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ANFIS Based Direct Torque Control of Induction Motor Drives

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ABSTRACT

This paper presents an adaptive Neural-Fuzzy control scheme to implement direct torque control (DTC) of induction motor (IM) drives. The Adaptive Neural-Fuzzy Inference System (ANFIS) is an intelligent control scheme that brings together the attributes of both Fuzzy Logic Control (FLC) & Artificial Neural Networks (ANN). Operation of the suggested ANFIS Controller is evaluated against that of the Proportional-Integral (PI) controller used in Space Vector Modulated DTC (SVM-DTC), and the two systems have been compared with classical DTC as well. The results of scalar speed control method have also been presented for the purpose of comparison. The ANFIS based controllers can be more economically developed, cover a wider range of operating conditions and are easier to adapt. The simulation results show that substituting the PI controller with the ANFIS controller has considerably reduced the ripples and overshoot in torque, as well as the momentary speed fluctuations due to step changes in load. The system implementation has taken place by the means of MATLAB/Simulink application with the aid of Fuzzy Logic Toolbox.

***Keywords* — ANFIS, Direct Torque Control, Induction Motor, Neuro-Fuzzy Control.**

1. INTRODUCTION

In the year 1984, M Depenbrock originally received a patent for conventional direct torque control (DTC), known as direct self - control (DSC) at that time [1]. I Takahashi and T Noguchi described the DTC technique as it is known today in a paper published in late 1986 [2]. This new and simpler approach replaced the existing Field-Oriented Control (FOC) strategy. This scheme entails directly regulating the flux and torque of the motor. Efficient and accurate implementation of DTC depends on the estimation of induction motor's torque and flux. However, pulsations in the torque, flux, and current were observed during steady state operation under this scheme. Consequently, a novel DTC schema dependant on space vector PWM control was introduced in an attempt to eliminate these flaws from the system [3], [4].

Several modern techniques to achieve optimization of direct torque control have also been explored over the years [5].

The Proportional-Integral (PI) controllers used in classical DTC of IM drives are ridden with problems of overshoot, slow settling time and complicated tuning [6]. Furthermore, they are sensitive to variations in parameters, system non-linearities, and undesired disturbances. These limitations can be eliminated by incorporating AI based control systems like Neuro-Fuzzy Control in the system [7].

Fuzzy logic is a method for controlling a system without the need of any mathematical model of plant [8]. It relies on the expertise of individual's knowledge to create its rule base [9]. An Artificial Neural Network (ANN) has learning abilities and thus, it has the ability to foresee how a system would behave based on its prior experience gained using an array of training data [10].

An ANFIS controller, thus, combines into a single framework the working and advantages of ANN and FLC to obtain desired results [11]-[13]. This paper presents improvements in the already existing SVM-DTC methodology using the ANFIS controller.

The proposed system displays satisfactory results over a wide range of parameters. Simulation models of Classical DTC, SVM-DTC and ANFIS based SVM-DTC are created in MATLAB/Simulink. The simulation data shows that the ANFIS controller lowers torque and current ripples while enhancing the motor drive's dynamic performance and decreasing fluctuations in speed due to step changes in load.

2. DIRECT TORQUE CONTROL

The Direct Torque Control (DTC) method aims to control the flux and torque independently after decoupling them and so it is similar to its predecessor, Field Oriented Control technique. However, DTC regulates motor torque in a more direct manner, by excluding the voltage/current modulating blocks and bypassing the need of transforming coordinate axes, resulting in a considerably quicker torque response.

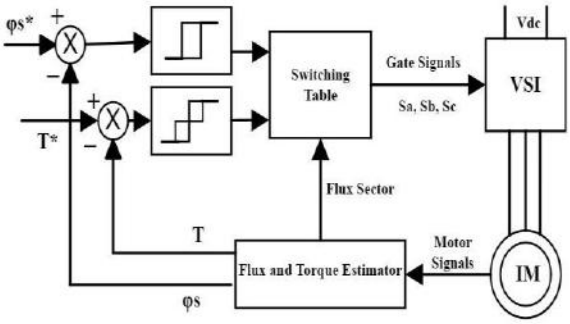


Fig.1 Block Diagram of conventional DTC

The block diagram of DTC is shown in Fig.1. Two different loops are present – one for controlling flux and the other for controlling torque. Torque produced by the IM drive can be written as

$$T_e = \frac{L_m}{\sigma\, L_s\, L_r} \varphi_s\, \varphi_r\, sin\gamma_{sr}$$

where, φ_s and φ_r are respectively the stator and the rotor fluxes, and γ_{sr} is the angle between φ_s and φ_r. This implies that by altering the position of stator flux vector with regard to rotor flux vector's direction it is possible to control the motor torque directly.

