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Switched Reluctance Motor Drive Controller Design using Adaptive Neuro-Fuzzy Controller

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Abstract: Switched reluctance motors (SRM) has dominant features like simple structure and robustness has raised quest among the researchers to make them suitable even in fault tolerant, poor operating conditions and employed for high- performance motion control applications. However, SRM possess higher torque ripple due to presence of flux harmonics in the air gap which reduces the functionality of the high- performance drive applications compared to other conventional drives. This paper intent at the torque ripples minimization (TRM) of SRM drive using Adaptive Neuro-Fuzzy Inference System (ANFIS). Artificial Neural Network (ANN), Fuzzy Logic Control (FLC) and ANFIS controllers are designed and simulated using Matlab/Simulink.The results of the simulations demonstrate that the considered ANFIS controller produces an excellent dynamic performance of the machine. The performance of ANN & ANFIS based techniques is superior to FLC based controller. Owing to the strong learning & generalization characteristics, ANFIS performs better than ANN & FLC, which enhances the dynamic performance of SRM drives. ANFIS gives improved performance than ANN and FLC due to its good learning and generalization capabilities thereby improves the dynamic characteristics of the SR Motor based drives.

Keywords: *Torque ripple, Switched Reluctance Motor (SRM), Fuzzy Logic Control (FLC), Adaptive Neuro-Fuzzy Inference System (ANFIS), Artificial Neural Network (ANN).*

1. Introduction

Owing to its inherent advantages like simplicity, ruggedness, large torque/inertia proportion, flexible in the harmful atmosphere, high speediness of SRM drives finds wide application in both domestic and industrial applications [1] to [2]. Nevertheless, its double salient structure and non-linearity becomes the major cause of torque ripple causing acoustic noise resulting in vibration and which in turn limits its widespread application in adjustable speed drives [3] to [4]. Different literatures report on various methods suggested in order diminishing torque ripple, their control methods, comparative analysis of various controllers and their applications [1] to [15]. At present, the torque ripple reduction involves basically two fundamental techniques. They are by improving the magnetic model of the drive and another one is the employment of advanced electronic equipment based control. The change in stator and pole structures could Reduce torque ripples, still it affects the motor performance. The electronic control involves operating parameters like the input voltage, ON & OFF boundaries, level of current & the amount of loading on shaft. However, the reduction of torque ripples leads to a decrease of the normal torque. The motor proficiencies are not fully utilized at each rotor position. Therefore, torque improvement and ripple minimization could not be realized simultaneously [16] to [18] There are many classical torque controlling methods to reduce torque ripple analyzed in the literature, they are Direct Instantaneous torque control technique, Pulse width Modulation Method, Artificial Neural network, Fuzzy Compensation Method which are most adequately applied control means to decrease torque ripple. Another method for torque ripple minimization is by using apt converters. Several power electronics converter topology has been developed over the year purely for SRM drives. The converter acts as the power supply unit to regulate the current to meet the SRM drives requirement. [19] to [22-26]. This study aims at description of SRM model and its functionality analysis. The three different intelligent controllers namely fuzzy logic control (FLC), ANN&ANFIS are studied and assessed. The performance analysis in terms of voltage, current, flux, speed and torque are investigated. The ANFIS control algorithm which combines the merits of the expert knowhow of the FLC & learning capability of neural systems to reduce the torque ripple so as to obtain the dynamic performance of SRM drives. The ANFIS methodology be able to diminish torque ripple through controlling torque inside the band limit of quantified hysteresis

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2. Literature Survey

The remaining sections of the paper is categorized as follows, section III briefs the modelling of SRM drive and section IV describes the adaptive Neuro-fuzzy system architecture and their implementation in SRM drive. Section V analyses the simulation results and their comparative analysis with ANN and FLC system. By using ANFIS method the results are improved when compared to conventional control methods and Conclusions are presented in section VI

2.1. Modeling of SRM and its description

The rotor of an SRM is comprised of steel laminations deprived of conductors & permanent magnets and it solely has stator windings.This drastically lowers its cost and simplifies its construction. The enhanced power electronics components and its mechanical simplicity have led to additional research discoveries in the past few years. The SRM's motion is caused due to the fluctuating reluctance along air gap among the stator & rotor. Exciting the stator coil creates a magnetic field, and the rotor's propensity to move to its minimal reluctance location results in the reluctance torque.Fig.1 illustrates the cross-sectional view of 8/6 SRM.

