Design of Adaptive Neural Fuzzy Controller for Speed Control of BLDC Motors

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ABSTRACT
The purpose of this paper is to design an adaptive neuro-fuzzy controller to control the speed of the BLDC motor. This paper throws overall view of the performance of fuzzy PID controller and compares with fuzzy - adaptive neural controller. Taking suitable characteristics in PID controller is difficult, but fuzzy is has the ability to take appropriate control parameters and calculations easier. An adaptive neuro fuzzy control system has the advantages of both types of fuzzy control system and neuro system. This paper examines the BLDC motor speed control based on adaptive neuro – fuzzy, first by simulating fuzzy PID controller and then designing controller adaptive neuro - fuzzy using ANFIS toolbox for the motor. The characteristics of speed, torque, current and voltage in the three controllers finally are compared and it was concluded that the characteristic of the controller adaptive neuro - fuzzy (ANFIS) is better than the other two controllers.

KEYWORDS: BLDCM, Fuzzy PID Controller, ANFIS.

1. INTRODUCTION

There are mainly two types of dc motors used in industry. The first one is the conventional dc motor where the flux is produced by the current through the field coil of the stationary pole structure. The second type is the brushless dc motor where the permanent magnet provides the necessary air gap flux instead of the wire-wound field poles. BLDC motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal Back EMF waveform shape [1]. As the name implies, BLDC do not use brushes for commutation; instead, they are electronically commutated. Recently, high performance BLDC motor drives are widely used for variable speed drive systems of the industrial applications and electric vehicles [2].

The advantages of this engine can be low weight, low volume, high efficiency, low inertia and high control accuracy. Also BLDCM has desirable physical properties of a conventional direct current motor and may be used in a wide range of industrial applications. Development of modern industry is required to increase the efficiency of BLDC motors and its controller, but each until now involved a lot of engineers and researchers work and study and modeling and simulation, manufacturing and testing [3-7].

In practice, the design of the BLDCM drive involves a complex process such as modeling, control scheme selection, simulation and parameters tuning etc. An expert knowledge of the system is required for tuning the controller parameters of servo system to get the optimal performance. Recently, various modern control solutions are proposed for the speed control design of BLDC motor. However, Conventional PID controller algorithm is simple, stable and has easy adjustment and high reliability. But, in fact, most industrial processes with different degrees of nonlinear, parameter variability and uncertainty of mathematical model of the system. Tuning PID control parameters is very difficult, poor robustness; therefore, it is difficult to achieve the optimal state under field conditions in the actual production. Because of non-linearity of load and changing specification of the machine at different speeds, a fixed controller does not have a good performance at all speeds and it is best to use adaptive controller.

In this study, we improve the performance BLDC motor speed controller using ANFIS. The article is as follows:

In section 2 model of BLDC motors is presented. Section 3 presents an overview of fuzzy PID controller and design of a fuzzy neural adaptive control, Section 4 represents the results of the comparison between the three methods of control and Section 5 presents the results of this method.

2. SPEED CONTROL SYSTEM OF BLDC MOTOR

The complete block diagram of speed control of three phases BLDC Motor is below Fig. 1. Two control loops are used to control BLDC motor. The inner loop synchronizes the inverter gates signals with the electromotive forces. The outer loop controls the motor's speed by varying the DC bus voltage. Driving circuitry consists of three phase power convertors, which utilize six power transistors to energize two BLDC motor phases concurrently. The rotor position, which determines the switching sequence of the MOSFET transistors, is detected by means of 3 Hall sensors mounted on the stator. By using Hall sensor information and the sign of reference current (produced by Reference current generator), Decoder block generates signal vector of back EMF. The basic idea of running motor in opposite direction is by giving opposite current.

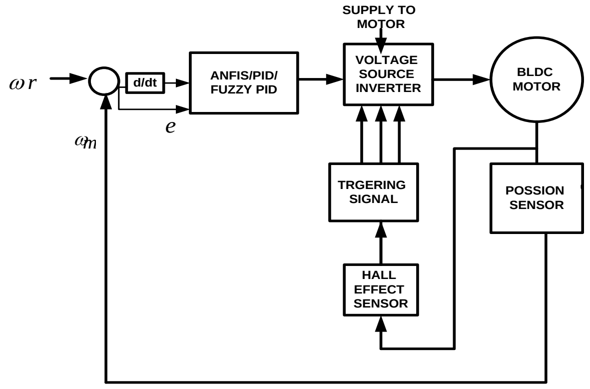


Fig. 1. The block diagram of speed control of the BLDC Motor

2.1 Mathematical model of the BLDC motor drive

The BLDC motor mathematical model can be represented by the following equation in matrix form:

$$\begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (1)$$

Where V_a, V_b and V_c denote phase voltages of the motor. R_a, R_b and R_c represent stator winding resistances. Phase currents of the motor are represented by i_a, i_b and i_c. Self-inductances of the motor winding are represented by L_a‘L_b‘L_c and the mutual inductances between stator windings are denoted by M_{ab}‘M_{ac}‘M_{ba}‘M_{bc}‘M_{ca}‘M_{cb}. Electromagnetic torque can be expressed as follows:

$$T = J\frac{d\omega_r}{dt} + B\omega_r + T_L \qquad (2)$$

- moment of inertia of the rotor: J
- coefficient of friction: B
- Engine speed: $\omega(t)$
- torque load: T_L

Since the electromagnetic torque of 3-phase BLDC motor is dependent on the current, speed and back-EMF waveforms, the equation for instantaneous electromagnetic torque can be modified and represented as:

$$T_{em} = \frac{1}{\omega_m}(e_a i_a + e_b i_b + e_c i_c) \qquad (3)$$

3. CONTROLLER

3.1. Design of Fuzzy PID Controller

Fuzzy PID controller used in this paper is based on two input FLC structure with coupled rules. The overall structure of used controller is shown in Fig. 2. Real interval of variables is obtained by using scaling factors which are Se, Sde and Su. The fuzzy control rule is in the form of: IF $e = E_j$ and $de = dE_j$ then $U_{PD} = U_{PD}(i,j)$. These rules are written in a rule base look-up table which is shown in table.1. The rule base structure is Mamdani type.

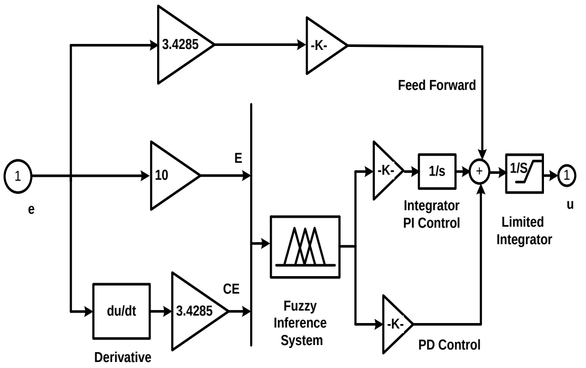
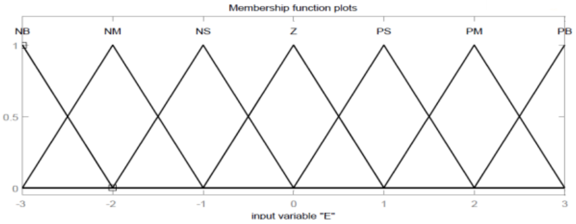
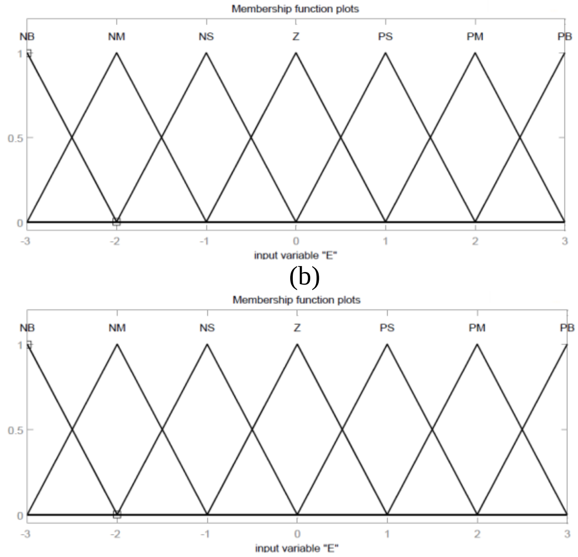


Fig. 2. The Simulation of the Fuzzy PID Controller

FLC has two inputs and one output. These are error (e), error change (de) and control signal, respectively. A linguistic variable which implies inputs and output have been classified as: NB, NM, NS, Z, PS, PM, PB. Inputs and output are all normalized in the interval of [-3,3] as shown in Fig. 3.