The hysteresis comparators compare the stator flux and torque generated by the motor to their corresponding reference values. To maintain the electromagnetic torque inside its hysteresis band, the voltage space vectors are appropriately selected.

A three-level hysteresis comparator is utilised for this purpose. When it comes into contact with the lower band, torque is increased promptly, and when it comes into contact with the higher band, torque is immediately reduced. If the torque error status is dT_e = -1, a drop in torque is necessary, whereas dT_e = 1 necessitates an increase in torque magnitude. dT_e = 0 indicates that no torque adjustment is required [14]. These conditions can be summarised as

$$dT_e = 1 \quad if \quad T_e \leq T_e{}^*$$
$$dT_e = 0 \quad if \quad T_e = T_e{}^*$$
$$dT_e = -1 \quad if \quad T_e \geq T_e{}^*$$

where, $T_e{}^*$ denotes the reference value of torque, T_e is the actual torque and dT_e is the status of torque error delivered by the hysteresis comparator. The diagram of torque hysteresis regulation is shown in Fig. 2.

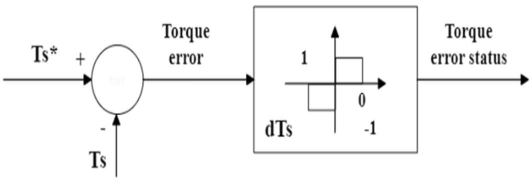


Fig. 2 Torque Hysteresis Control

The absolute value of stator flux is restricted inside its hysteresis band, causing it to trace a circular trajectory. To assess the relative magnitude of actual flux and evaluate it against a reference value, a 2-level hysteresis comparator is used. The block diagram of flux hysteresis control is depicted in Fig. 3

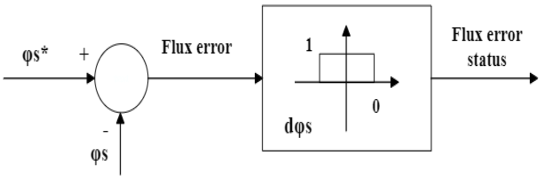


Fig. 3 Flux Hysteresis Control

The flux magnitude is increased by the controller when the value of flux exceeds the band's lower bound, and the flux magnitude is decreased when it hits the band's upper limit. If the flux error status is $d\varphi_s$ = 1, the stator flux value must be raised, and if it is $d\varphi_s$ = 0, then it is required to be lowered [14]. These conditions have been summarised as

$$d\varphi_s = 1 \quad if \quad |\,\varphi_s\,| \leq |\,\varphi_{s*}\,|$$
$$d\varphi_s = 0 \quad if \quad |\,\varphi_s\,| \geq |\,\varphi_{s*}\,|$$

The control signals are generated by combining the results of both the hysteresis comparators (dT_e and $d\varphi_s$), as well as the orientation of the vector of stator flux (γ_{sr}), and given to a voltage source inverter (VSI). After that, the inverter operates the induction motor by switching the appropriate voltage vector.

In order to identify the appropriate voltage vector, the VSI switches are operated according to the data shown in Table 1.

Table 2. Switching Table for Direct Torque Control

Sector		1	2	3	4	5	6
$d\varphi_s$	dT_e						
0	1	V_{011}	V_{100}	V_{101}	V_{110}	V_{001}	V_{010}
	0	V_{111}	V_{000}	V_{111}	V_{000}	V_{111}	V_{000}
	-1	V_{101}	V_{110}	V_{001}	V_{010}	V_{011}	V_{100}
1	1	V_{010}	V_{011}	V_{100}	V_{101}	V_{110}	V_{001}
	0	V_{000}	V_{111}	V_{000}	V_{111}	V_{000}	V_{111}
	-1	V_{110}	V_{001}	V_{010}	V_{011}	V_{100}	V_{101}

A graphical representation of the voltage space vectors has been shown in Fig.4. For a two-level inverter, the direct-quadrature (d-q) plane is divided into six identical sectors by the space vectors and each sector spans for 60º [15].

Fast dynamic reaction, a simple control system, the absence of coordinate system transformations, position feedback, and current regulators are all benefits of DTC. The several downsides of classical DTC include excessive ripples in torque and flux in steady state because to the existence of hysteresis bands, poor performance at low speeds and during acceleration, and distortions in the stator current.

The changeable switching frequency in DTC results from variations in how long it takes the error in torque to reach the lower and upper hysteresis limits. It ends up causing acoustic noise and vibrations. To overcome these drawbacks, space vector modulation was introduced to DTC as a correcting remedy [16].

