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Rotor Position Control of Brushless DC Motor using Adaptive Neuro Fuzzy Inference System

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Abstract: In this paper, Adaptive Neuro Fuzzy Inference System (ANFIS) based rotor position controller is developed for Brushless DC (BLDC) motor. The rotor position control of BLDC motor is simulated using MATLAB. The rotor position response of the BLDC motor with proposed ANFIS controller is considered for step and ramp reference input. The effectiveness of the proposed controller performance is compared with Proportional Integral Derivative (PID) controller and Fuzzy PID controller. The proposed controller is able to solve the problem of nonlinearities and uncertainty due to reference input changes of BLDC motor and confirm the fast and accurate rotor position response with a extraordinary stable state performance. Also, experimental hardware results are developed to reveal effectiveness of the proposed control scheme.

Key words: BLDC Motor · Proportional Integral controller · Fuzzy PID controller · ANFIS controller · dsPIC30F2010 microcontroller

INTRODUCTION

Generally there are two types of dc motor in the industrial they are brush dc motor and brushless dc motor. The first type is the conventional brush dc motor where the flux generated by the current through the field coil of the stator. The second type is brushless dc motor (BLDCM) where the permanent magnet rotate around a fixed armature, eliminating problems associated with connecting current to the moving armature. An electronic controller replaces the brush/commutator assembly of the brushed DC motor, which continually switches the phase to the windings to keep the motor turning. The electronic commutation made it has high efficiency, less vibration, less noise on the use at high speed, has a long age use and low maintenance costs. Currently brushless dc motor has been used widely in industrial applications, robotics, medical applications and in automotive [1-3]. There are several research projects that have been done related to brushless dc motor speed control are, in [4], Fuzzy Adaptive Control based speed controller is developed for Brushless DC Motor Speed. a comparison results of a brushless dc motor speed control with PID and Fuzzy PID is presented. In [5], implementation of Food Processor Application Using Brushless DC Motor Control has been developed. Also discussed about the PI control method application on brushless dc motor speed control, then the testing done by the swivel test CW - CCW and braking test. In [6], Fuzzy Logic Control of In-Wheel Permanent Magnet Brushless DC Motor is developed. Comparison of control wheel speed permanent magnet brushless dc motor using fuzzy control and PID control. The experiment results are obtained by measure the current, voltage and power of the motor dc. In [7], digital PWM control scheme has been implemented for the speed control of BLDC motor. But this controlling technique is more complex and it need precise model of the system.

An off-line identification of parameters of a PI controlled BLDC motor model has been cited in [8] and the identified model has produced more oscillations and larger steady error. Direct self control and proportional integral based speed controller has been implemented for BLDC motor [9]. But, it has produced more oscillations in torque response and uncertainty problem due to load disturbance as well as in set speed variations. In [10], digital control of BLDC motor with PI speed control has

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been developed. Gain values of proportional integral control have been determined by trial and error method. Most of the time, trial and error method could not give optimal result and also consumes more time. In [11], classical PID controller in parallel with fuzzy PID controller for speed control of BLDC motor has been discussed. But speed response has more overshoot and steady state error. Fuzzy logic based sliding mode controller has been developed for the BLDC motor [12]. Fuzzy logic controller clearly outperforms PID controller but the controller has uncertainty problem due to load variations. In [13], adaptive fuzzy logic controller has been developed for speed control of BLDC motor. Although it performs well, the controller has complex structure i.e., it combines two structure namely fuzzy PI and Fuzzy PD controller. Also it has produced uncertainty problem due to set speed variations.

In [14], single neuron PI controller has been developed for the speed control of the BLDC motor. It has produced large overshoot and large steady state error in the speed response. In [15], locally recurrent global forward neural network has been employed to model the BLDC motor speed control system. A global sliding mode control scheme employing neural networks has been developed for rotor position control of BLDC motor [16]. But the controller has produced larger steady state error in the rotor position. In [17], hybrid PI and Neuro fuzzy controller has been implemented for the BLDC motor. The speed response has larger overshoot and oscillations. In [18], comparative analysis between PI controller, Fuzzy logic controller and ANFIS controller for the speed control BLDC motor is described. It is made clear that, ANFIS controller outperforms the PI and Fuzzy logic controller under all operating conditions. The objective of the paper is given by, design of rotor position controller for BLDC motor using Adaptive Neuro-Fuzzy Inference System, the simulation of rotor position controlled BLDC motor using PID, Fuzzy PID and proposed ANFIS controller and implementation of proposed ANFIS controller for BLDC motor using dspic30F2010 microcontroller. The paper is organized as follows: Modeling of the BLDC motor in brief and rotor position controller concept is outlined in section 2. Adaptive Neuro-fuzzy inference system based rotor position controller is presented in section 3 and section 4 discusses simulation results. Experimental set up results are discussed in section 5. Concluding remarks is outlined in section 6.

