ANFIS Based Torque Control of Switched Reluctance Motor

Ponrajan. P, Jebarani Evangeline. S, Jayakumar. J

***Abstract* —This paper develops an ANFIS based torque control of SRM to reduce the torque ripple. The ANFIS has the advantages of expert knowledge of the fuzzy inference system and the learning capability of neural networks. This controller realizes a good dynamic behavior of the motor, a perfect speed tracking with no overshoot and a good rejection of impact loads disturbance. The results of applying the adaptive neuro-fuzzy controller to a SRM give better performance and high robustness than those obtained by the application of a conventional controller (PI). The above controller was realized using MATLAB/Simulink.**

***Index Terms*— ANFIS, Torque Control, Switched Reluctance Motor.**

I. INTRODUCTION

With concerns over energy efficient drive, Switched Reluctance Motor (SRM) has attracted the interest in fields of Electric Vehicle (EV) due to its robust construction, fault tolerant operation, high starting torque without the problem of excessive inrush current, and high-speed operation. However, SRM suffers from some drawbacks such as high torque ripple and acoustic noise which are very critical for EV applications. The research is progressing extensively for the mitigation of torque ripple and acoustic noise. In indirect torque control scheme of SRM, the torque of the motor is controlled by controlling the motor current. Due to high nonlinearity in torque and current relationship, the conversion of torque into equivalent current value is cumbersome. In the paper [1], the torque is directly proportional to the ideal phase inductance profile which increases or decreases proportionately with the angle of overlap. Due to magnetic saturation, the phase inductance varies with the motor current which leads to large amount of error in both instantaneous and average value of torque. In [2], the author had suggested a multiplication factor F to compensate for the error of torque and 'F' should be a function of current level. In [3], the author have suggested approximating the torque as proportional to the square of stator current, where the multiplying factor is assumed to vary as a sinusoidal function of rotor position alone. A two dimensional lookup table in which the torque value is stored as function of current and rotor position. The amount of time taken for computation of torque is very high [4, 5]. In [6], a Cerebellar Model Articulation Controller (CMAC) based torque control was presented.

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A closed loop torque controller based on B-spline neural network (BSNN) with online training was presented in [7]. Back-propagation (BP) based neural network controllers have been proposed in [8]-[10], but both of [8] and [9] used one-hidden-layer neural network which is not sufficient for estimating the stabilized motor current. In [11, 12], look-up tables were generated off-line by building an SRM model to profile the current for the flat torque waveform and stored in the controller.During on-line running, the controller searched the look-up tables for the current command.

Another comprehensive controller to maximize efficiency and peak overload capability of SRM by using look-up tables for electric vehicle drives has been designed. This controller has several look-up tables for different voltages. To calculate the control parameters for a certain torque -command/rotor-speed (operating point) and bus voltage, three interpolations have to be performed. The percentage error depends upon the resolution of lookup tables. At low speed, the torque ripple is sensitive to the current profile, and a slight deviation from the required profile may produce high torque ripple. In this paper, ANFIS based Direct Control of torque is proposed to minimize the torque ripple at low speed for its simple, easy to implement and fast dynamics. Computed results show that the proposed scheme can reduce the torque ripple and provide good dynamic performance with respect to changes in the torque commands.

II. DYNAMICS OF SRM

The SRM is a variable reluctance stepper motor that is designed to convert energy efficiently. The motor is doubly salient with an unequal number of rotor and stator poles. Torque is produced by the tendency of the rotor poles to align with poles of the excited stator phase and is independent of the direction of the phase current. For an SRM, the general equation governing the flow of stator phase current is written as:

$$v = Ri + \frac{d\psi}{dt} \qquad (2.1)$$

Where v is the voltage applied across the phase winding, Ri is the voltage drop due to winding resistance and ψ is the total flux-linkage of the coil. As mutual inductance is much less than the self inductance, the mutual coupling between phases is neglected. The magnetic core losses are also neglected. The second term on the right hand side of equation (2.l) defined as back emf,

$$e = \frac{d\psi}{dt} \qquad (2.2)$$

The relation between ψ and i is defined as follows

$$\psi = L(\theta, i)i \qquad (2.3)$$

Where L is the phase inductance of the motor. Due to double saliency of the machine, it depends on current '*i*' and rotor position θ. The magnetization characteristics at various values of rotor position θ is shown in the figure 2.1