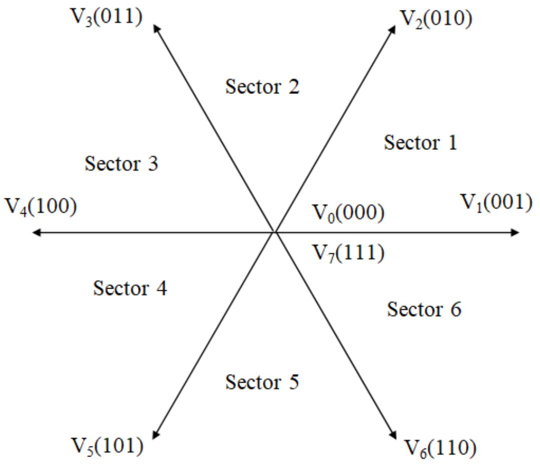


Fig. 4 Voltage Space Vector Diagram For DTC-Driven Induction Motor

3. ANFIS CONTROLLER

The retraining properties of neural networks and fuzzy logic's knowledge representation are put together to form fuzzy neural networks. Thus, the incapacity of neural networks to explain decisions (absence of transparency) as well as the shortcomings of fuzzy logic training have been overcome by adaptive neural network-dependant fuzzy inference system called ANFIS [17], [18].

The ANFIS Toolbox in MATLAB performs the membership function parameter adjustments. Fig.5 shows a five-layer Sugeno-type ANFIS Controller taking two inputs and giving a single output function.

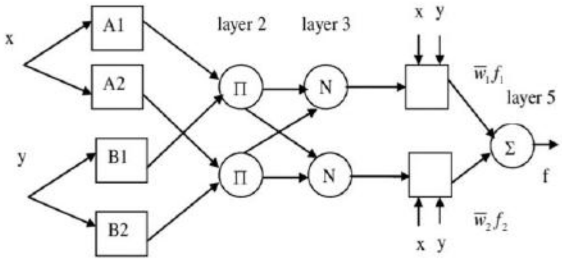


Fig. 5 Architecture of A 5-Layer ANFIS Controller

An FIS is created with the aid of a neural network. The neural network training approach can be used to identify the rule base and membership functions (MFs) of the fuzzy logic controller (FLC) from the input/output pairs of the target system. The weights are chosen at random at the commencement of ANFIS training. At the end of every epoch, the weights are modified until the difference between the calculated and desired values is within satisfactory bounds [19].

Sugeno-type Fuzzy Inference Systems give outputs that are a linear combination of their inputs and can be written as follows:

$$\text{If } x \text{ is } M_k \text{ AND } y \text{ is } N_k, \text{ then}$$

$$f_k = a_k x + b_k y + c_k$$

where number of rules is denoted by k, and a_k, b_k, and c_k are the linear parameters for the k^{th} rule.

The error difference between the actual and reference motor speeds is sent into the controller as input, and reference torque is generated at the output port. Hybrid training method is used to train the ANFIS. This methodology assimilates into one the backpropagation gradient descent method and method of least-squares.

In this present work, a number of membership functions were tested and it has been found that the triangular MF (trimf) gave minimal training error after 50 epochs when applied to train the ANFIS for SVM-DTC. This was, therefore, selected to design the Fuzzy Logic Controllers (FLC).

The Root Mean Square Error (RMSE) corresponding to different membership functions during the training of ANFIS is shown in Table 2.

Table 2. Training Errors for Different Membership Functions For SVM-DTC

Membership Function	RMSE
trimf	0.33043
trapmf	0.37382
gbellmf	0.36869
gaussmf	0.36053
gauss2mf	0.35440
pimf	0.38090
dsigmf	0.38191
psigmf	0.38398

4. SIMULATION RESULTS

The systems discussed in this paper have been modelled using Simulink application of MATLAB software package (version R2020b). A contrastive analysis of classical DTC, Space Vector Modulated DTC and SVM - DTC using ANFIS based controller has been done, under different load conditions. A study of scaler control method has also been done under the same conditions and presented alongside for the purpose of comparison.

The various parameters associated with the single squirrel cage induction motor drive used for simulation have been given in Table 3.

