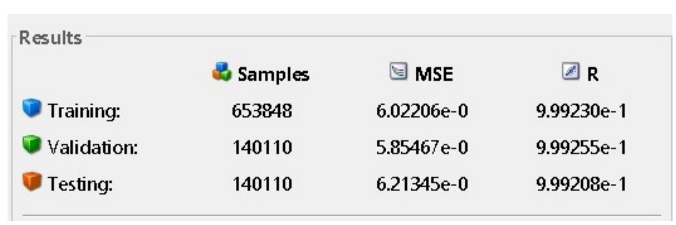


Fig. 13: ANN Training Performance



Results

	Samples	MSE	R
Training:	653848	6.02206e-0	9.99230e-1
Validation:	140110	5.85467e-0	9.99255e-1
Testing:	140110	6.21345e-0	9.99208e-1

Fig. 14: Function Fitting Results

The ANN closed loop control simulation model built using MATLAB/SIMULINK is shown in Fig. 15.

Parameter	Value
Input Layers	7
Hidden Layers	1
Hidden Neurons	5
Training Epochs	1000
Training Algorithm	trainlm
Training Samples	653848
Validation Samples	140110
Testing Samples	140110

TABLE VII. ANN Controller Parameters

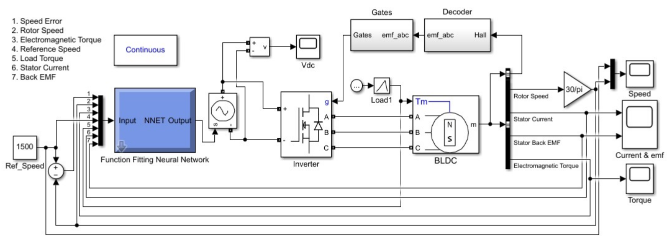


Fig. 15: ANN Closed Loop Simulation Model

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.

IV. Simulation Results

The parameters like rotor speed, electromagnetic torque, stator current, back emf are plotted against time for variation of load torque. For each second, load is increased by 1/4 times the full load from no load to full load.

A. Open Loop Simulation

The results from simulation of Open Loop Control model is given in Fig. 16, 17, 18.

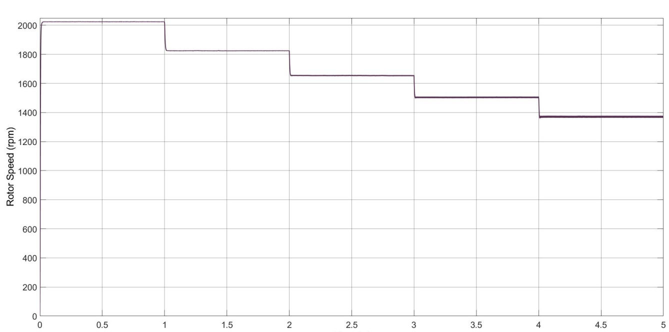


Fig. 16: Speed(rpm) Vs Time(s) Graph

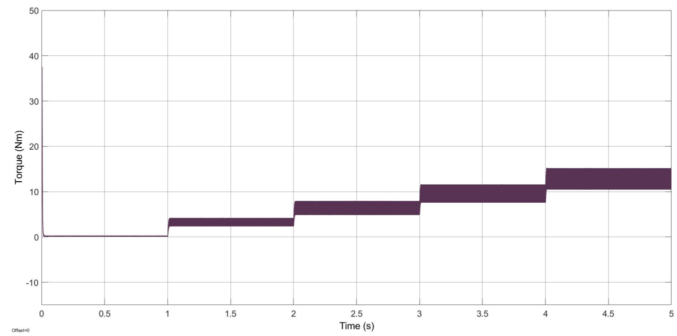


Fig. 17: Torque(Nm) Vs Time(s) Graph

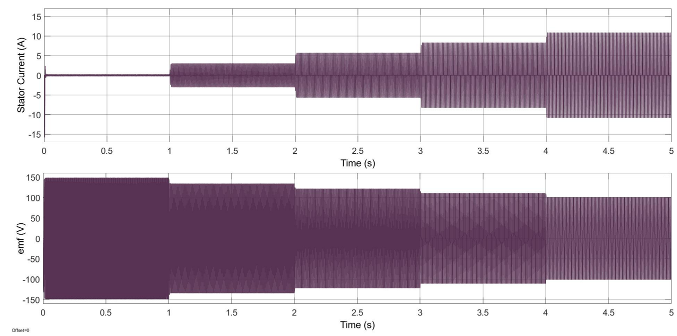


Fig. 18: Stator Current(A) & emf(V) Vs Time(s) Graph

B. PI - Closed Loop Simulation

1) Ziegler Nichols Tuning: The results from simulation by utilizing the K_p, K_i got from Ziegler Nichols tuning method in PI controller is shown in Fig. 19, 20, 21.