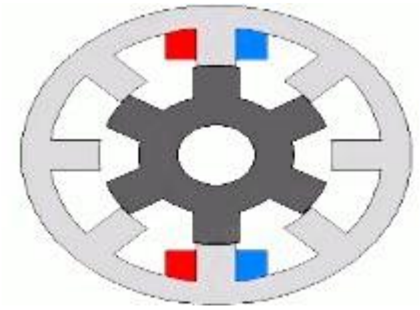

Fig.1. 8/6 Switched Reluctance Motor

The system employed for investigation is as depicted in the figure number 2. The Half-bridge asymmetric converter is the main component of power circuit. The stator of SRM is excited by the output of the converter. The feedback and the reference speed forms the basis for ANFIS inputs, while the current reference is generated by integrating the ANFIS output. The dynamic modelling equations of SRM is developed using the following equations (1) – (10). The instantaneous voltage applied to stator of SRM is given by (1). The non-linear association of the flux linkages, current & the rotor position (angle θ) is expressed as (2).

$$V_j = Ri_j + \frac{d\psi_j(\theta, i_j)}{dt},$$

j= {1, 2, 3, 4} (1)

The double saliency of SRM effects its magnetizing characteristics resulting in variation of flux with the change in current & position of the rotor. The equation (1) is modified as (2)

$$V = Ri + \frac{d\psi}{di}\frac{di}{dt} + \frac{d\psi}{d\theta}\frac{d\theta}{dt} \quad (2)$$

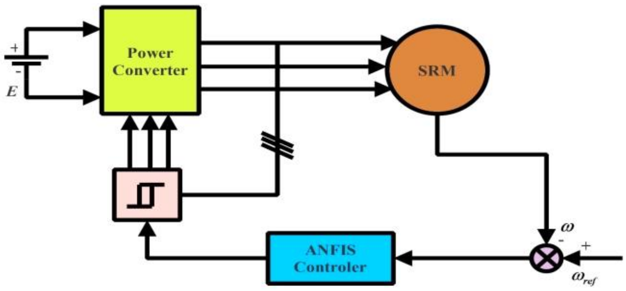

Fig.2. SRM Control structure using intelligent controller

Here $\partial\psi/\partial i$ indicates the instantaneous inductance L(θ,I) & $\frac{\partial\psi}{\partial\theta}\frac{\partial\theta}{\partial t}$ denotes instantaneous back emf..The partial differentiation of total energy function w.r.t rotor position represents the torque. The relation between magnetic torque and space distribution of inductance is given by equation (3)

$$T = \frac{1}{2}\left(\frac{\partial L}{\partial\theta} i_a^2 + \frac{\partial L}{\partial\theta} i_b^2 + \frac{\partial L}{\partial\theta} i_c^2\right) \quad (3)$$

3. Principle of Adaptive Neuro-Fuzzy Control

The schematic of the proposed system is shown in Figure number3. Equations (11) & (12) are used to model the error & change in error as inputs of ANFIS controller. ANFIS structure is presented inFigure4 where fixed node and adaptive node are indicated by circle and square respectively. Here, the 2 inputs are *x*, *y* and single output *z* are considered. Amidst with available FIS structures, due to its excellent interpretability, high computational efficiency, and integrated optimal and adaptive strategies, the Sugeno model is the one that is used the most frequently. The main advantage of Sugeno model no membership function is required at output it is well suited for mathematical analysis sugeno model contains more flexibility in the system design Equation number (4) is used to represent the common rule with 2 fuzzy if-then decrees for a 1storder Sugeno model.