Table 3. Parameters of Induction Motor

Nominal Power, P_n	164 KW
Rated Voltage, V_n	550 V
Rated Frequency, f_n	60 Hz
Rated No Load Speed	1800 rpm
Stator Resistance R_s	0.0139 pu
Rotor Resistance R_r	0.0112 pu
Stator Leakage Inductance L_{ls}	0.0672 pu
Rotor Leakage Inductance L_{lr}	0.0672 pu
Rotor Inductance, L_r	2.7842 pu
Magnetizing Inductance, L_m	2.717 pu
Stator Inductance, L_s	2.7842 pu
Moment Of Inertia, H	0.2734 kg m^2
Number of Pole Pairs	2
Friction Coefficient, F	0.0106 pu

Reference speed of 1600 rpm has been given to the drive system at 0.4 seconds. Load torque has been taken in steps of 1 pu and -1 pu at time t = 1.6 seconds and t = 2.1 seconds respectively. The base value of torque is 870 N-m. The response of the controllers to changes in speed and torque conditions has been studied and compared from various characteristics obtained. The Simulink model of SVM - DTC and ANFIS based DTC used for simulation has been shown in Fig. 6. A manual switch has been used to toggle between the two control modes – PI and FLC.

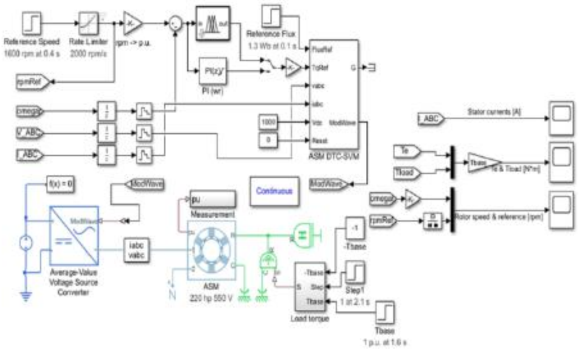
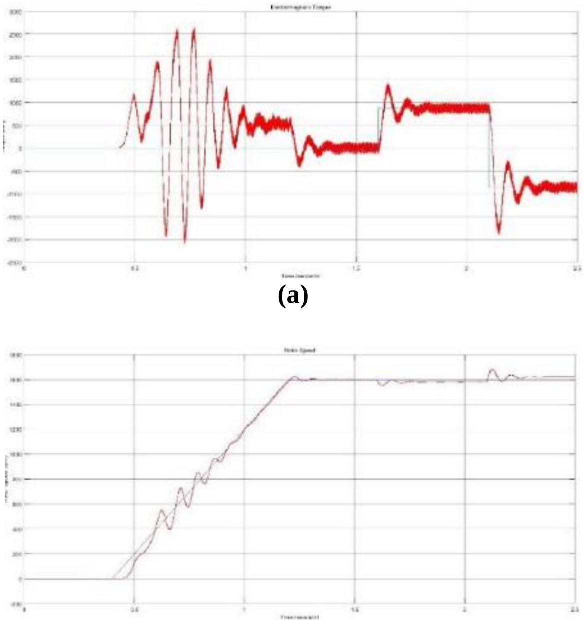


Fig. 6 Simulink Model for Implementation of SVM - DTC and ANFIS Based SVM-DTC

Fig. 7 (a) & (b) displays the torque and speed curves of the induction motor against time for scaler speed control method. The torque and speed both exhibit substantial ripples and large overshoot whenever there is a change in the corresponding reference values.

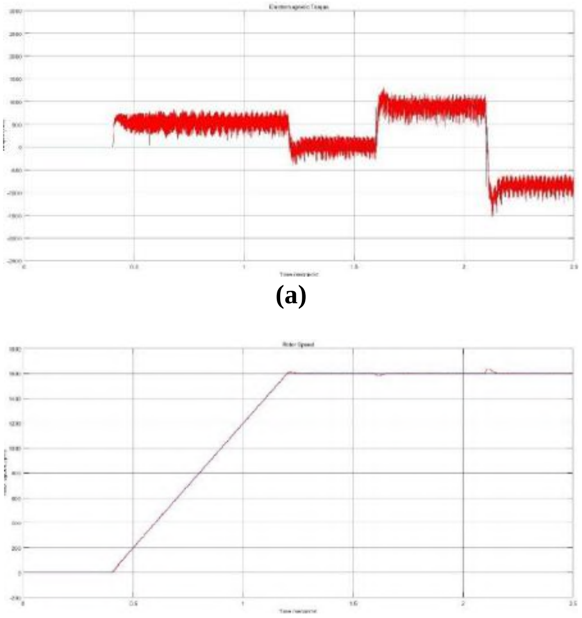


(a)

(b)

Fig.7 (a) Torque vs Time, (b) Rotor Speed vs Time for Scalar Speed Control

Fig. 8 (a) & (b) depicts the torque and the speed characteristics plotted against time, for the IM drive under conventional DTC scheme. The ripples in both torque and speed, and speed fluctuations are all significantly less in contrast to the scalar control method.