Modeling and Rotor Position Control of BLDC Motor: The BLDC motor mathematical model can be represented by the following equation (1) in matrix form,

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

where, V_a, V_b and V_c denotes phase voltages of the motor. R_a, R_b and R_c represents 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 and L_c and the mutual inductances between stator windings are denoted by M_{ab}, $M_{ac,}$ M_{ba}, M_{bc}, M_{ca} and M_{cb} respectively.

The electromechanical torque is expressed as;

$$T_{em} = J\frac{d\omega_r}{dt} + B\omega_r + T_L \tag{2}$$

where, J, B and ω_r denotes the moment of inertia, frictional coefficient and angular velocity of the motor respectively. T_L is the load torque. Since the electromagnetic torque of 3-phase BLDC motor is dependent on the current, speed and back-EMF waveforms [18], the equation for instantaneous electromagnetic torque can be modified and represented as,

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

The rotor position control scheme of BLDC motor is shown in Figure 1. The control structure consists of two loop namely inner loop and outer loop. Inner loop is used for synchronizing the inverting gate signal with back electro motive force or rotor position of the motor. Outer loop is used to sense the actual rotor position of the rotor using rotor position encoder. The actual rotor position is compared with reference rotor position thereby error (e) and rate of change of error (Δe) are obtained. Error and rate of change of error is processed by the rotor position controller and provides control signal (U_m) to the switching logic circuit. The switching logic circuit provides the necessary pulse width modulated (PWM) signal for the inverter gate with respect to rotor position of the motor and the control signal output obtained from controller.

