Analysis of fuzzy and neural controllers in direct torque controlled synchronous motors

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ABSTRACT

In this study, multiple intelligent control systems for direct torque-controlled Synchronous motors are implemented and compared. Using a lookup table to pick a vector through the inverter voltage space, the direct torque control (DTC) system can be obtained. To replicate the state selector in relation to the look-up table, intelligent controllers are deployed. Intelligent logic controllers like fuzzy and neural are used to regulate the performance of permanent magnet synchronous motors (PMSM). In steady-state applications, neural and fuzzy controllers reduce the torque ripple and stator current harmonic distortion. These outcomes are compared with those obtained when the synchronous motor was put under the basic direct torque control method using a proportional integral (PI) controller. The accuracy and effectiveness of the suggested control topologies have been verified using computer simulation software like MATLAB/Simulink.

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NOMENCLATURE

Vs(d,q)	: Stator voltage in d and q axis	Vdc	: DC link voltage
Rs	: Stator resistance	V1(1,2)	: Weights between input layer and hidden layer
Ls	: Stator inductance	Bh	: Bias value connected to hidden layer
Te	: Electro magnetic torque	W1(1,2)	: Weight values connected to output layer
Tload	: Load torque	Bo	: Bias value connected to output layer
J	: Moment of Inertia	N(b,m,s)	: Negative (big, medium, small)
Is(d,q)	: Stator current in d and q axis	P(b,m,s)	: Positive (big, medium, small)
nP	: Number of poles	Ze	: Zero
S(a,b,c)	: Switching sectors of inverter	E	: Error
Test	: Estimated torque	ΔE	: Change in error
Tref	: Reference torque		
			Greek symbols
Ψ*	: Reference flux	Ψs	: Stator flux
Ψ	: Total flux	ω	: Rotor speed
Ψs(d,q)	: Stator flux in d and q axis	ω*	: Reference speed

1. INTRODUCTION

Drives for permanent magnet synchronous motors that are vector controlled play a significant role in the sector. These regulated drives, however, call for intricate coordinate transformation, exact system settings, and an inner current control loop [1]–[3]. The direct torque control (DTC) technique, on the other hand, provides a powerful and quick torque response while avoiding current regulators, coordinate transformation, and pulse-width modulation (PWM) pulse production [4], [5].

Because no inverter-switching vector can deliver the precise stator voltage at the right times and in space, this approach is severely limited by steady state torque ripple and flux [6]–[8]. Torque and flux ripples produce substantial acoustic noise and harmonic losses, which have an impact on speed estimation accuracy [9]–[11]. To lessen this flux and torque ripple, various techniques are available: i) the different inverter topologies, matrix converters, and multilevel inverters [12] that increase the quantity of switches and, as a result, the cost and operational complexity; ii) the content of harmonic in current for stator, Stator torque and ripple in flux decreases with the increase in switching of frequencies. The stress and losses in the semiconductor switches of the inverter will increase due to these increased switching frequencies [13]–[15]; iii) space vector modulation is a different approach to decreasing flux and torque ripples [16], although it has the drawback of having a variable switching frequency [17]–[21]. The discrete space vector modulation [22] technology solves the drawbacks of the support vector machine (SVM) approach with a precise switching table and five level hysteresis bands, yet this scheme cannot guarantee its performance at low speed ranges, especially with heavy load [23]–[25]; and iv) additionally, this method requires more complex control systems than classical DTC and is dependent on machine parameters.

Alternate switching additional alternative techniques that have been discussed in the literature include table-based DTC [26], flux and torque hysteresis bands are under open loop control with variable amplitude control [27], [28], combining flux and torque hysteresis bands with variable amplitude control based on fuzzy logic [29]–[31]. Similar to simple DTC, by using the chosen inverter voltage vector only for a portion of the switching time rather than the entire switching period, the torque and flux ripple can be reduced. Without increasing the number of semiconductor switches in the inverter model, this control method, often referred to as duty ratio control, increases the number of voltage vectors beyond the eight discrete ones that are now present [32]–[34]. Similar studies reported in [35], [36] claim that ripple has been reduced to a value of one-third. Because artificial neural network (ANN) architectures provide several benefits over conventional algorithmic techniques, many scholars from all over the world are interested in the presentation of fuzzy logic and artificial neural networks [37].