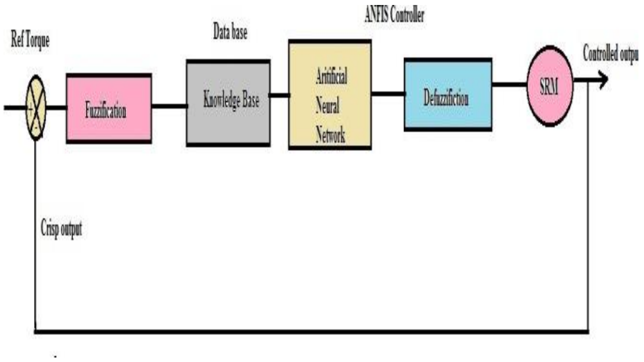

Fig 3 Schematic of ANFIS controllers

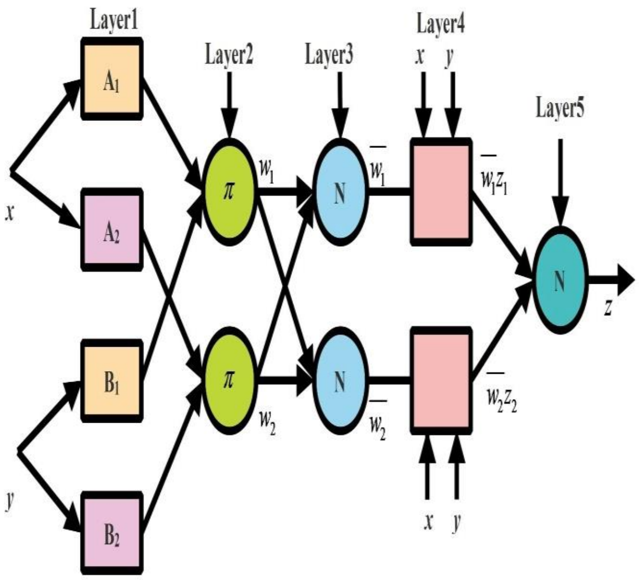

Fig 4 ANFIS structure

Rule 1: x is A_1 and y is B_1 then $z_1=p_1x+q_1y+r_1$

Rule 2: x is A_2 and y is B_2 then $z_2=p_2x+q_2y+r_2$'

where Ai and Bi - fuzzy sets in the antecedent p_i,$q_i$and r_i – design parameters determined in the training process

ANFIS structure considered for analysis has 5 layers where

Layer 1: The following equation (5) gives each node *i* in the first layer which utilizes a node function

$$O_i^1 = \mu_{A_i}(x), \quad i = 1,2 \tag{5}$$

$$O_i^1 = \mu_{Bi}(y), \quad i = 3,4$$

where any fuzzy membership function (MF) can be adopted by μ_{A_i} and μ_{Bi}

Layer2: Here, each node calculates the rule's firing strength using multiplication

$$O_i^2 = w_i = \mu_{A_i}(x)\mu_{Bi}(y), \quad i = 1,2 \tag{6}$$

Layer 3: The i[th] node ofcurrent layer computes the ratio of the firing strength of i[th] rule to the total firing strength of other all rules.

$$O_i^3 = \bar{w_i} = \frac{w_i}{w_2+w_2}, i = 1,2 \tag{7}$$

Here $\bar{w_i}$ is defined the normal firing strength

Layer 4: The following function is present in every node of this layer

$$O_i^4 = \bar{w_i}z_i = \bar{w_i}(p_ix+q_iy+r_i), \quad i = 1,2 \tag{8}$$

Here $\bar{\bar{w}}_i$ indicates the output of layer 3 &$\{p, q, r\}$ represent the set of parameters.