(a)



(b)

(c)

Fig. 3. Membership functions of the output

The linguistic labels used to describe the Fuzzy sets were 'Negative Big' (NB), 'Negative Medium' (NM), = 'Negative Small' (NS), 'Zero' (Z), 'Positive Small' (PS), 'Positive Medium' (PM), 'Positive Big' (PB). It is possible to assign the set of decision rules as shown in Table IV. The fuzzy rules are extracted from fundamental knowledge and human experience about the process. These rules contain the input/the output relationships that define the control strategy. Each control input has seven fuzzy sets so that there are at most 49 fuzzy rules.

Table 1. Table of fuzzy role

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

3.2. Design of Adaptive Neuro-Fuzzy controller (ANFIS)

The general ANFIS control structure contains the same components as the FIS except for the neural network block. The structure of the network is composed of set of units (and connections) arranged in five connected network layers, i.e., layer 1 to layer 5. The proposed ANFIS controller structure consists of four important blocks that are fuzzification, knowledge base, neural network and the Defuzzification. Fuzzy system has 49 roles that ANFIS system reduced this amounts to 2. It is assumed that the fuzzy inference system under consideration has two inputs x, y and one output z=f(x,y),where x=e is error input and y=de is Ratio error variations. The rule base contains the fuzzy if-then rules of Takagi and Sugeno's type as follows that for a first order two rule Sugeno fuzzy inference system, the two rules may be stated as:

Rule 1: if x is A_1 and y is B_1 then:

$$f_1 = P_1 e + R_1 \Delta e + s_1 \tag{4}$$

Rule 2: if x is A_2 and y is B_2 then:

$$f_2 = P_2 e + R_2 \Delta e + s_2 \tag{5}$$

Where

$$e = \omega_{ref} - \omega_r \tag{6}$$

$$\Delta e = \frac{d(\omega_{ref} - \omega_r)}{dt} \tag{7}$$

$$f_i = P_i e + R_i \Delta e + s_i \tag{8}$$

ω_{ref} Reference speed, Then the performance of this system of ANFIS controller can be displayed as shown in Figure 5.

$$f_1 = P_1 e + R_1 \Delta e + s_1 \tag{9}$$

$$f_2 = P_2 e + R_2 \Delta e + s_2 \tag{10}$$

$$f = \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2} = \bar{w}_1 f_1 + \bar{w}_2 f_2 \tag{11}$$

Weights of the W_1 and W_2 in Figure 4 are usually obtained as the product of the degrees of membership of preceding section and the output f weighted average output of any law or rule [8-11].

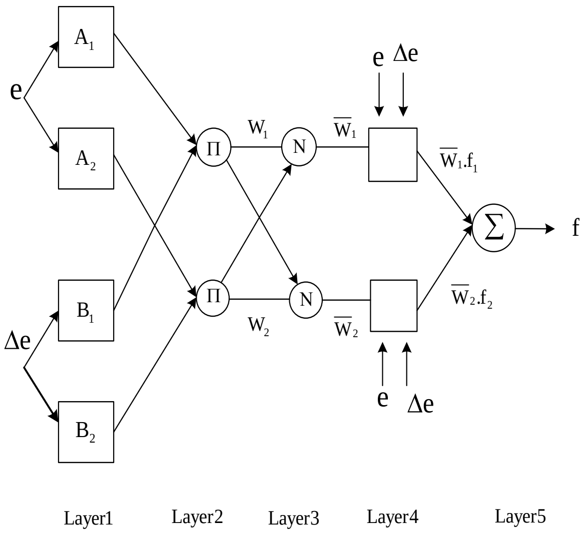


Fig. 4. The structure of ANFIS controller

The network structure is composed of 5 layers connected together with the notations $L_{1,i}$ for the output node i from layer 1 of the 5 layers, ANFIS model can be described as follows.

Layer 1: Every node i in this layer is adaptive with a node function:

$$L_{1,i} = \mu_{A_i}(e) \qquad (12)$$

$$L_{1,i} = \mu_{B_{i-2}}(\Delta e)$$

Where e and de are input to a node and A_i and B_{i-2} are assigned fuzzy function to the node.