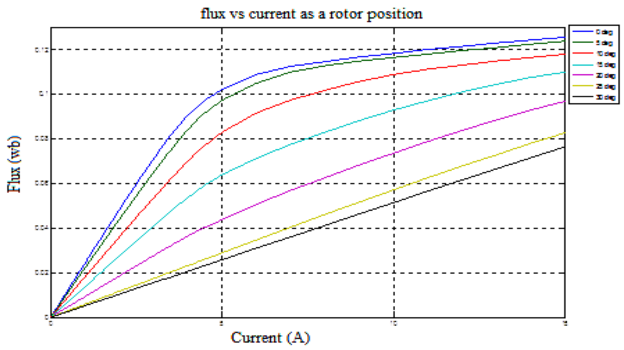

FIG.2.1. Flux Linkage Characteristics of SRM using MAGNET 7.1

Electromagnetic torque is produced in the SRM by the tendency of the rotor to attain the minimum reluctance position when a stator phase is excited. The general expression for the torque produced by one phase at any given rotor position θ, is

$$T = \left(\frac{\partial W}{\partial \theta}\right)_{i=constant} \qquad (2.4)$$

Where W is the co-energy. Total instantaneous torque is given by the sum of the individual phase torques

$$T_e(\theta, i) = \sum_{j=1}^{N} T_{ph}(\theta, i) \qquad (2.5)$$

The mechanical dynamics of the motor and the load are governed by the equation of motion and are given in (2.6)

$$T_e - T_L = J\frac{d\omega}{dt} \qquad (2.6)$$

Where, T_L is the load torque and *J* is the moment of inertia of rotating masses. The load torque is a function of the angular speed, depending on the type of load.

It can be seen from (2.4) that the torque is highly non-linear due to the three-dimensional relationship between the magnetic flux linkage, excitation current, and rotor position. Methods of torque control are dependent on how many phases are excited simultaneously and the current control capability of the system. The approach can be split into two opposite categories: (1) the torque control is dependent on the number of reference currents with constant switching angles, which is simple but limits the operating area and does not optimize efficiency. (2) All control parameters are varied, which is complex but the control algorithm itself does not limit the obtainable operating area. For tractive application, the vehicle control unit expects a precise average torque of the electric drive which tracks precisely the reference torque with a small torque ripple at low speed to avoid speed oscillations. This paper will propose an ANFIS based torque control to control the average torque with minimum torque ripples at medium speed range.

III. TORQUE CONTROL

One of the efficient methods for control of torque in individual phases is Torque Sharing Function (TSF). The TSF are function of rotor position θ and motor speed ω. The torque/flux/current controllers tracks the expected value of torque/flux/current based on TSF. With TSF, the SRM drive operates either on hysteresis or PWM control. In order to maintain the desired instantaneous torque, a high bandwidth current regulator is need. TSF defined could be linear or nonlinear. In order to maintain the desired instantaneous torque, a high bandwidth current regulator is need as shown in fig 3.1

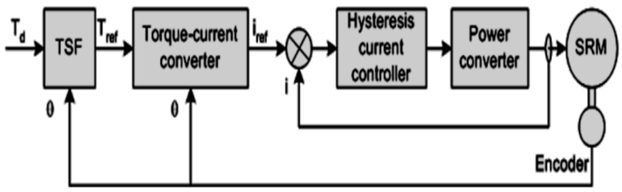

FIG.3.1 Block Diagram of TSF

To generate a ripple-free output torque, there must be overlapping between phases. During phase overlapping, the current in one phase is decreasing, and that in the other phase is increasing. To obtain a constant torque, the summation of the torque generated by these currents must equal to the torque generated in non-overlapping period. To determine the desired torque produced by each phase, torque factors are introduced here, which are defined as

$$T = \sum_{j=1}^{N} T_j = \sum_{j=1}^{N} f_j(\theta)T_{ref} \qquad (3.1)$$

So the phase overlapping for each two adjacent phases is π /8 - π /12 = π /24. During phase overlapping, the total torque is distributed in the two phases according to a sine function of the rotor position. The torque factor for phase *j* is expressed as follows.