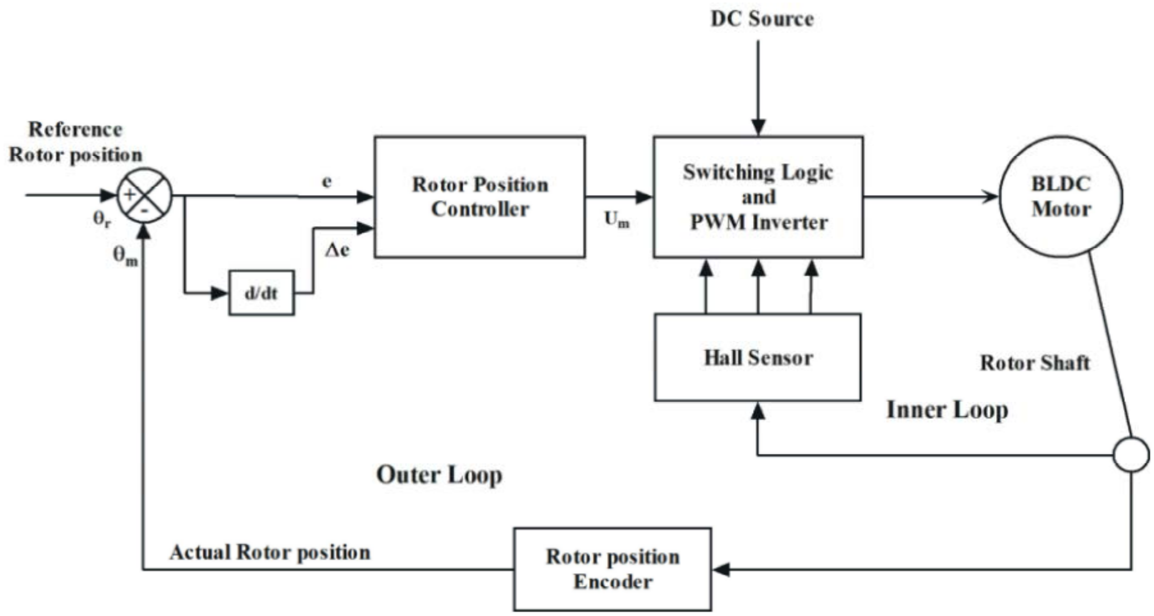


Fig. 1: Rotor position control scheme of BLDC motor

Proposed Rotor Position Controller Employing Anfis: In this section, Adaptive Neuro Fuzzy Inference System structure for rotor position control, design steps involved and the training process are explained. ANFIS eliminates the disadvantages of neural network and fuzzy logic control. First introduced by Jang in 1993, it is a universal approximator and, as such, is capable of approximating any real continuous function on a compact set to any degree of accuracy. ANFIS is a method for tuning an existing rule base with a learning algorithm based on a collection of training data [18]. The ANFIS is composed of two parts. The first is the antecedent part and the second is the consequent part, which are connected to each other by fuzzy rules base in network form. ANFIS has five layers, Layer 1node is known as adaptive node and the parameters in this layer are referred to as premise parameters. These parameters are updated during learning process. Layer 2 node is known as fixed node, the node output is the product of all the incoming signals from the previous layer and Each node output represents the firing strength of a rule. Layer 3 node is known as fixed node and in this layer calculates the rule's firing strength. Layer 4 node is known as adaptive node and parameters in this layer are referred to as consequent parameters. These parameters are updated during learning process. Layer 5 has single node in this layer is a fixed node, which computes the overall output as the summation of all incoming signals. The premises parameter of Layer 2 is updated using steepest descent method and consequent parameter of Layer 4 is updated using least- squares method. Combination of these methods is known as hybrid learning of the ANFIS parameters. Hybrid learning consists of two pass namely, forward pass and backward pass. In the forward pass of the hybrid learning algorithm, nodes output go forward until layer 4 and the consequent parameters are identified by the least-square method. In the backward pass, the error signals propagated backward and the premise parameters are updated by gradient descent. The hybrid approach converges much faster since it reduces the search space dimensions of the original pure back propagation method [18].

Design Steps for the ANFIS Based Rotor Position Controller: The design step for the ANFIS based rotor position controller for BLDC motor has been explained in this section.

Step 1: Selection of input

Rotor position error (e) and rate of change of error (Δe) were given as input to the ANFIS controller.

Step 2: Selection of linguistic variables for the inputs

Five linguistic variables were used to describe each of the input variables namely, Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB).

Step 3: Selection of membership functions for the inputs

Gaussian membership functions were used to define the degree of membership of input variables. A Gaussian membership function was specified by two parameters (c, σ), where c and σ represents the membership function's center and width respectively. These parameters were obtained automatically through learning processes by hybrid learning algorithm.

Step 4: Selection of fuzzy model for the ANFIS controller

A first-order fuzzy model Sugeno (T-S) was chosen in this design because of its computational efficiency [18].

Step 5: Preparation of training data pairs for the ANFIS controller

Rotor position error (e), rate of change of error (Δe) and control signal (Um) were taken as training data pairs for the ANFIS controller.

Step 6: Optimization of premises and consequent parameters of the ANFIS controller.

The premises parameters of the Gaussian membership function, such as center and spread and the consequent output of each rule of the first-order Sugeno fuzzy model were optimized by using a matrix of training data pairs. All initial values for the center and the spread of each input membership function were assumed as zero for each rule. Furthermore, the input and output parameters were optimized using the back-propagation algorithm and least squares estimation (LSE) method, respectively.

Training Process for ANFIS Based Rotor Position Controller: For the training process, collection of training data pair i.e., also known as identification process, is the most important step in the design of ANFIS controller. In the identifier, development of clustering involves the determination of clusters in data space and the conversion of these clusters into fuzzy rules such that the model obtained is very close to the identified system. Identification process of the ANFIS controller is modeled through input and output data of fuzzy PID controller. To prevent the system from probable saturation condition, the input–output data set is processed through closed loop using fuzzy PID controller. Two inputs to the ANFIS based identifier are the input error signal (e) and rate of change of error (Δe) of the BLDC motor. The problem is to find the proper premises and consequent parameter values for the ANFIS structure and control signal for the switching logic circuit to minimize identifier output error for all input values of e and Δe. The training processes were performed using hybrid learning methods with 18*103 data points and shown in Figure 2(a). Grid partition clustering methods are used for generating the initial membership function and number of fuzzy rules for input–output training data sets. Initial membership function for error and rate of change of error is shown in Figure 2(b) and 2(c). Figure 2 (d) shows the initial fuzzy rules for the ANFIS controller.