Layer 1 is consisting of the input variables (membership functions). Membership functions can be defined as a triangular form or Gaussian, and so on. For example, Ai can be membership by Gaussian function parameters as follows:

$$\mu_{A_i}(e) = \frac{1}{1+\left[\left(\frac{e-c_i}{a_i}\right)^2\right]^{b_i}} \qquad (13)$$

Layer 2: Each node in this layer is a fixed node which calculates the firing strength w_i of a rule. The output of each node is the product of all the incoming signals to it and is given by,

$$L_{2,i} = W_i = \mu_{A_i}(e)\mu_{B_i}(\Delta e) \qquad (14)$$

Layer 3: Every node in this layer is a fixed node. Each i^{th} node calculates the ratio of the i^{th} rule's firing strength to the sum of firing strengths of all the rules. The output from the i^{th} node is the normalized firing strength given by,

$$L_{3,i} = \overline{W}_i = \frac{W_i}{W_1+W_2} \qquad (15)$$

i=1,2

Layer 4: Every node in this layer is an adaptive node with a node function given by

$$L_{4,i} = \overline{W}_i * f_i = \overline{W}_i.(P_i e + R_i \Delta e + s_i) \qquad (16)$$

i=1,2

Where $\overline{W}_i$ is the output of Layer 3 and $\{P_i, R_i, s_i\}$ is the consequent parameter set.

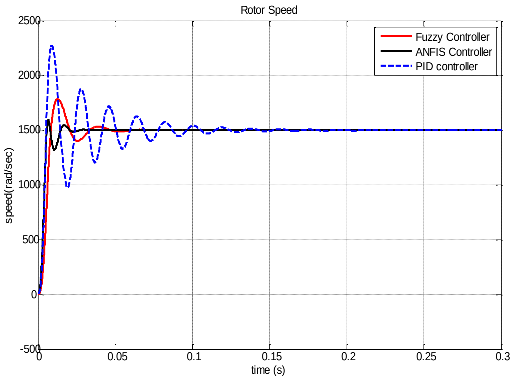
Layer 5: This layer comprises of only one fixed node that calculates the overall output as the summation of all incoming signals, i.e.

$$L_{5,i} = \sum_i \overline{W}_i.f_i = \frac{\sum_i W_i f_i}{\sum_i W_i} \qquad (17)$$

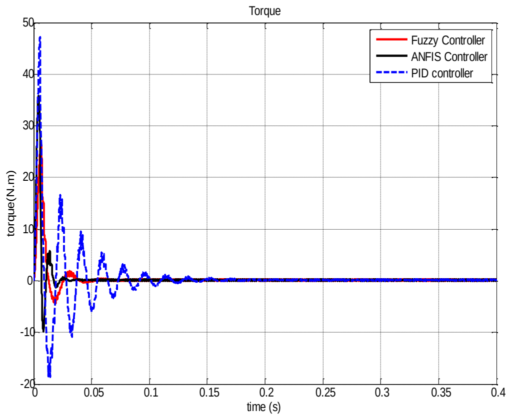
The base fuzzy designed motor system is done with the way of sub-clusters. Then fuzzy system using hybrid was trained to the number of laws and other functions and adjustable parameters determine the fuzzy system. To train ANFIS controller, network offline is trained using simulation toolbox.

4. SIMULATION RESULT AND DISCUSSION

Fig. 5 and 6 represent the performance of the ANFIS controller, Fuzzy PID controller and Conventional PID Controller of BLDC Motor on Reference speed of 1500rpm with no load condition and when the load of 5 N.m is applied to BLDC motor, (a) speed and (b) Torque. The results show that conventional PID controller reach settling time is 0.15 sec and fuzzy PID controller reaches the settling time in 0.10 sec, but in ANFIS controller reach settling time is less than 0.05 sec.