The ability to approximate nonlinear functions, ease of training and generalisation, insensitivity to network distortion, simple architecture, and imperfect input data are only a few of the advantages of ANN [38]. In this study, the three stator currents are employed to examine the flux and torque using the input inverter's voltage. The voltage space vector that the inverter would create has been employed as the output of fuzzy logic and neural network controllers [39]. Torque error and stator flux error were the inputs employed in these controllers. When calculating the duty ratio of the inverter switching vectors, fuzzy logic controllers take the difference between the estimated flux and the reference flux into account [40]. Comparing the current work to that in [41]–[43], the torque ripple and stator current harmonics have been greatly reduced. Theoretical concepts, simulation techniques, and their outcomes are examined and contrasted with the fundamental DTC method.

The structure of the full document is as follows: In section 2, it is taught how the permanent magnet synchronous motor's mathematical model and typical DTC work. The use of fuzzy logic controllers in DTC for synchronous motors is discussed in section 3; the use of neural network controllers is discussed in section 4. Section 5 presents the simulation results, comparison, and comments. The job is concluded in section 6.

2. MOTOR WITH PERMANENT MAGNET SYNCHRONOUS DIRECT TORQUE CONTROL

From the corresponding equations provided below, the mathematical model of permanent magnet synchronous motors (PMSM) in the stationary reference frame may be found. In (1) and (2) are the PMSM's stator voltage and current formulae for the d-q reference axis.

$$V_{ds} = R_s i_{ds} + P\Psi_{ds} - \omega\Psi_{qs} \tag{1}$$

$$V_{qs} = R_s i_{qs} + P\Psi_{qs} + \omega\Psi_{ds} \tag{2}$$

In the reference d-q axis, the stator and rotor flux equations are expressed as shown in (3)-(7):

$$\Psi_{ds} = \int (V_{ds} - R_s i_{ds}) dt + \Psi_{ds} \Big|t = 0 \tag{3}$$

$$\Psi_{qs} = \int \left(V_{qs} - R_s i_{qs}\right) dt + \Psi_{qs} \Big|t = 0 \tag{4}$$

$$\Psi_s = \sqrt{(\Psi_{ds}^2 + \Psi_{qs}^2)} \tag{5}$$

$$\Psi_{ds} = L_s i_{ds} \tag{6}$$

$$\Psi_{qs} = L_s i_{qs} \tag{7}$$

the PMSM's relative speed can be calculated as shown in (8):

$$\omega = \int (T_e - T_{load}) \frac{nP}{J} \tag{8}$$

the PMSM's generated electromagnetic torque can be expressed as shown in (9):

$$T_e = \frac{3}{2}\frac{P}{2}(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \tag{9}$$

Figure 1 depicts the block diagram for the fundamental direct torque control approach for PMSM.