After initialization of membership function and fuzzy rule base, training process is started. Twenty iterations are considered for training process and at the end of last iteration; root mean square error is 0.1102. It is evident that, training data is well trained in the ANFIS controller. The error plot for training process is shown in Figure 3. Figure 4 (a) shows the test result of trained ANFIS controller. Figure 4 (b), (c) and (d) shows the final trained membership for error and rate of change of error and final rule base for proposed ANFIS controller.

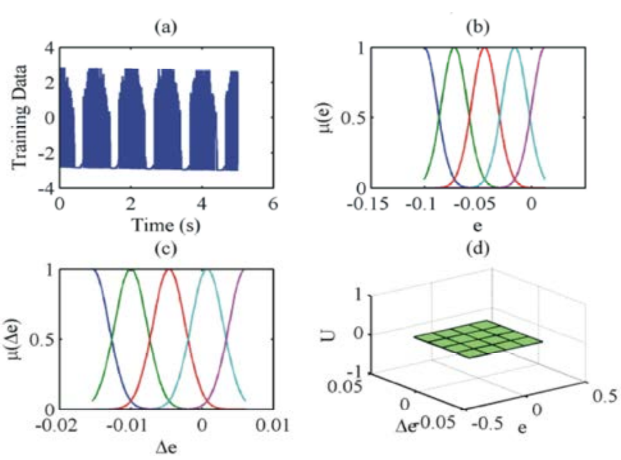


Fig. 2: (a) Training data for the ANFIS controller, (b) Initial membership function for error (e), (c) Initial membership function for rate of change error (Δe), (d) Initial fuzzy rule base for the ANFIS Controller

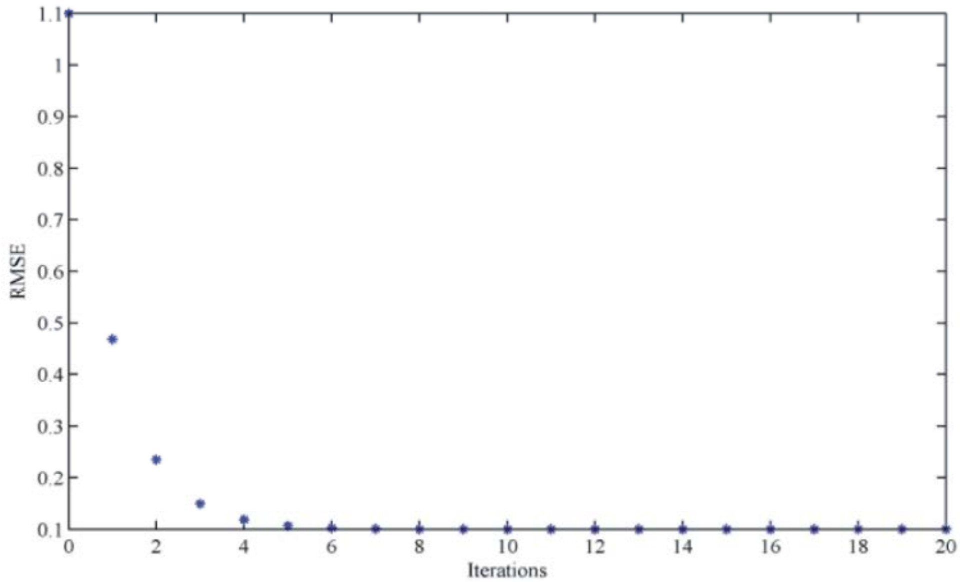


Fig. 3: Training error plot for the ANFIS controller

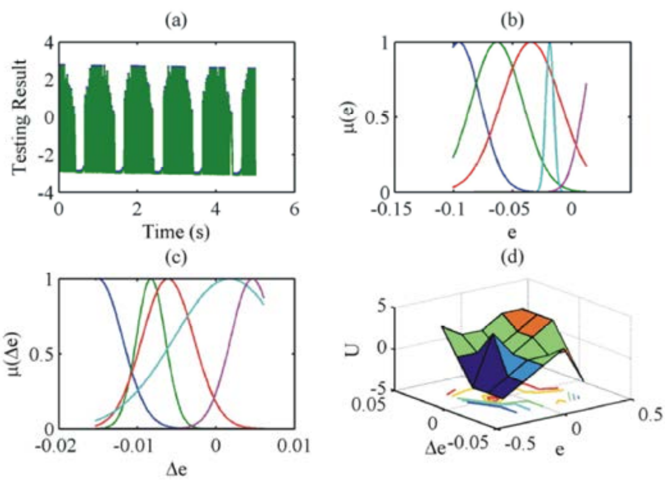


Fig. 4: (a) Testing result for the ANFIS controller, (b) final membership function for error (e), (c) final membership function for rate of change of error (Δe), (d) final fuzzy rule base for the ANFIS Controller,

Once the training process is completed, ANFIS controller is ready for testing with training data, testing data and checking of data. The testing and checking data were collected from the ramp and step reference input of the system. The average testing error for training data, testing data and checking data are 0.1102, 0.21224 and 0.3422 respectively.

