ANFIS Based Speed Control of BLDC Motor with Bidirectional DC-DC Converter

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Abstract—In this paper we have designed Adaptive Neuro fuzzy Inference System (ANFIS) controller for the speed control of bidirectional brushless DC motor (BLDC). The fuzzy models under the framework of adaptive networks are called Adaptive Neuro Fuzzy Inference System. The ANFIS controller is used in three phase BLDC Motor drive system to control the four quadrants operations without loss of power. In this process energy is conserved during the regenerative period and storage of excess energy in battery takes place during regenerative braking. The bidirectional DC-DC converter is used for the battery charging and discharging purpose. The bidirectional dc-dc converter can be operated in buck-boost mode. The stored energy in the battery provides power to the BLDC motor in motoring mode, while during regenerative braking mode the energy is fed back to the source by the same bidirectional buck-boost converter. The simulation will be done for Brushless DC motor with ANFIS controller using MATLAB/Simulink software the effectiveness of the proposed ANFIS controller is compared with that of the fuzzy controller.

Keywords—BLDC motor, bidirectional DC-DC converter, Fuzzy logic controller, ANFIS controller, Artificial neural network, Fuzzy inference system, four quadrants, battery.

I. INTRODUCTION

The bidirectional dc-dc converter which is also known as buck boost converter has many applications such as controlled battery charging. These buck boost converter are being used to achieve power transfer between two dc power sources in both direction [1]. The dc-dc converter can be categorized in to buck, boost and buck boost types and they are of low cost, compact in size and reliable operation. In this paper a bidirectional dc-dc converter will be developed to control power flow between the battery and BLDC motor, hence the desired control variables are both output current and voltage. The bidirectional buck-boost converters are applicable in energy storage based on battery applications. From this deduction it can be concluded that the best selection of DC–DC converter BLDC motor system is the buck–boost DC–DC converter since it gives optimal operation irrespective of the load value [2].

Brushless DC (BLDC) motors are more popular in industrial and traction applications. BLDC motor has less inertia, hence it is easier to start and stop the motor. The BLDC motor is operates on trapezoidal voltage pulses and they are coupled with the given rotor position. To obtain maximum torque voltages pulses must be properly align in the phases and the angle between the stator flux and the rotor flux is almost 90\degree. The actual rotor position of BLDC motor can be detected with or without sensors to sense the position of rotor in this paper rotor position is detected by hall sensor. The electric machine is operated in the motor mode on acceleration command. Output torque of BLDC motor is controlled by a voltage source inverter (VSI) by adjusting the direction and amplitude of the phase current. If the input phase voltage is in phase with back EMF, motoring torque is developed and when the input current is out of phase with back EMF, braking torque is developed. The regenerative braking refers to charge a battery using back EMF voltage of the motor.

In this paper ANFIS controller is used for controlling the speed of brushless DC motor using bidirectional converter.

The main difference resides in the control technique, which is much simpler for the BLDC motors [13]. BLDC motor has a wide range of speed hence speed control is very important issue for it. The efficient speed control mechanism for the motor is done using meaningful fuzzy sets and rules.

ANFIS is the combination of both neural networks and fuzzy logic principles. Neural networks are supervised learning algorithms which utilize a past experienced dataset for the prediction of future values. In fuzzy logic, the control signal of BLDC motor is generated from firing the rule base. This rule base is drawn on past experienced data which is random in nature. This implies that the controller's output is also random which may prevent optimal results. But if we use ANFIS it can make the selection of the rule base more adaptive to the load condition on BLDC motor. In this technique, the rule base is selected utilizing the neural network techniques through the back propagation algorithm. To enhance its applicability and performance, the properties of fuzzy logic is harnessed in this ANFIS technique, by approximating a non-linear system through setting IF-THEN rules. This integrated approach, makes ANFIS to be a universal estimator.

II. METHODOLOGY

A. Bidirectional DC-DC Converter

A bidirectional buck-boost converter is shown in figure 1 MOSFET or IGBT is used instead of diode to switch the operation of circuit in both mode i.e. motoring and...
regenerative braking. The bi directional DC-DC converter can either operate as a Buck converter by stepping down a higher voltage to a lower voltage or as a Boost converter by stepping up from a lower voltage to a higher voltage. Diodes do not allow current to flow in both directions, but with MOSFET the period of each position can be easily controlled [4].

The kinetic energy is wasted as heat energy in previous methods but in this method the conversion of kinetic energy into electric energy which is rectified and stored in a chargeable battery in automotive applications DC/DC converters allow the power flow between two voltage sources [5]. To accomplish this power transfer the current flow must go through the circuit in both directions. Since battery implies the capacity of charging and discharging so the use of a bidirectional converter allows avoiding a complex system of twin circuits to accomplish the charge and discharge of the battery.