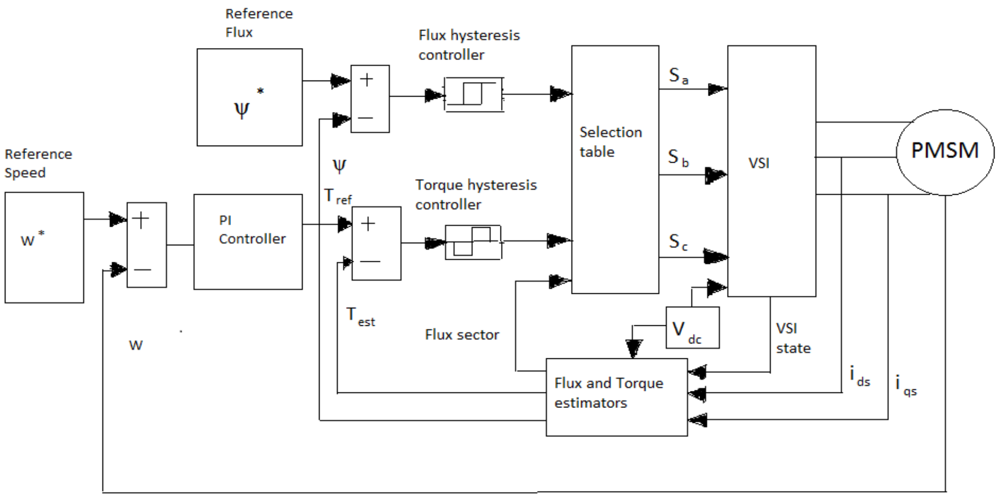

Figure 1. PMSM's fundamental direct torque control system

When little time period $\Delta\Psi s^1 = V_s^1 \Delta t^1$ is applied to the voltage of stator, then, throughout this time, the stator flux space vector moves in the same direction as the applied stator voltage space vector. If the stator resistance (Rs) voltage drop is not included, the stator voltage equation can be expressed in a fixed reference frame as shown in (10):

$$V_s^1 = \frac{d\Psi s^1}{dt} \tag{10}$$

The comparators are used to compare the calculated and reference values of the stator flux linkage and electromagnetic torque. There is a three-level torque comparator as well as a two-level stator flux comparator. As shown in Table 1, the estimated stator flux space vector sector in the complex plane and the comparator outputs serve as the inputs for the best switching lookup table.

Table 1. Basic direct torque control switching section

$\Delta\Psi_s$	ΔT_e	SW1	SW2	SW3	SW4	SW5	SW6
1	1	V_2^1	V_3^1	V_4^1	V_5^1	V_6^1	V_1^1
	0	V_7^1	V_8^1	V_7^1	V_8^1	V_7^1	V_8^1
	-1	V_6^1	V_1^1	V_2^1	V_3^1	V_4^1	V_5^1
0	1	V_3^1	V_4^1	V_5^1	V_6^1	V_1^1	V_2^1
	0	V_8^1	V_7^1	V_8^1	V_7^1	V_8^1	V_7^1
	-1	V_5^1	V_6^1	V_1^1	V_2^1	V_3^1	V_4^1

3. IMPLEMENTATION OF FUZZY CONTROLLER IN DIRECT TORQUE CONTROL OF PMSM

The fundamental DTC scheme of the PMSM is used to create the simulink design for the fuzzy controller-based DTC of the PMSM. Figure 2 depicts the block diagram for the fuzzy logic controller's integration into the PMSM with direct torque control. A collection of rules known as fuzzy rules are derived on the linguistic variables in Mamdani fuzzy logic controller, as depicted in Figure 3. With the two inputs and one output, seven membership functions are fuzzified. Additionally, 49 rule bases are built based on knowledge and computed for decision-making. The centre of gravity (CG) technique is utilised for defuzzification. The control instructions required to select an acceptable voltage vector will be provided by the output of the defuzzification unit. The torque of the drive is then governed by this voltage vector. As shown in (11) and (12) are used to calculate both the error and the change in error;

$$e(k) = \Psi_{ref} - \Psi_{est} \tag{11}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{12}$$