RESULTS AND DISCUSSION

The specifications of the BLDC motor drive system are: Output Power-50 Watts, Current-2.5 Amps, Voltage-28 V DC, Speed-1500 rpm, Torque- 0.38 N-m. Rotor position, error, control effort, speed and electromagnetic torque responses of the brushless motor are measured and analyzed for standard control system input, i.e., sinusoidal, ramp and step reference input for proposed, fuzzy PID and PID controller. PID controller were tuned using Ziegler-Nichols method and values for Kp=1.1, Ki=0.1 and Kd=0.2. The fuzzy PID controller is quite taken from [11].

Response of the Drive for Ramp Input: The simulation result has been obtained for ramp reference input having amplitude 2Π radian with frequency of 0.5 Hz and load torque is maintained constant at 0.25 Nm.

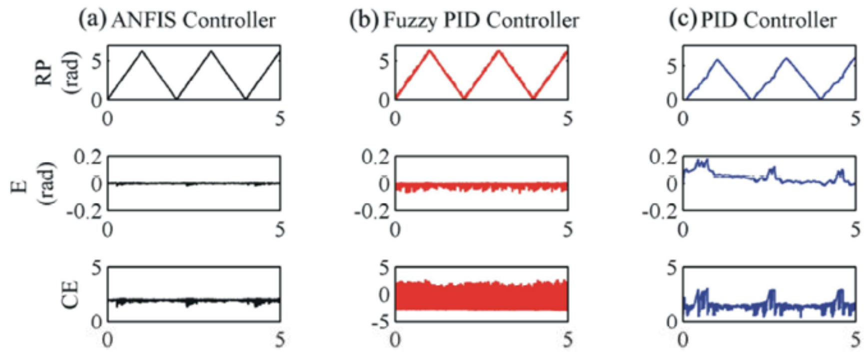


Fig. 5: The response of the BLDC motor with ramp reference input

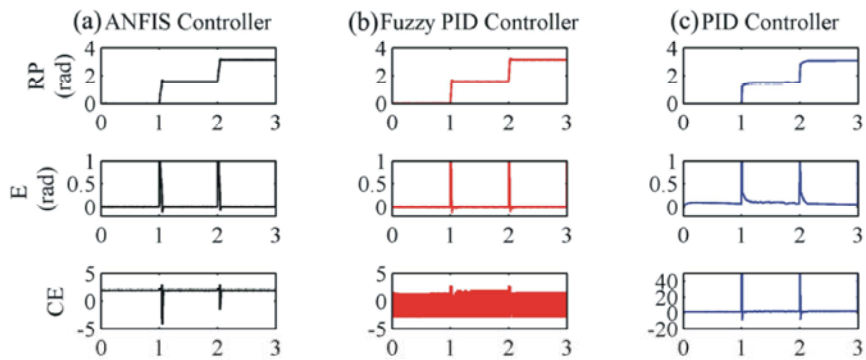
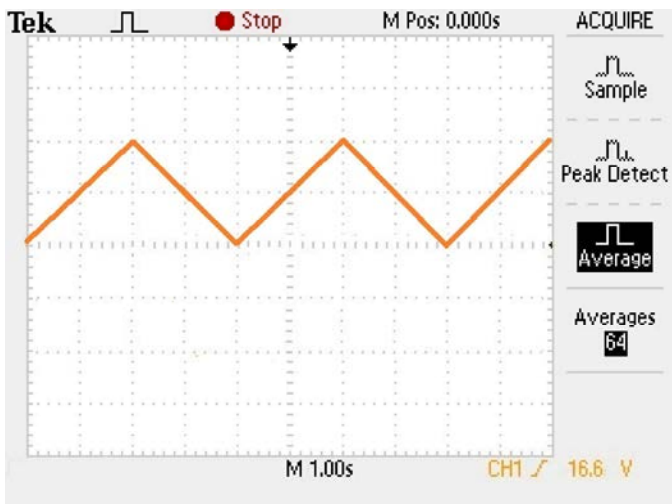