Layer 5: This level gives the complete output which is the total sum of every single inputs given by (9)

$$O_i^5 = \sum_{i=1}^{2} \bar{w_i}z_i = \frac{w_1z_1+w_2z_2}{w_1+w_2} \tag{9}$$

The output z derived from (5)-(9) is simplified as

$$z = (\bar{w}_1 x)p_1 + (\bar{\bar{w}}_1 y)q_1 + (\bar{\bar{w}}_1)r_1)$$

$$+ (\bar{w}_2 x)p_2 + (\bar{\bar{w}}_2 y)p_2 + (\bar{\bar{w}}_2)r_2 \tag{10}$$

The reference current (I_{ref}), s generated by ANFIS controller depending upon the error in speed (e) & its derivative (de)

$$e = \omega_{ref} - \omega \tag{11}$$

$$de = \frac{d(\omega_{ref}-\omega)}{dt} \tag{12}$$

Here ω_{ref} & ω represents the reference value of speed &real speed.

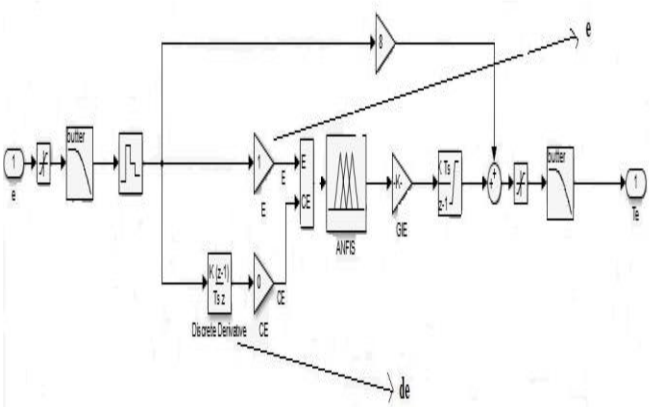

Fig.5 Simulation diagram of ANFIS control

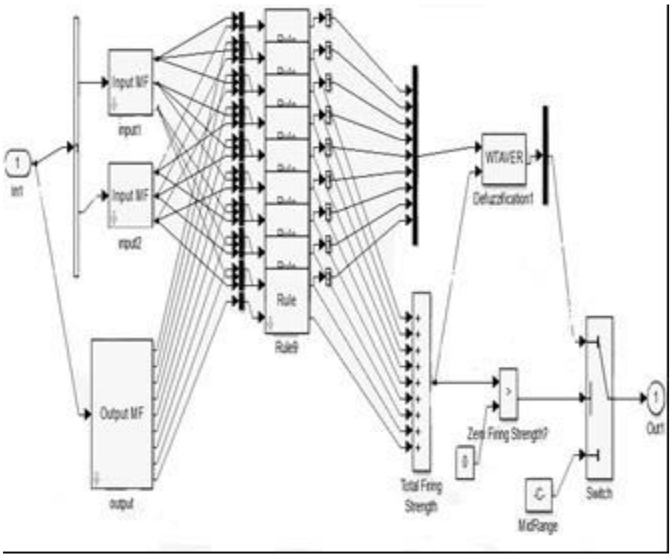

Fig.6 Sugeno Model FIS

Fuzzy rule based on Sugeno Model based FIS is utilized in this system & it's given by (13)

If e is A_i & de is Bi then z=f(e,de) (13)

Fuzzy sets in antecedent are illustrated as *A, B* and crisp function in consequent are given by z = *f(e,de)*

The ANFIS structure's significance employed here is described as:

Layer 1: Here, node function is triangular membership function where every adaptive node of this step produces the membership grades of input vectors *Ai=1, 2, & 3*

$$O_i^1 = \mu_{A_i}(e) = \{0\ ;\ e \leq a_i,\quad \frac{e-a_i}{b_i-a_i}\ ;\ a_{i\leq e\leq b_i}\quad \frac{c_i-e}{c_i-b_i}\ ;\ b_{i\leq e\leq c_i} \tag{14}$$

