MODELING AND DIRECT TORQUE CONTROL OF INDUCTION MOTOR BY USING HYBRID CONTROL TECHNIQUE

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ABSTRACT

In this paper, an adaptive neuro fuzzy interference (ANFIS) based hybrid field oriented speed controlling of an induction motor is proposed. The proposed hybrid field oriented speed controller results attractive performance of induction motor with the potential features of both Artificial Neural network (ANN) and Fuzzy Logic Controller (FLC). In this topology the Artificial Neural Network (ANN) used to estimate the suitable inputs to control the system and Fuzzy Logic Controller used to evaluating the system inputs in terms of logic variables. In the proposed Direct Torque Controller (DTC) scheme the actual motor torque and change in torque is possess through the proposed adaptive neuro fuzzy interference system. Then the speed of the induction motor is controlled by using the controlled electromagnetic torque i.e., output of the ANFIS controller. The entire proposed system is implemented in MATLAB/SIMULINK environment. And simulation results are also presented to demonstrate the attractive performance of the proposed ANFIS based DTC speed control of the induction motor. And also the comparative steady and dynamic performance of conventional Fuzzy Logic Controller and ANFIS based controller is presented.

KEYWORDS

ANFIS, DTC, Fuzzy logic controller & Induction motor.

1. INTRODUCTION

Induction Motor plays a major role in industrial applications when compared to other AC motors due to its simple and robust construction. However, the control of IM is complex due to the nonlinear nature and the parameters changes with operating conditions [4]. An Induction Motor (IM) is an AC motor, where power is supplied to the rotor by means of electromagnetic induction [2]. The motor efficiency can be improved by reducing the flux and by balancing the motor iron and copper losses [19]. The impreciseness of the estimation of the electrical parameters of the machine will degrade the speed control performance [7]. In general the mechanical speed of the motor is varied under this the estimation of speed is more complex due to the speed of revolving magnetic field is not equal to the rotor speed [18].

In recent years many have been carried out to develop different solutions for the induction motor control for quick torque response by reducing circuit complexity of field oriented algorithms. Direct Torque Control (DTC) technique controls the torque and speed of the motor, which is directly based on the electromagnetic state of the motor [1]. The name direct torque control is derived from the fact that on the basis of the errors between the

reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the permissible limits [8]. The DTC method is a simple and give fast transient response against the speed variations of the motor, hence most of the industrial drives are equipped with DTC [15]. However, the main limit of conventional DTC scheme is high torque ripple, variable switching frequency and the torque does not match the torque demand [5][15].

So, in this paper main focus on reducing the swing levels of the flux and torque, for that improving the dynamic performance. For the controller the PWM pulse generation places a major role to control the speed with reduced flux and torque fluctuation. The different induction motor control techniques such as DTC with space vector pulse width modulation (SVPWM) technique, artificial intelligence techniques etc., [5] [9] were in development currently. In this paper proposes the ANFIS based Hybrid field oriented speed controller. The proposed ANFIS based DTC are robust and fast torque response, no requirements for coordinate transformation, requirements for PWM pulse generation and current regulators. The present paper concerns with the implementation of Fuzzy and ANFIS techniques to improve the speed/torque characteristics of the induction motor.

2. MATHEMATICAL MODEL OF DTC OF INDUCTION MOTOR

The mathematical model of the induction machine is used for analyzing the dynamic behavior of the motor. The dynamic behavior of the motor affects the changes in motor parameters such as speed, torque, resistance, flux etc. So, the dynamic model is essential for analyzing the performance of the induction motor. The dynamic model of the induction motor is derived by transforming the three phase quantities into two phase direct and quadrature axes quantities by using Clark's transformation. The mathematical equation of DTC of the induction motor is given below.

2.1. Voltage equations:

The mathematical equations of the stator and rotor voltages as follows:

$$V_{s\alpha} = r_s i_{s\alpha} + P\psi_{s\alpha} \quad (1)$$

$$V_{s\beta} = r_s i_{s\beta} + P\psi_{s\beta} \quad (2)$$

$$V_{r\alpha} = r_r i_{r\alpha} + P\psi_{r\alpha} + \psi_{r\beta} \omega_r \quad (3)$$

$$V_{r\beta} = r_r i_{r\beta} + P\psi_{r\beta} - \psi_{r\alpha} \omega_r \quad (4)$$

Where, $V_{s\alpha}$, $V_{s\beta}$, $V_{r\alpha}$ and $V_{r\beta}$ are the α – axis and β – axis voltages of stator and rotor respectively. Then, $i_{s\alpha}$, $i_{s\beta}$, $i_{r\alpha}$ and $i_{r\beta}$ are the α – axis and β – axis currents of stator and rotor respectively. The resistance and inductance of the stator and rotor winding are denoted by r_s , r_r , and L_r respectively. The stator and the rotor flux of the motor are described as $\psi_{s\alpha}$, $\psi_{s\beta}$, $\psi_{r\alpha}$ and $\psi_{r\beta}$ respectively.