The battery need to be charged and discharged via bidirectional DC-DC power converter. The battery must be able to supply power to the BLDC motor drive. The brushless motor can operate in all four quadrants. The excess energy created during regenerative braking condition is stored in the battery.

The brushless motor is controlled using a fuzzy logic controller. The difference between the actual speed and reference speed determine the error. The error signal is generated according to the variation in the reference speed and the actual speed of the motor which is sensed by the hall signal utilized for the formulation of fuzzy rules. ANFIS is used to construct a set of fuzzy if-then rules with appropriate membership functions to generate the gate signals to drive the switching circuit [6].

C. Four Quadrant Control Operations

There are four possible modes of operation in a three phase Brushless DC Motor. we get high value of supply vortage than the back EMF when motor operates in first and third quadrant that is forward motoring and reverse motoring mode respectively [7]-[8]. But the direction of current differs. When the motor operates in the second and fourth quadrant that is forward braking and reverse braking modes respectively, the value of the back EMF generated by the motor should be greater than supplied voltage and the direction of current flow is reversed.

D. Modelling Of BLDC Motor

BLDC motor has better characteristics and performance therefore it is very popular [10]. The stator windings are star connected to an internal neutral point. The rotor is non-salient pole type with trapezoidal flux pattern in the air gap .By Hall
Effect sensor Hall signals and actual rotor speed are obtained as output from the motor. The mathematical model of the motor is developed based on the assumption as shown in figure 4.

Fig.4.: Equivalent circuit of brushless motor

The phase A terminal voltage with respect to the starpoint of the stator $V_{an}$ is given in as,

$$V_a = R_aI_a + L\frac{di_a}{dt} + e_a$$

(1)

Where,

- $R_a$ = Stator resistance of phase ‘A’
- $I_a$ = Phase current
- $L$ = Inductance
- $e_a$ = Back EMF

Similar equation can be written For the other two phase,

$$V_b = R_bI_b + L\frac{di_b}{dt} + e_b$$

(2)

$$V_c = R_cI_c + L\frac{di_c}{dt} + e_c$$

(3)

In three phases BLDC motor, we can represent that back EMF as a function of rotor position and it is clear that the Back EMF of phase has 120° shift in phase angle.

$$E_a = K\omega f(\theta_e)\omega$$

(4)

$$E_b = K\omega f(\theta_e - \frac{2\pi}{3})\omega$$

(5)

$$E_c = K\omega f(\theta_e + \frac{2\pi}{3})\omega$$

(6)

$K\omega f$ - Per phase back EMF constant (V/rad s$^{-1}$)

$\theta_e$ - Electrical rotor angle (rad)

$\omega$ - Rotor speed (rad/sec)

The electromagnetic torque is given by,

$$T_e = \frac{e_{a_1}I_a + e_{b_1}I_b + e_{c_1}I_c}{\omega}$$

(7)

The mathematical torque is given by,

$$T_m = J\frac{d\omega}{dt} + B\omega + T_L$$

(8)

Where

$e_a, e_b, e_c$ = Back-EMF of phase a, b and c

B = Damping constant

J = Rotor inertia

$T_L$ = Load torque.

E. Fuzzy Inference System

Fuzzy inference systems are also known as fuzzy-rule-based systems, fuzzy controllers when used as controllers. Basically a fuzzy input output inference system is composed of five functional blocks as shown in figure 5

Fig.5.: Fuzzy inference system

Fuzzy logic controller consist of knowledge base, fuzzification, inference system, and defuzzification. The knowledge base is consist of a data and a rule base. The data base consist of input and output variable’s membership functions, that provides information for the appropriate fuzzification operations. The rule base consist of a set of linguistic rules relating the fuzzy input variables into the desired fuzzy control actions. The fuzzy logic control is designed using the fuzzy inference systems (FIS) with the defined input and output membership functions. The fuzzy sets and rules are designed and accordingly the motor can be controlled [11]-[12]. The inputs for fuzzy logic controller are the speed error (e) and change in speed error ($\Delta e$). Speed error is calculated with comparison between reference speed and the actual speed Fuzzy rule has $7 \times 7$ decision table with two input variables and one output variable [13]. The look up table with the input and output rules defined with seven linguistic variables are as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB) respectively are given in table I.

<table>
<thead>
<tr>
<th>Table 1: Fuzzy Rule Base</th>
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<td>$e$</td>
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F. ANFIS: Adaptive Neuro Fuzzy Inference System

An adaptive network consists of adaptive nodes which are connected through directional links. Adaptability means each output of these nodes depends on the parameter(s) related to this node and the learning rule describe how these parameters should be changed to minimize a prescribed error measure [14].