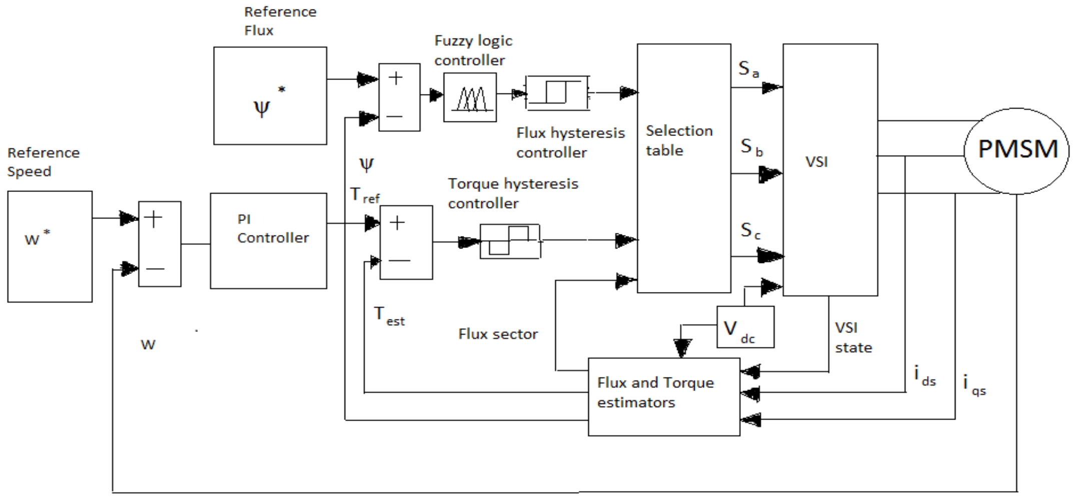

Figure 2. Fuzzy controller-based DTC scheme for PMSM

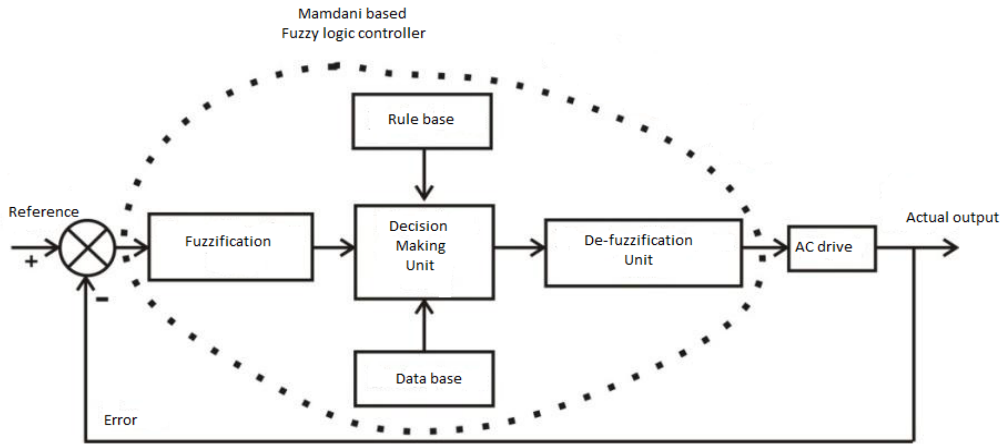

Figure 3. Mamdani-based FLC

Inputs for the direct torque control based PMSM model with flux error and change in flux error are shown in Figure 4 of the generated Simulink fuzzy controller model. A two-input Mamdani fuzzy inference system (FIS) with two rules is implemented via the gauss membership function. The knowledge of the users is used to create a set of language rules that are employed for control techniques, as illustrated in Table 2.

Table 2. Rule base for DTC of PMSM using FLC

er→ Δer ↓	Neb	Nem	Nes	Zoe	Pes	Pem	Peb
Neb	Neb	Neb	Neb	Neb	Nem	Nes	Zoe
Nem	Neb	Neb	Neb	Nem	Nes	Nes	Nes
Nes	Neb	Neb	Nem	Nes	Nes	Nes	Nes
Zoe	Nem	Nem	Nes	Zoe	Pes	Pem	Peb
Pes	Pem	Pem	Pem	Pem	Pem	Peb	Peb
Pem	Nes	Zoe	Pes	Pem	Peb	Peb	Peb
Peb	Zoe	Pes	Pem	Peb	Peb	Peb	Peb