The stator flux equations are rewritten as follows:

2.2. Stator Flux:

$$\psi_{s\alpha} = \int (V_{s\alpha} - r_s i_{s\alpha}) dt \quad (5)$$

$$\psi_{s\beta} = \int (V_{s\beta} - r_s i_{s\beta}) dt \quad (6)$$

The magnitude of the stator flux (ψ_s) is the combination of $\alpha - axis$ and $\beta - axis$ flux which is expressed as follow,

$$|\psi_s| = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \quad (7)$$

The magnetic track phase angle (θ) is expressed as follow,

$$\theta = \arctan\left(\frac{\psi_{s\alpha}}{\psi_{s\beta}}\right) \quad (8)$$

The electromagnetic torque of the motor is estimated from the inductance and the $\alpha - \beta$ axis current. The $\alpha - \beta$ axis currents of the motor is obtained from the flux linkages that transpired in the stator and rotor of the motor. The expression of the electromagnetic torque that is produced by the motor is given as follows.

2.3. Electromagnetic Torque:

$$T_e = \frac{3}{2} \cdot \frac{P}{2} (\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \quad (9)$$

The actual torque developed by the motor in terms of rotor speed is illustrated as follow.

$$T = T_e - T_L = \frac{P}{2} \left(J \frac{d\omega_r}{dt} + B \omega_r \right) \quad (10)$$

Where, P is the number of poles,
 J is the moment of inertia of rotor,
 B is the damping coefficient,
 ω_r is the rotor speed,
 T_L is the load torque,
 T_e is the electromagnetic torque.

2.4. Vector Diagram:

The vector diagram of flux linkages in the stator and rotor winding is illustrated in fig.1. The three phase currents i_a, i_b and i_c are converted to a two-phase orthogonal system with axes α and β by the Clark's Transformation technique. Here α component is assumed as it is equal to the axis a as per our convenience as shown in fig. 1. Obtained orthogonal

currents i_α and i_β are again transformed into a time-invariant, rotating orthogonal system corresponds to the field and torque components d and q of the equivalent rotor currents i_d and i_q . The α/β coordinate frame is rotated counterclockwise to line up with the rotor flux axis ψ_r . The angle of rotation (θ) is determined with the help of the motor model.

Figure 1: Vector Diagram of DTC of Induction Motor

Figure 2: Proposed ANFIS Based DTC System

The overall control designing of the proposed ANFIS controller is shown in fig.2. In the proposed model stator voltage and current calculators estimates the two-phase orthogonal system components with axes α and β respectively. With this components the actual torque and the flux is evaluated. The reference values of the torque are depends upon the load variation. So, here the optimization of reference torque is required. For the optimization of the reference torque the speed controller is adopted. The speed controller estimates the reference values of torque. By comparing reference torque values with the actual values estimating the change torque. The estimated actual torque and change torque

is applied to the proposed ANFIS controller, this produces the controlled torque. This controlled torque is fed to PWM controller to generate control signals for gate terminals of the inverter. Here, the space vector PWM modulation technique is used for generating the gate control signal. The SVM based switching table is referred from [29] switching output, the IGBT gate is controlled.

3. ADAPTIVE NEURO FUZZY INTERFERENCE SYSTEM

This section describes the detail description of the proposed ANFIS model. Adaptive neuro-fuzzy interference system is the combination of neural network (NN) and fuzzy logic controller (FLC) [28]. The adaptive neuro-fuzzy interference system facilitates the attractive control performance with the potential features of both Artificial Neural network (ANN) and Fuzzy Logic Controller (FLC). The enactment of the ANN and Fuzzy logic in the interference system based on the feed forwarding technique. The fuzzy structure and neurons of neural network are implemented based on feed forward technique. In the hybrid system, the data set is developed by neural network in terms of actual torque and change of torque and reference torque of the motor. The generated data set is fed to fuzzy interference system and the fuzzy control rules are generated. This adaptive system is generated in two phases, one is training phase and other is testing phase. The training and testing phase are explained as follows.

3.1. Training Phase:

The first phase of ANFIS is training phase which used for generating training data set. In the proposed control approach, the actual torque and change of torque of the motor values are generated in the form of vector and the data is applied to the neural network. Then, the data is trained by back propagation training algorithm with respect to the actual torque of motor. Then, the trained data is applied to the fuzzy interference system for generating the control fuzzy rules. In ANFIS, the fuzzy rules base control interference system is automatically generated.