![Fig 6: Adaptive Neural Network](image)

The basic learning rule of adaptive neural networks is based on the gradient descent and back propagation algorithm is used for this purpose. Fuzzy logic control (FLC) is a great tool to deal with complicated, non-linear and sophisticated systems. Artificial neural network (ANN) has the powerful capability for learning, adaptation, robustness and rapidity. In ANFIS has advantage of both FLC and ANN. ANFIS is a class of adaptive networks that is functionally equivalent to fuzzy inference system. This control methodology solves the problem of non-linearity and parameter variations of BLDC drive. In this section ANFIS is designed for BLDC motor. The adaptive neural network, shown in figure 6 is a multilayer feed forward network in which each node performs a particular function (node function) on incoming signals as well as a set of parameters pertaining to this node. The formulae for the node function may vary from node to node.

Consider a sugeno type of fuzzy system having the rule based.

i. If x is $A_1$ and y is $B_1$, then $f_1 = p_1 x + q_1 y + r_1$
ii. If x is $A_2$ and y is $B_2$, then $f_2 = p_2 x + q_2 y + r_2$

If the triggering strengths of the rule are $w_1$ and $w_2$ respectively, for the particular values of $A_i$ and integral of $B_i$, then the output computed as weighted average,

$$f = \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2} \quad (9)$$

Let the membership function of fuzzy sets $A_i, B_i$, i=1,2, be $\mu A_i$ and $\mu B_i$.

Layer 1: Each neuron “i” in layer 1 is adaptive with a parametric activation function. Its output is the grade of membership function.

$$\mu(x) = \frac{1}{1 + [(x-a)/c]^2} \quad (10)$$

Where [ a, b, c] is the parameter set. As the values of the parameters change, the shape of the bell-shape function varies.

Layer 2: Every node in layer 2 is a fixed node, whose output is the product of all incoming signals

$$W_i = \mu A_i(x) \mu B_i(y), \; i=1,2 \quad (11)$$

Layer 3: This layer normalizes each input with respect to the others (The $i^{th}$ node output is the $i^{th}$ input divided the sum of all the other inputs).

$$\overline{W_i} = \frac{w_i}{w_1 + w_2} \quad (12)$$

Layer 4: Fourth layer’s $i^{th}$ node output is a linear function of third layer’s $i^{th}$ node output and the ANFIS input signals

$$\overline{w_i f_i} = \overline{w_i} (p_i x + q_i y + r_i) \quad (13)$$

Layer 5: This layer sums all the incoming signals

$$f = \overline{f_1 W_1 + f_2 W_2} \quad (14)$$

![Fig. 7: ANFIS Layer](image)

Below Figure shows proposed sugeno’s fuzzy inference system which is designed with 49 fuzzy rule with 7 linguistic variables.

![Fig.8- proposed system](image)

![Fig. 9: membership function for speed error (e)](image)
III. SIMULATION RESULTS AND DISCUSSION

Above figure shows simulation diagram of proposed speed control of BLDC motor with ANFIS Controller. In this work the drive model with fuzzy speed controller is developed and simulated, first and then ANFIS.

Experimental results are recorded for the same motor using proposed ANFIS system Simulink model in Matlab. Figures 12 and 13 show simulated results. The transient and steady state responses are obtained for a 3 phase, 24 V, 4-pole, 1500 rpm, 10.6 A, motor. For moment of inertia \(48e^{-7}\text{Kg-m}^2\) it reaches the steady state torque and speed suddenly at time of starting and for the step of 0.2 sec it has peak up to 0.207 sec which is transient condition and again it reach to its steady state. Two input variables which are speed error and change in speed error obtained using fuzzy logic controller is fed as the input of layer 1 in ANFIS structure and trained in Matlab simulation software. The resultant membership functions for speed error and change in speed error (trained membership function)

ANFIS has the neural network’s ability to classify data and find patterns. ANFIS system develops a fuzzy expert system that is more transparent to the user and also minimise error than single neural network. ANFIS has the advantages of a fuzzy expert system, which is used to remove the need for an expert. The problem with ANFIS design is that large amounts of training data require developing an accurate system. Figure 12 and 13 show the speed and torque responses. The speed curve does not show any overshoot and proves the success of the designed ANFIS controller. The ANFIS analyse the behaviour of the drive system and compare the actual performance with desired reference track. The learning algorithm modifies the ANFIS to more closely match the desired system behaviour.
IV. CONCLUSIONS

In this paper, ANFIS control scheme for the speed control of Brushless motor using bidirectional converter is proposed. In braking modes of operation, instead of wasting kinetic energy it can be stored in a battery. The excess energy is effectively stored in the battery based on the mode of operation of the bidirectional converter. Simulation studies were conducted to evaluate the performance of fuzzy controller and ANFIS Controller logic based speed control method. The advantages of this proposed method are excellent speed control irrespective of load variation, smooth transition between the quadrants and efficient conservation of energy.

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