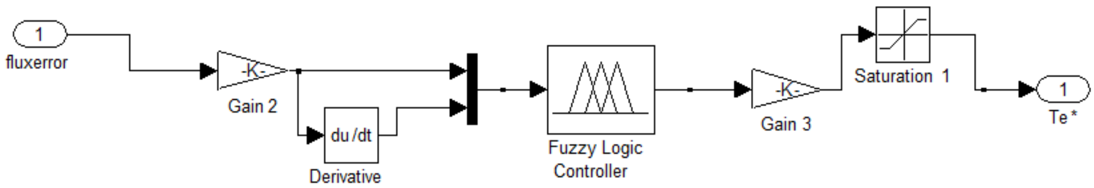

Figure 4. Simulink design of fuzzy controller in DTC

4. IMPLEMENTATION OF NEURAL NETWORK CONTROLLER IN DIRECT TORQUE CONTROL OF PMSM

The fundamental DTC scheme of the PMSM is the foundation upon which the Simulink design for the neural network controller-based DTC of the PMSM is built. The block diagram for synchronous motor direct torque control using neural networks is shown in Figure 5. Because it has at least one feedback loop, a recurrent neural network, like in Figure 6, sets itself apart from other neural networks. One of the most used strategies for training a network is back propagation. During the training phase, the weights are initially initialized at random inside the network. The network's output is then collected and contrasted with the target value. Output layer's weights are adjusted based on the network error, which is estimated and applied. The weights of the earlier levels are updated similarly by propagating the network mistake backward.

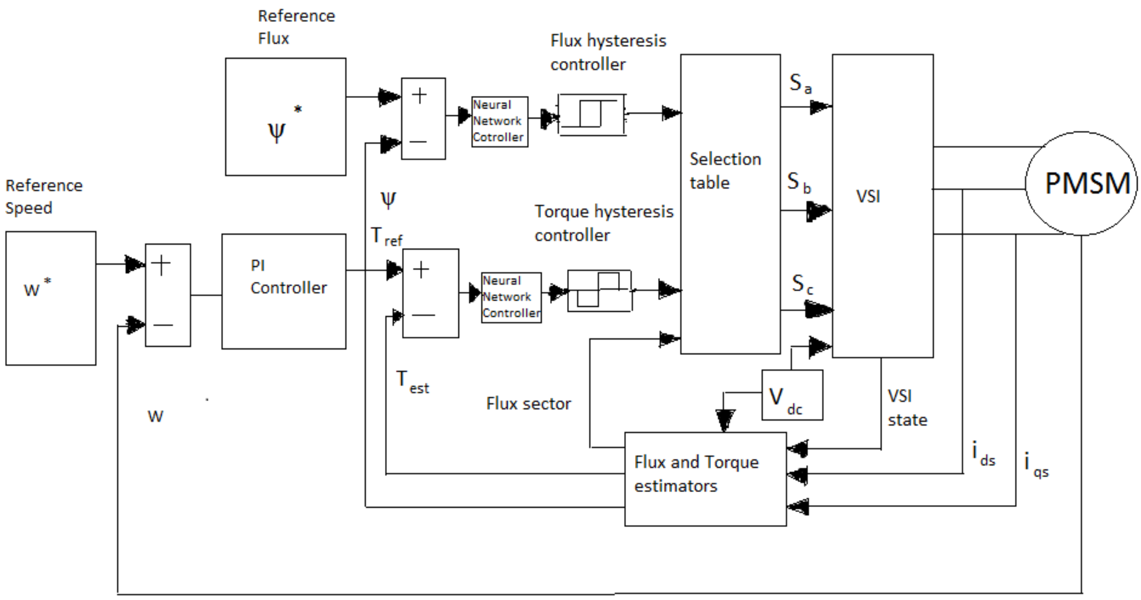

Figure 5. DTC for PMSM with a neural network controller

Figure 6 depicts the suggested recurrent neural network's configuration, which consists of three layers: input layer, hidden layer, and output layer. The neurons are represented by the circles in the neural network.