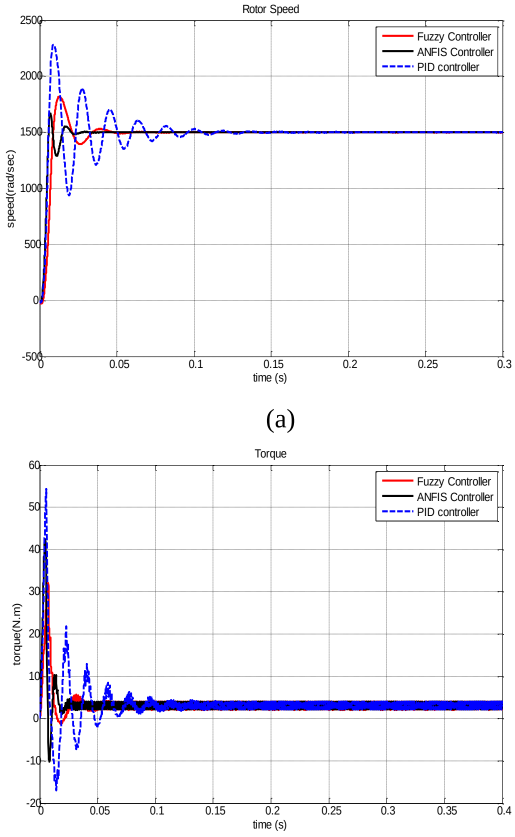


(a)



(b)

Fig. 5. The reference speed of 1500 rpm with no load (a) Speed and (b) Torque

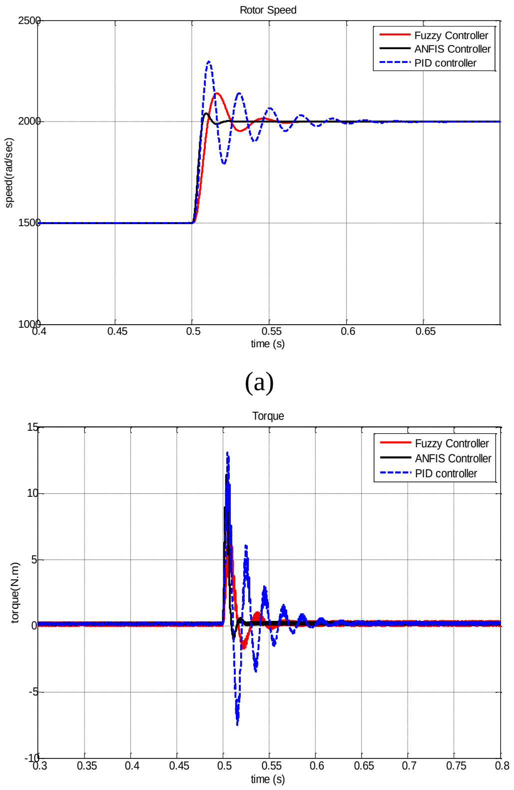


(a)

(b)

Fig. 6. The reference speed of 1500 rpm with load (a) Speed and (b) Torque

Fig. 7 shows the performance of three controller of BLDC Motor on Step up speed of 1500 - 2000rpm with no load condition of (a) speed and (b) Torque. The results show that conventional PID controller reach settling time is 0.15 sec and in fuzzy PID controller reach settling time is 0.10 sec, but ANFIS controller reaches the settling time in less than 0.05 sec.

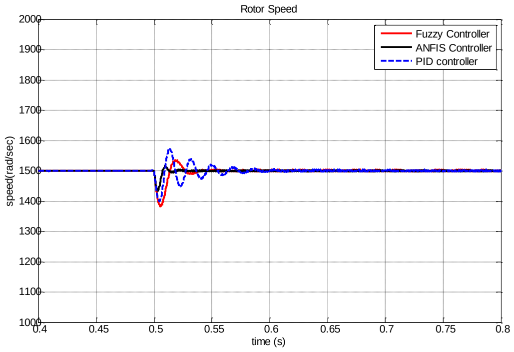


(a)

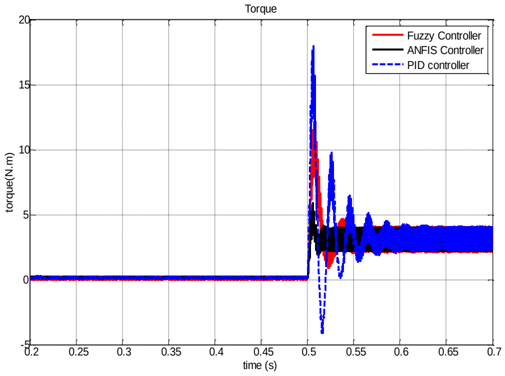
(b)

Fig. 7. Step up speed of 1500 - 2000 rpm with no load (a) Speed and (b) Torque

Fig. 8 shows the performance of the ANFIS controller, Fuzzy PID controller and Conventional PID Controller of BLDC Motor on Reference speed of 1500rpm when the load of 5 N.m is applied to BLDC motor in 0.5 sec (a) speed and (b) Torque. The load of 5 N.m is applied to BLDC motor, the results show that conventional PID controller reach settling time is 0.12 sec and in fuzzy PID controller reach settling time is 0.05 sec, but ANFIS controller reaches the settling time in less than 0.025 sec.