$$f_j(\theta) = \begin{cases} 0, & (0 \le \theta \le \theta_{on}) \\ 0.5 - 0.5\cos\frac{\pi}{\theta_{ov}}(\theta - \theta_{on}), & (\theta_{on} \le \theta \le \theta_{on} + \theta_{ov}) \\ 1, & (\theta_{on} \le \theta \le \theta_{off}) \\ 0.5 + 0.5\cos\frac{\pi}{\theta_{ov}}(\theta - \theta_{off}), & (\theta_{off} \le \theta \le \theta_{off} + \theta_{ov}) \\ 0, & (\theta \ge \theta_{off} + \theta_{ov}) \end{cases} \qquad (3.2)$$

Once the torque factors are chosen, the reference current for different phases at specified rotor position can be calculated mathematical using the equation 3.3.

$$I_{ref} = \sqrt{\frac{T_{ref}^2}{l_u N_r \sin(N_r\theta + (j-1)\frac{2\pi}{n})}} \qquad (3.3)$$

From the above formula, knowledge of unaligned inductance is essential for the computation of phase current. To overcome the above problem, an ANFIS based torque control is implemented. Fuzzy neural network has two advantages of easy-to-express human knowledge and self-learning ability.

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Using the fuzzy logic and neural network is a very powerful approach in building a complex and nonlinear relationship between a set of input and output data. In this work, the reference torque and rotor position were trained by an adaptive neural fuzzy inference system (ANFIS) to obtain the phase current.

IV. ANFIS IMPLEMENTATION

THE ANFIS CONTROLLER (FIG 4.1) GENERATES THE PHASE CURRENT BASED ON THE VALUE OF TORQUE AND ROTOR POSITION. IN THIS PAPER, THE SRM IS OPERATED WITH THE FIXED COMMUTATION ANGLE SCHEME.

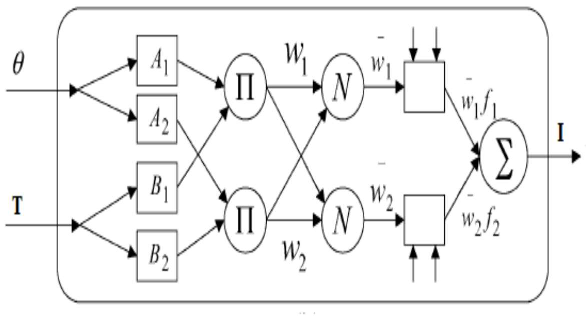


Fig.4.1 ANFIS Model for Current Calculation

In order to train an ANFIS model, the first and usually longest step is to collect data from the system. Obtaining accurate data is an important step in training the ANFIS more accurately. The data sets used in training ANFIS are usually obtained by measurement or FEM simulation. Here, the measurement was used to generate data for training the ANFIS current model as shown in figure. 3.1. For the ANFIS, the inputs are torque and rotor position, and the output is current. The training scheme consists of the following steps.

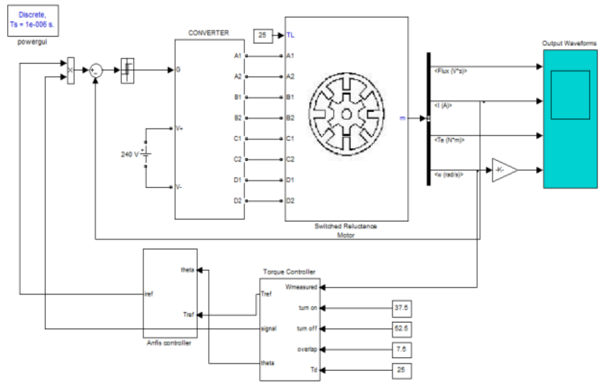
Step 1: Initialization of ANFIS. In this case, the input domains are rotor position and torque, which are defined to have a range of 30 - 60 degree and 0-200A. The variable spaces of rotor position and torque are divided into 7 regions, then the number of original rules is 49 (7×7).

The Gaussian MF is used for two input variables. It is clear that the Gaussian MF is specified by two parameters. Therefore, the ANFIS used here contains a total of 175 fitting parameters, of which 28 ($7 \times 2 + 7 \times 2$) =28 are the premise parameters and 147($3 \times 49 = 147$) are the consequent parameters.