3.2. Testing Phase:

The next phase of ANFIS is testing which used for creating the test speed control system model. In the testing phase, the actual torque and the change of torque of the motor is applied as the input, the appropriate control electromagnetic torque is obtained from the interference system.

3.3. Features of ANFIS

In the proposed speed control system, the ANFIS is used for the set of features which is based on neural network and fuzzy system. The feature of the neural network is the structure network of feed forward type and the network training algorithm is back propagation. In the back propagation training algorithm, the data is trained based on the network error. The error of the network is the difference between the target value and the actual value. Hence, the appropriate control model can be developed. The model proposed in fuzzy interference system is based on the Sugeno model [30] which contains a set of rules. The fuzzy concept consists of three steps *i.e.* fuzzification, rule base decision making and fuzzification. In the fuzzy process, the vector of the firing strengths is normalized and the resulting vector is defuzzified by utilizing the first order Sugeno model. The normalization processes consist of fuzzification and decision stage.

3.4. Structure of ANFIS:

The structure of ANFIS system consist of five layers which are categorized as input layer, input membership function layer, rule layer, output members function layer and output layer respectively. The fuzzy inference decision tree is to classify the data into one of 2^n (or P^n) linear regression models to minimize the sum of squared errors (SSE).

$$SSE = \sum_i er_i^2 \quad (11)$$

Where, n is the number of input variables, P^n is the number of fuzzy divisions for each input variable and er_i^2 is the error between the desired and actual output respectively. The first order two input sugeno fuzzy model is given as in follow.

Figure 3: Two input first order Sugeno fuzzy model with two rules.

The typical fuzzy if-then rule set for the first order Sugeno fuzzy inference model [31], can be stated below,

If x_1 is A_1 AND x_2 is B_1 , then $f_1 = p_1 T_e^* + q_1 \Delta T_e^* + r_1$
 If x_1 is A_2 AND x_2 is B_2 , then $f_2 = p_2 T_e^* + q_2 \Delta T_e^* + r_2$

Where, A_i and B_i are the antecedent fuzzy sets and parameters p_i, q_i and r_i are the fuzzy design parameters calculated during the training process ($i=1, 2, \dots, n$). The two input and single output ANFIS structure is given as following them.

Figure 4: Structure of ANFIS.

In Figure 4, the mechanism for obtaining the actual torque (T_e) of the motor for a given input vector $[T_e^*, \Delta T_e^*]$ Sugeno model is illustrated. The structure of the ANFIS and the each layers are explained as following.

Layer 1: In this layer, the adaptive nodes with node functions are consisted; the node function is defined as following:

$$O_i^{layer\ 1} = \mu_{A_i}(T_e^*) \quad (12)$$

$$O_i^{layer\ 1} = \mu_{B_i}(\Delta T_e^*) \quad (13)$$

Where, ω^* is the input to node i & A_i is the linguistic label related to that node function. The membership function $O_i^{layer\ 1}$ indicates the extent to which the specified T_e^* satisfies the quantifier A_i . Generally, a bell-shaped $\mu_{A_i}(T_e^*)$ that has a maximum of 1 and a minimum of 0 is considered as shown below.

$$\mu_{A_i}(T_e^*) = \frac{1}{1 + \left| \frac{T_e^* - c_i}{a_i} \right|^{2b_i}} = \exp \left\{ - \left(\frac{T_e^* - c_i}{a_i} \right)^{2b_i} \right\} \quad (14)$$

Where, the parameter set $\{a_i, b_i, c_i\}$ which modifies the membership functions on linguistic label A_i is known as premise parameter. Similarly, the value of $\mu_{B_i}(\Delta T_e^*)$ is selected.

Layer 2: By multiplying the input signals and sending out the product by each node of the layer, the firing strength of the rule is calculated.

$$O_i^{layer\ 2} = w_i = \mu_{A_i}(T_e^*) \mu_{B_i}(\Delta T_e^*), i = 1, 2 \quad (15)$$

Layer 3: The i^{th} node of this layer is used to determine the ratio between the firing strength of the i^{th} rule and the sum of firing strengths of all rules.

$$O_i^{layer\ 3} = \bar{w}_i = \frac{w_i}{w_1 + w_2} \quad i = 1, 2 \quad (16)$$

The output of this layer is expressed in terms of normalized firing strengths.

Layer 4: The involvement of i^{th} rule in the overall output is calculated by the i^{th} node of this layer as follows,

$$O_i^{layer\ 4} = \bar{w}_i f_i = \bar{w}_i (p_i T_e^* + q_i \Delta T_e^* + r_i) \quad (17)$$

Where, $\bar{w}_i$ is the output of layer 3 and $\{p_i, q_i, r_i\}$ are the parameter set of the layer 3. The term consequent parameters are used to indicate the parameters of this layer.