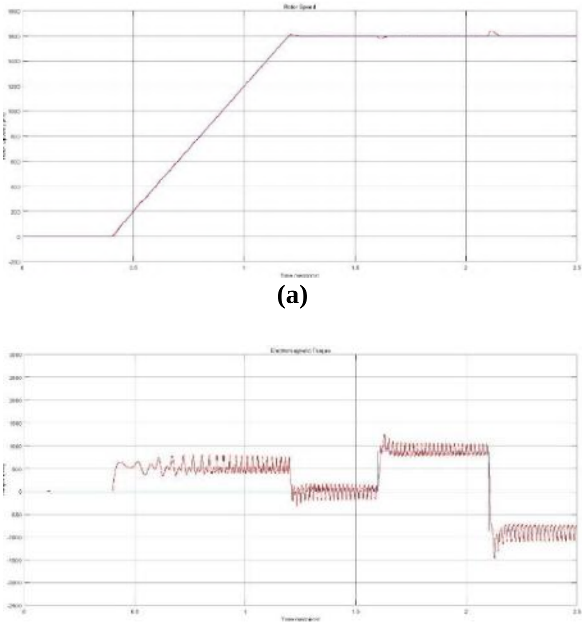


(a)

(b)

Fig.8 (a) Torque vs Time, (b) Rotor Speed vs Time for Conventional DTC

Fig. 9 (a) & (b) shows the characteristics of torque and speed for an IM drive when operated using the SVM - DTC approach. In relation to the traditional DTC operation, current and torque ripples are very less and speed fluctuation is comparable.

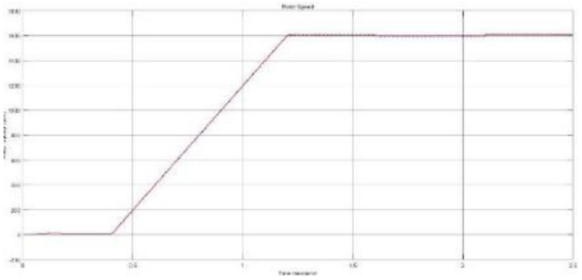


(a)

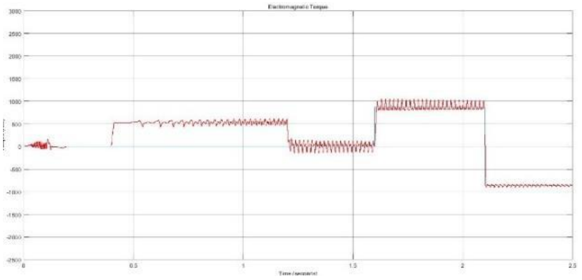
(b)

Fig.9 (a) Torque vs Time, (b) Rotor Speed vs Time for SVM-DTC

Fig.10 (a) & (b) presents the characteristics of speed and the torque of an IM drive under the application of ANFIS based SVM - DTC. The torque ripples in this case are minimal and the overshoot in speed and torque has been eliminated. The speed fluctuations at the instances of step load changes have also been greatly subdued.



(a)



(b)

Fig.10 (a) Torque vs Time, (b) Rotor Speed vs Time for ANFIS Based SVM-DTC

The results of simulation have been summarised in Table 4 and Table 5.

Table 4. Peak Overshoot in Torque

Peak Overshoot in Torque (in %)			
Time	**C-DTC**	**SVM-DTC**	**ANFIS Based SVM-DTC**
At 1.6 sec	26.55%	22.18%	7.19%
At 2.1 sec	48.38%	42.18%	9.71%

Table 5. Fluctuation in Motor Speed for Step Change in Load

Fluctuation in Motor Speed for Step Change in Load (in %)			
Time	**C-DTC**	**SVM-DTC**	**ANFIS Based SVM-DTC**
At 1.6 sec	-1.19 %	-1.19 %	-0.38 %
At 2.1 sec	2.31 %	2.50 %	0.87 %

5. CONCLUSION

Implementation of the ANFIS Regulator has been put forth in this paper for an IM drive. Software simulations were used to carry out the system analysis under various conditions of operation.

The speed of the drive can be managed more efficiently with the ANFIS controller in contrast to standard PI controllers. Incorporating the ANFIS controller in space vector modulation technique has positively enhanced its characteristics. The torque ripples have been reduced to a satisfactory level. Furthermore, the system's transient response has improved and most notably the overshoot in torque and speed has considerably diminished. The momentary changes in rotor speed produced at the instances of step change in load have also been decreased.

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