Two neurons are present in the previous design's buried layer. One-two-one network best describes this topology. The neural network is fully connected, meaning that each neuron's output is weightedly coupled to every other neuron in the forward layer. Additionally, a weight connects each neuron in the hidden and output layers to a bias signal.

The input is linked at node X. The weights between the input layer and the hidden layer are made up of V11 and V12. The hidden layer is linked to the bias value, bias value connected to hidden layer (Bh). The weight values for the output layer are W11 and W21, and the bias value is bias value connected to output layer (Bo). The RNN is subjected to the back propagation training technique. The network's architecture weights are modified as:

$$w_{ej}(new) = w_{ej}(old) + \Delta w_{ej} \qquad ej = 0,1,2,\dots,en \tag{13}$$

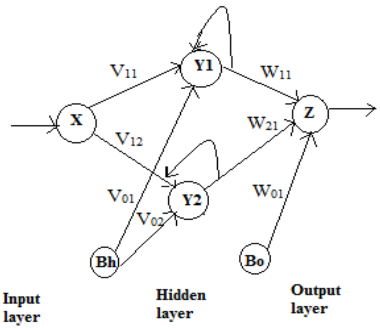

Figure 6. RNN architecture-based neuro- controller

By altering the voltage vector selection approach employed by the DTC, the flux and torque parameters of a synchronous motor powered by the DTC are altered. The inputs for the two distinct neural controllers are the flux error and torque error. The selection of an appropriate voltage vector, which in turn controls the torque of the motor, is influenced by the combined influence of the improved outputs from both controllers. The Simulink model designed in MATLAB/Simulink to implement fuzzy and neural controllers to control PMSM is shown in Figure 7

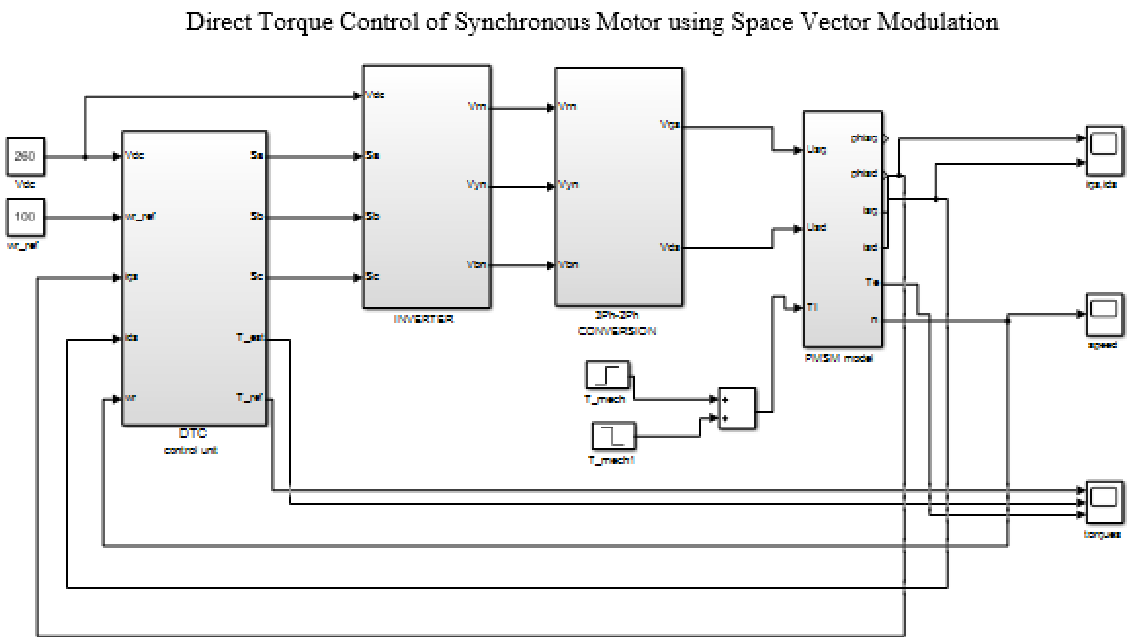

Figure 7. Simulink model for implementation of fuzzy and neural controllers in direct torque controlled synchronous motor

5. RESULTS AND DISCUSSION

Figure 8 displays stator current THD values that were obtained using the PMSM's fundamental DTC technique. Figure 9 displays the stator current THD values that were obtained using the PMSM DTC technique and a fuzzy controller. Figure 10 displays the stator current THD value produced by incorporating neural network controllers in the DTC based PMSM.