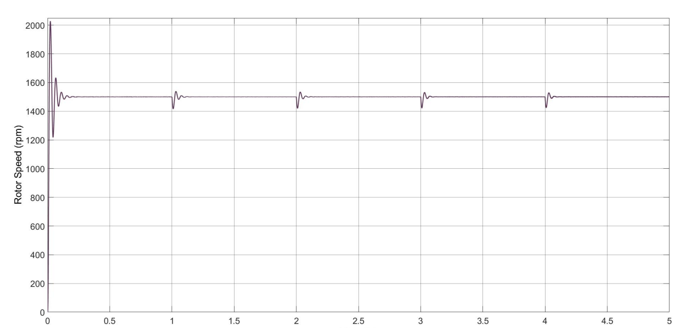


Fig. 19: Speed(rpm) Vs Time(s) Graph

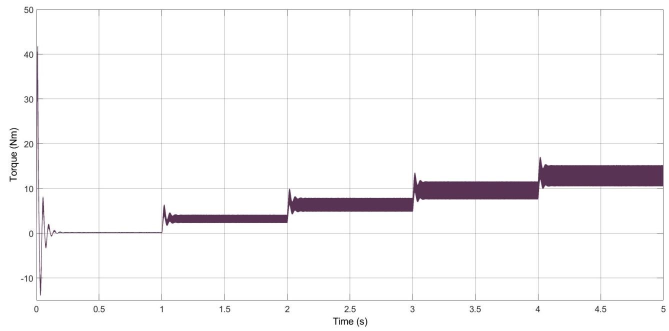


Fig. 20: Torque(Nm) Vs Time(s) Graph

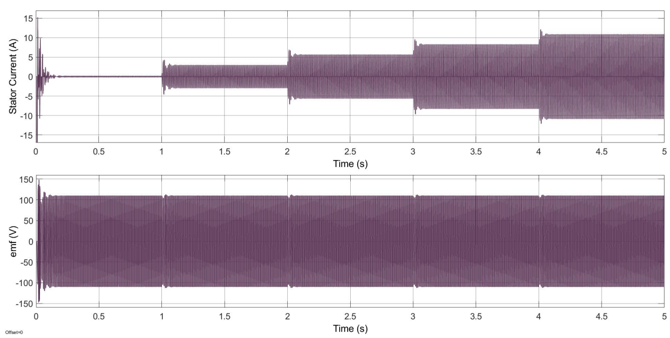


Fig. 21: Stator Current(A) & emf(V) Vs Time(s) Graph

2) *Genetic Algorithm Tuning:* The results from simulation by utilizing the K_p, K_i got from Genetic Algorithm tuning method in PI controller is shown in Fig. 22, 23, 24.