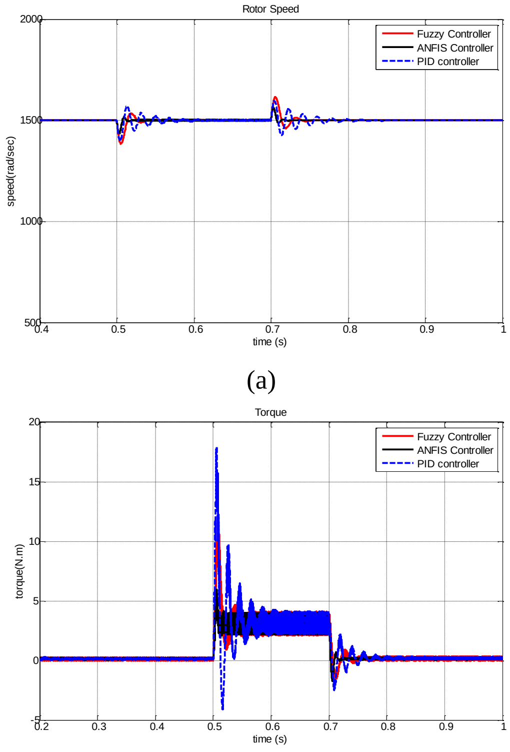
(a)



(b)

Fig. 8. The reference speed of 1500 rpm with load in 0.5 sec (a) Speed and (b) Torque

Fig. 9 shows the performance of the ANFIS controller, fuzzy PID controller and Conventional PID Controller of BLDC Motor on speed of 1500rpm with load impact condition of (a) speed and (b) Torque. During running conduction of BLDC motor, suddenly the load of 5 N.m is applied at time of 0.5 sec and released at 0.7 sec. The results show that conventional PID controller reach settling time is 0.12 sec and in fuzzy PID controller reach settling time is 0.05 sec, but in ANFIS controller reach settling time is less than 0.025 sec.



(a)

(b)

Fig. 9. The reference speed of 1500 rpm with load impact (a) Speed and (b) Torque

And in Figures 10 and 11 we can see that the current and voltage fluctuations in adaptive neural fuzzy controller are much less than the other two controllers when a disturbance applied to the motor in 0.5 seconds.

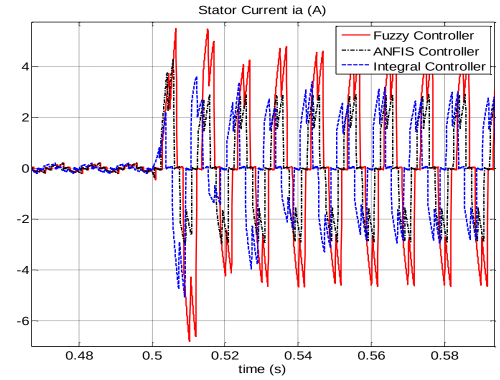


Fig. 10. The flow graphs with perturbation to the motor in 0.5 seconds

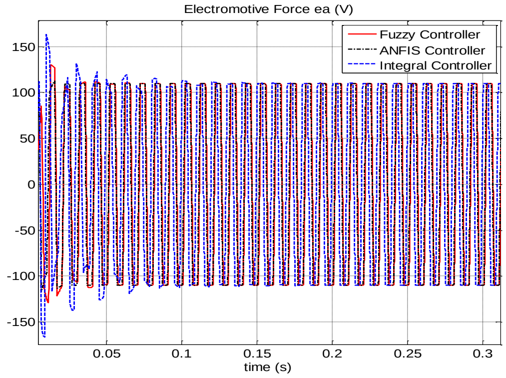


Fig. 11. The voltage graph

5. CONCLUTION

This paper presents simulation results of conventional PID controller and Fuzzy PID controller and ANFIS controller of three phase BLDC motor. Regarding to the results obtained from simulation, it was confirmed that for the same operation condition the BLDC speed control using ANFIS controller technique had better performance than Fuzzy PID controller and conventional PID controller, mainly when the motor was working at lower and higher speeds. In addition, the motor speed is constant when the load varies.

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