Layer 2: There are 25 rules in all in this tier. The triggering level of every rule indicates the output of each node:

$$O_i^2 = w_i = \min\ (\mu_{A_i}(e)\mu_{Bi}(de), \quad i = 1,2\ \&\ 3 \tag{15}$$

Layer 3: The proportion of i^{th} rule's triggering level to sum of all triggering levels is obtained by fixed node I of this tier.

$$O_i^3 = \bar{w_i} = \frac{w_i}{\sum_{j=1}^{n} w_j} \tag{16}$$

Layer 4: A flexible node i use the succeeding node function to compute the i^{th} rule's contribution to the overall output at this tier.

$$O_i^4 = \bar{w_i}z_i = \bar{w_i}(p_i e + q_i de + r_i) \tag{17}$$

Layer 5: This layer's lone fixed node calculates the total output as the sum of the contributions with very rule.

$$O_i^5 = \sum_{i=1}^{2} \bar{w_i}z_i = \frac{w_1 z_1 + w_2 z_2}{w_1 + w_2} \tag{18}$$

A total of one hundred epochs are utilized for the training purposes. The input variables e has 3 MF's and de has 3 respectively. Hence the over-all count of rules comprises of the product of MF's of e and de and is then 9 (3·3 = 9). The 2 input variables employ triangular MF. Equation (14) makes it very evident that 2 parameters define the triangular function.

4. Results

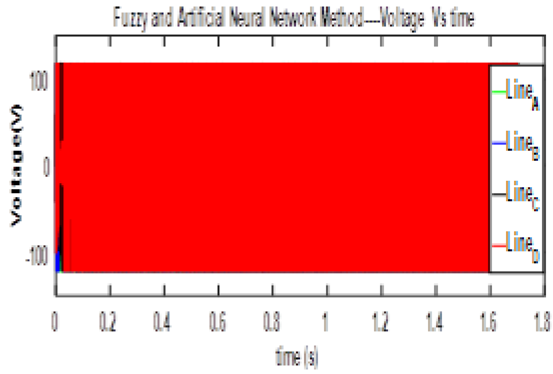

Figure shows the voltage curve of the 8/6 SRM drive Voltages VA, VB, VC, VD are plotted with respect to Time using the ANFIS controller

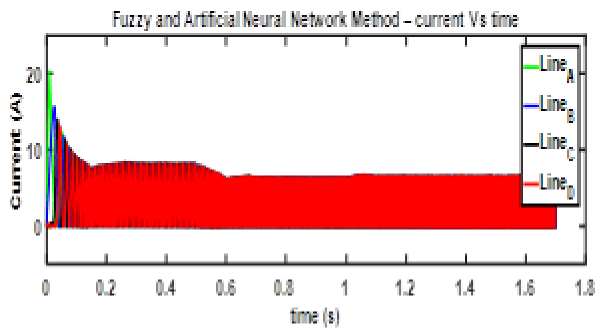

Figure shows the current curve of the 8/6 SRM drive Currents IA, IB, IC, ID are plotted with respect to Time using the ANFIS controller

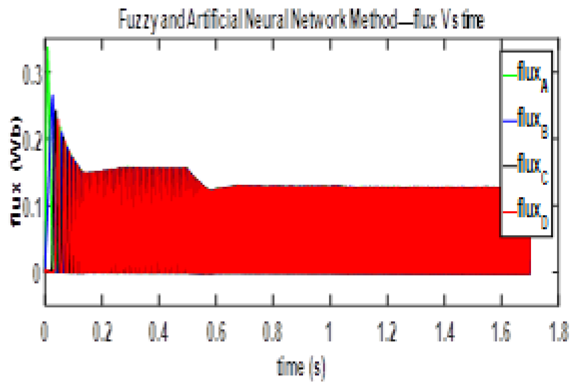

Figure shows the flux curve of the 8/6 SRM drive   Fluxes ϕA, ϕB, ϕC, ϕD, are plotted with respect to Time using the ANFIS controller