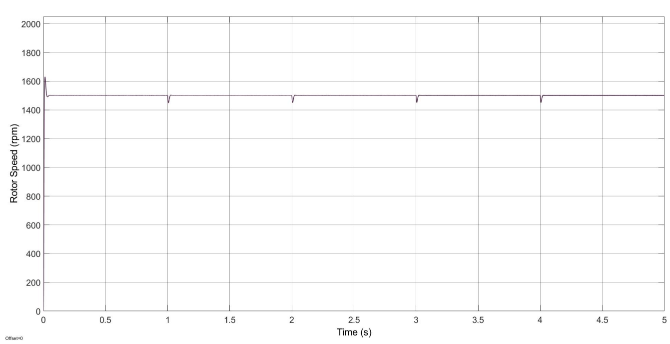


Fig. 22: Speed(rpm) Vs Time(s) Graph

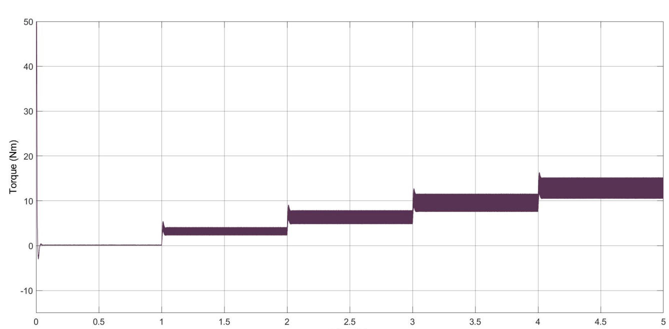


Fig. 23: Torque(Nm) Vs Time(s) Graph

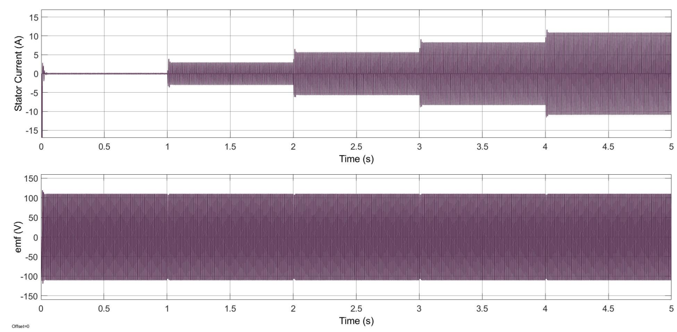


Fig. 24: Stator Current(A) & emf(V) Vs Time(s) Graph

C. *ANN - Closed Loop Simulation*

The results from simulation by replacing the PI controller with ANN controller is shown in Fig. 25, 26, 27.

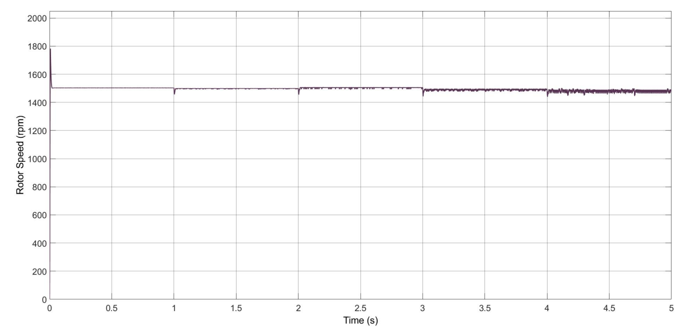


Fig. 25: Speed(rpm) Vs Time(s) Graph

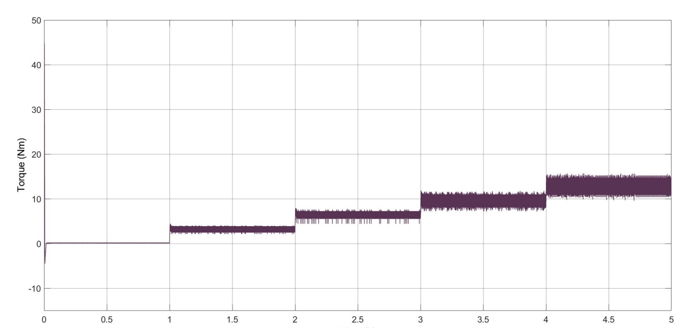


Fig. 26: Torque(Nm) Vs Time(s) Graph

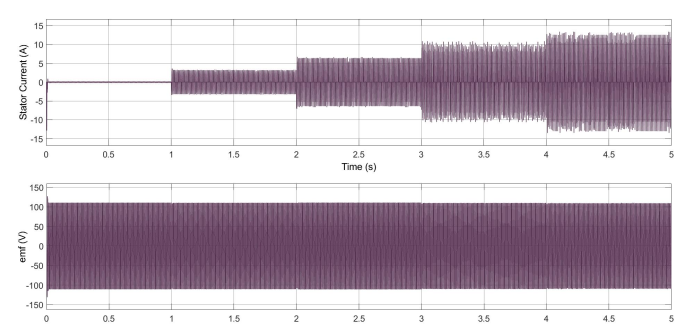


Fig. 27: Stator Current(A) & emf(V) Vs Time(s) Graph

D. Comparison

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

TABLE VIII. Comparison of Controllers - 6.25Nm

V. Conclusion

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.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.

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