Fig. 6: The response of the BLDC motor with step reference input

Simulation results of rotor position response of BLDC motor with PID controller, Fuzzy PID controller and proposed ANFIScontroller are shown in Figure 5. From Figure 5(c), it is proved that, the PID controller has produced average error of 0.14 rad. The control effort of the PID controller has chattering problem and it has degraded the tracking performance of the BLDC motor. The speed of the BLDC motor also has more oscillations. It is also not desirable for system under control. The fuzzy PID controller has produced an average error of 0.052 rad and it is shown in Figure 5(b). The control effort of the fuzzy PID controller has more oscillations and it has ruined the stability and tracking performance of the BLDC motor. The speed and torque of the BLDC motor also has more oscillations when compared with PID controller. It also has degraded the system performance and leads to instability of the system under control. The proposed ANFIS controller has produced an average error of 0.002 rad and the response characteristics are shown in Figure 5(a). The control effort of the ANFIS controller is smooth and has no chattering problem. The speed and torque of the BLDC motor also has no oscillations. It also has enhanced the system performance and it leads to stable operation of the system under control. It is proved that, the proposed ANFIS rotor position controller is superior when compared with the other considered controllers.

Response of the Drive for Step Input: The simulation result has been obtained for step reference input having amplitude Π/2 radian with sample time of 1 second and load torque maintained constant at 0.25 Nm. Simulation results of rotor position response of BLDC motor using PID, fuzzy PID controller and proposed ANFIS controllers are shown in Figure 6. PID controller, fuzzy PID controller and proposed ANFIS controller has produced a steady error of 0.2 rad, 0.1 rad and 0.05 rad respectively. Overshoot produced by the controllers in the same order are more than 5%, 5% and 3% respectively. The control effort generated by the proposed ANFIS controller is very smooth and there are no oscillations in electromagnetic torque response when compared with other controllers. From the analysis with standard control system inputs, it has been proved that, the proposed controller has shown improved performance. Experimental verification of the proposed ANFIS controller is also presented in the subsequent section.

(a)



(b)

(c)

Fig. 7: (a) Experimental setup for ANFIS based rotor position controller, (b) Ramp rotor position response of BLDC motor, (c) Step rotor position response of BLDC motor

Experimental Results and Discussion: The experimental studies are carried out to evaluate and ascertain the performance of the proposed ANFIS controller. Configuration is the Process by which the bit streams of design, as generated by the development software are loaded into the internal configuration memory of the dsPIC30F2010 microcontroller. To verify the performance of the controller design on hardware, C program code is downloaded into the Target dsPIC30F2010 microcontroller. Figure 7(a) shows the experimental setup for the ANFIS based rotor position control of BLDC motor.

After the BLDC motor is booted, its actual rotor position is first obtained by the rotor position encoder's count circuit and is increased by 15 bits through the dspic30f2010 microcontroller hardware's motor angle count module. It is then sent to the central processing unit with motor angle tracking command generated by the control command function generator module. After the program is interrupted, the count circuit calculates the motor control effort using the proposed ANFIS control rule and conveys it to the Digital to Analog Converter (DAC) module. It outputs to the external DAC chip to control the BLDC motor via PWM inverter module. Figure 7(b) shows the experiment result of ramp rotor position tracking response of the BLDC motor and Figure 7(c) shows the experiment result of ramp rotor position tracking response of the BLDC motor. Using a digital oscilloscope, control results are observed and performance of the proposed ANFIS rotor position control system is verified. It is evident that, the proposed ANFIS rotor position controller can effectively control the rotor position of the BLDC motor.

CONCLUSION

ANFIS based rotor position controller has been presented for BLDC motor. The effectiveness of the proposed controller has been observed and discussed through simulation and experimental results. The dynamic response of the proposed controller is obtained and analyzed for the sinusoidal, ramp and step reference inputs. By assessment of the dynamic response, it can be understood that, great reduction of torque ripple is obtained and there is no chattering problem due control effort signal with the proposed rotor position controller. Besides, the superiority of the proposed controller has been validated through hardware implementation also. It is evident that, the proposed controller clearly outperforms the other considered controllers.

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