Layer 5: By taking the summation of all the inputs by the single node that exists in this layer indicated as Σ , the overall output is calculated.

$$\text{Overall output} = O_i^{\text{layer 5}} = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (18)$$

For the ANFIS structure shown in Figure 4, the fact that the overall output f can be expressed as a linear combination of the consequent parameters for the case of fixed premise parameters is a most evident from. The output of ANFIS can be represented more precisely as,

$$T_e = \bar{w}_1 f_1 + \bar{w}_2 f_2 \quad (19)$$

$$i.e \quad T_e = (\bar{w}_1 T_e^*) p_1 + (\bar{w}_1 \Delta T_e^*) q_1 + (\bar{w}_1) r_1 + (\bar{w}_2 T_e^*) p_2 + (\bar{w}_2 \Delta T_e^*) q_2 + (\bar{w}_2) r_2 \quad (20)$$

In the proposed control system, the ANFIS structure is trained by giving the vector as input. Then, the appropriate control output is applied to SVPWM for generating control signal. The generated control signal is applied to the inverter to control the speed of induction motor.

4.SIMULATION

Fig. 5 shows the simulation diagram of Fuzzy logic controller based DTC technique of induction motor. The speed control performance of the fuzzy logic controller is tested with induction motor 2.2Kw/400V, the performance of the controller is observed under different reference speeds. The proposed ANFIS based hybrid DTC technique was implemented and tested in MATLAB/SIMULINK environment and it is illustrated in Fig.6. The speed control performance of proposed control technique was compared with fuzzy controller to demonstrate the attractive performance of the proposed system. The implementation parameters of proposed model is depicted in appendix-A.

Figure 5: Simulink Model of Fuzzy Logic Speed control System.

Figure 6: Simulink Model of Proposed (ANFIS) Speed control System.

5. RESULTS AND DISCUSSION

To describe the dynamic response of the IM choosing the speed set point is 80 rad/sec from rest at duration of 0.5 sec. Then the speed set point is varied from 80 rad/sec to 60 rad/sec at duration of 0.5 sec. After that the speed set point is varied from 60 rad/sec to 100 rad/sec at duration of 1sec. The performance of current, voltage, flux, torque, speed of the motor with the fuzzy logic controller are depicted from Fig.7 to Fig.11 respectively.

Figure 7: Dynamics of Stator Current.

Figure 8: Transformed d-q axis of Stator Voltage.

Figure 9: Dynamics of d-q axis Stator Flux.

Figure 10: Variations of Electromagnetic Torque.

Figure 11: Performance of Speed.

The motor performance characteristics under the proposed adaptive neuro-fuzzy interference system are shown in Fig.12 to Fig.16 respectively. The speed of the motor with the Fuzzy logic controller and proposed ANFIS controller is compared in Fig.17.

Figure 12: Dynamics of Stator Current.

Figure 13: Transformed d-q axis of Stator Voltage.

Figure 14: Dynamics of d-q axis Stator Flux.

Figure 15: Variations of Electromagnetic Torque.

Figure 16: Performance of Speed.

Figure 17: Comparison Performance of Rotor Speed.

From the comparative analysis, the proposed ANFIS speed controller provides smooth speed control performance with less settling time, peak overshoot and steady state error when compared to the Fuzzy logic controller. The fuzzy controller offers high overshoot, oscillations. Hence, the proposed ANFIS speed controller is better than fuzzy speed controller.

6. CONCLUSIONS

The proposed ANFIS based DTC method was implemented in MATLAB/SIMULINK platform. The performance of the proposed control technique was tested on 2.2Kw/400V induction motor. The mathematical model of the induction motor was analyzed in terms of stator voltage and torque equation. The actual torque and the change of torque of the motor were applied to the ANFIS and the electromagnetic torque was determined from the output of interference system. The output of ANFIS was converted into stator voltage and the stator voltage was applied to SVM. From the output of SVM, the control signal was generated to control the speed of the motor close to reference speed. The performance speed and the torque are analyzed and the analyzed performances are compared with fuzzy controller. From the comparative analysis, the proposed ANFIS speed control technique is better than fuzzy control technique.

APPENDIX-A

Table 1: Implementation parameters.

Parameters	Values
Nominal power	2200 watts
Line to line voltage	400 volts
Frequency	50 Hz
Stator resistance	3.67 ohm
Stator inductance	0.0269 H
Rotor resistance	2.1 ohm
Rotor inductance	0.0269 H
Mutual inductance	0.0324 H
Inertia	0.0155 kg.m ²
Friction	0.0025 N.m.s
Number of poles	2

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