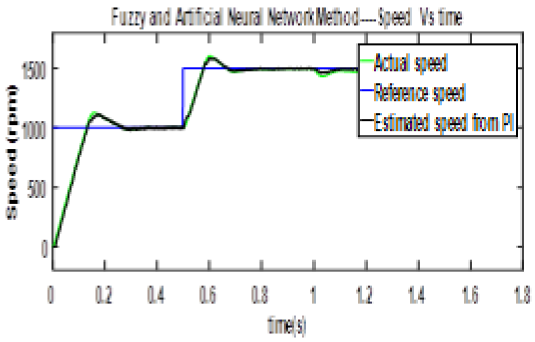

Figure shows the speed curve of the 8/6 SRM drive Speed in RPM are plotted with respect to Time using the ANFIS controller

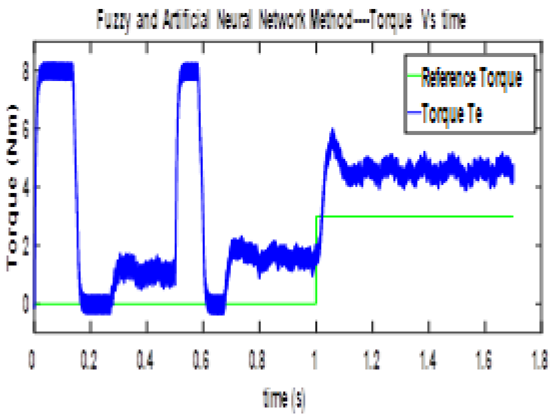

Figure shows the speed curve of the 8/6 SRM drive Torque in N-M are plotted with respect to Time using the ANFIS controller

5. Discussion

The torque ripple minimization utilizing ANFIS is investigated in this study where the proposed controller is utilized to limit the torque swell and to give better torque reaction. The torque ripples in SRM machine are currently being reduced using current compensating approaches based on FLC & ANFIS in this research. The total torque, speed's settling time & coefficient of torque ripple are all presented. The implementation of a traditional PI based controller is too taken into account for comparing purposes. According to the results of the simulation, FLC &ANFIS based controllers perform better than PI based controllers.

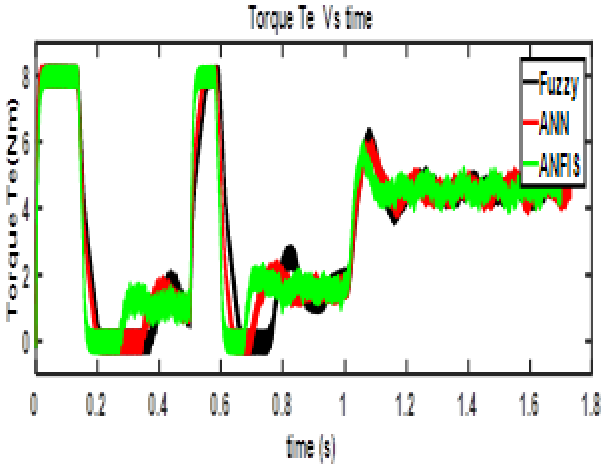

Figure shows Steady state results of FLC, ANN and ANFIS controller

6. Conclusions

ANFIS amongst the intelligent controllers enhances the dynamic operation of the SRM drives more than FLC because of its strong generalization and learning skills. The torque ripple reduction employing ANFIS is investigated in this study where the projected controller is applied to restrict the torque raise and to provide improved torque response. The torque ripples in SRM machine are currently being reduced using current compensating approaches based on FLC & amp; ANFIS in this research. The simulation findings show how the machine with the ANFIS controller has better robust characteristics. More dynamic performance is provided by ANFIS and ANN controllers than FLC controller. The ANFIS's strong learning and generalisation skills provide it potential performance over ANN and FLC, which boosts the SRM drives' dynamic performance.

Author contributions

Nagesh Kudupudi1: Conceptualization, ANFIS, Matlab Software, Field study **Lenine D2:** Data curation, Writing-Original draft preparation, Software, Validation. Field study **Sujatha P 3:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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