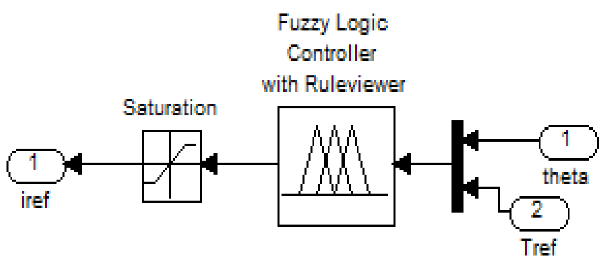
Step 2: Creating the input–output data for ANFIS. The input–output sample data come from the static magnetization characteristics of the motor.

Step 3: Learning and training of the ANFIS. Training an ANFIS with the use of the hybrid learning algorithm to compute the torque value and involves presenting it sequentially with different sets and corresponding desired and values. The differences between the desired output and the actual output of the ANFIS are evaluated by the hybrid learning algorithm. The adaptation is performed after the presentation of each set until the calculation accuracy of the network is deemed satisfactory according to some criterion (for example, when the error between the desired and the actual output for all the training set falls below a given threshold) or when the maximum allowable number of epochs is reached. In this work, the number of epochs was 100 for training. After the training is completed, the ANFIS defines function mapping input values of rotor position and torque to output values of current.

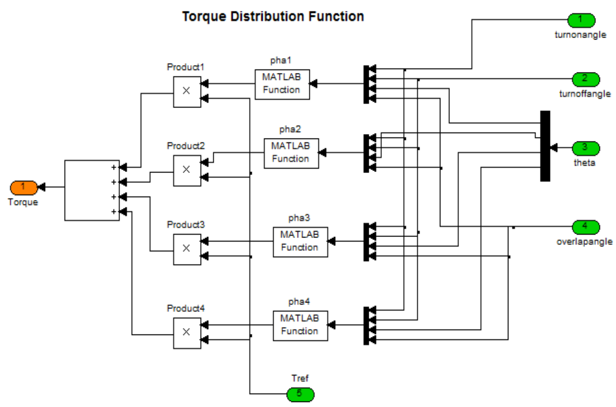
Figure 4.2 illustrates the Simulink diagram of the SRM drive that is used in simulations. Figures 4.3(a), (b) and (c) represent the Simulink diagrams of the anfis current control, torque sharing function (or torque control) and commutation of the SRM drive, respectively.



4.2 Simulink model of ANFIS based Torque control of SRM



4.3 (a) ANFIS current model



4.3 (b) Torque Sharing Function

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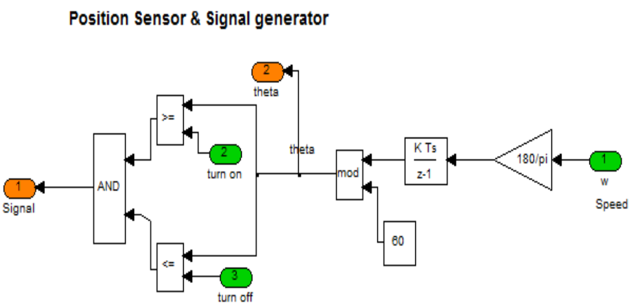
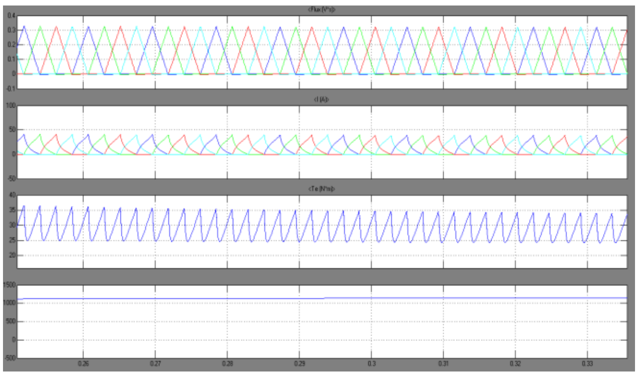


4.3 (c) Commutation

To analyze the controller performance under steady-state, the torque command (Td) was set to 25 N.m, the motor speed was 1000 rpm, and the rotor inertia was set to a very high value to keep the vehicle speed constant. The output of all the four phases is shown in figure 4.4.



4.4 Flux, current, torque and speed of a SRM with a torque reference of 25 Nm.

V. CONCLUSION

ANFIS based torque controller has been presented in this paper for tractive application at low speeds. By using ANFIS controller, the SRM exhibits good steady-state and dynamic performances. The SRM can produce maximum torque quickly while needing short duration overload ability.

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