Waveforms of the current for stator and ripple for torque generated using the PMSM's fundamental DTC approach is shown in Figure 11. The waveforms of the current for the stator and ripple for the torque obtained by utilising a fuzzy controller in the DTC of the PMSM are shown in Figure 12. The torque ripple and stator current waveforms generated by integrating neural network controllers into the PMSM's DTC are shown in Figure 13. In Table 3, the fundamental DTC of the PMSM and the stator current THD derived using fuzzy and neural controllers are contrasted with the DTC-based PMSM. From Table 3, it can be inferred that, in comparison to the basic DTC technique of PMSM, the THD values of stator current and steady-state torque ripple have decreased as a result of the inclusion of proposed neural network and fuzzy controllers in a loop of the DTC scheme of PMSM.

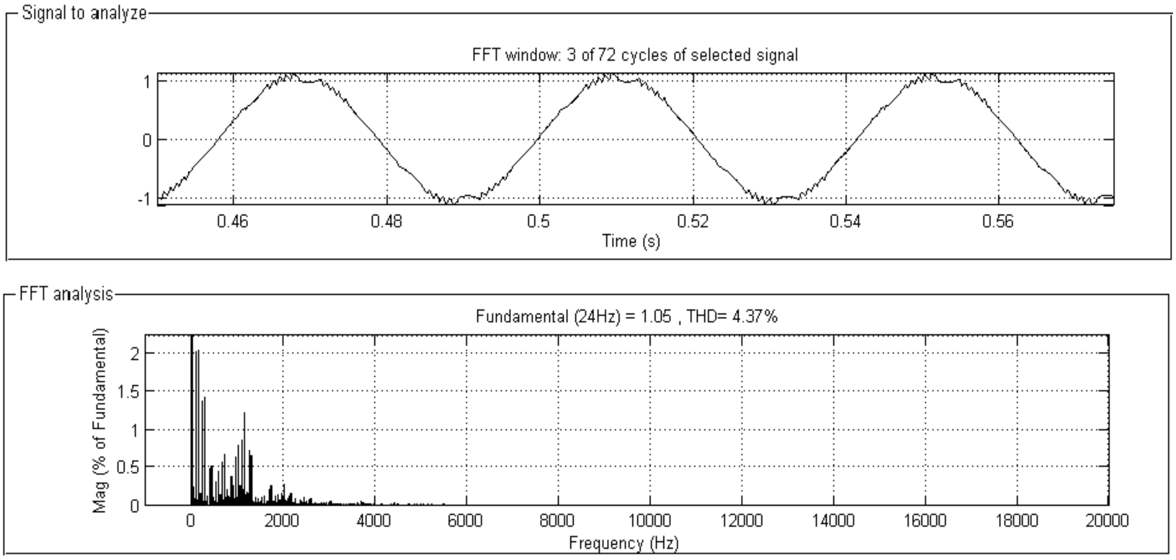

Figure 8. Stator current total harmonic distortion for basic DTC scheme of PMSM

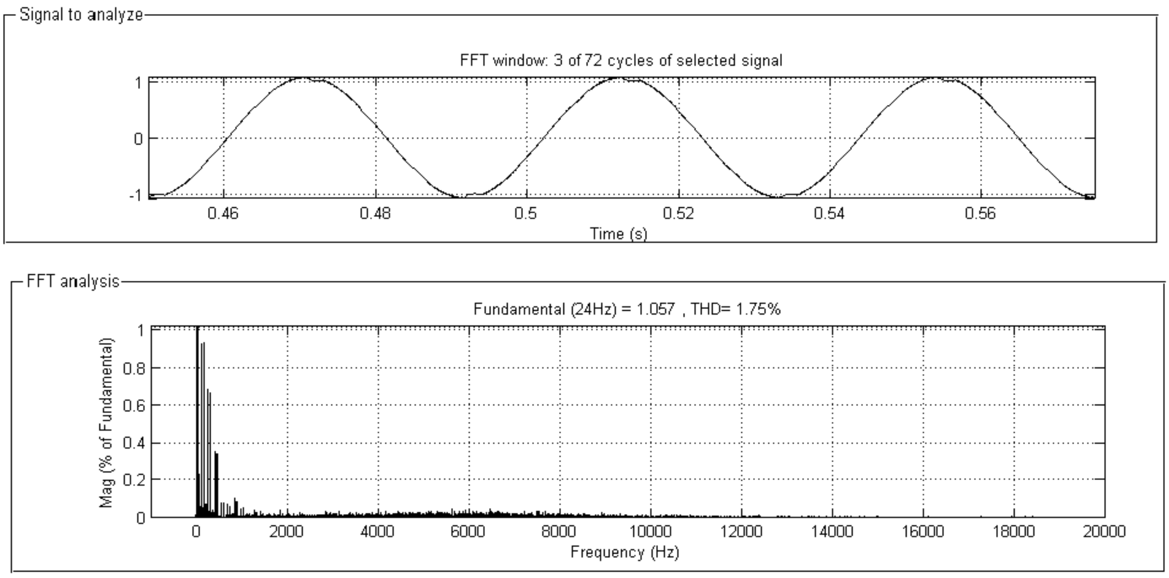

Figure 9. Stator current THD-based DTC of the PMSM using fuzzy logic

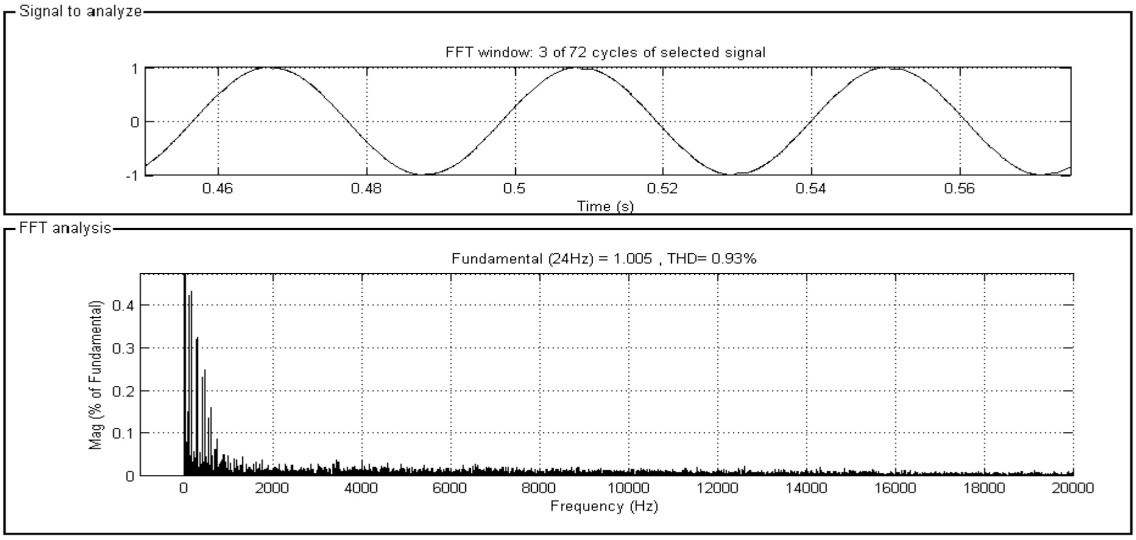

Figure 10. Stator current THD based on a neural network for the PMSM DTC

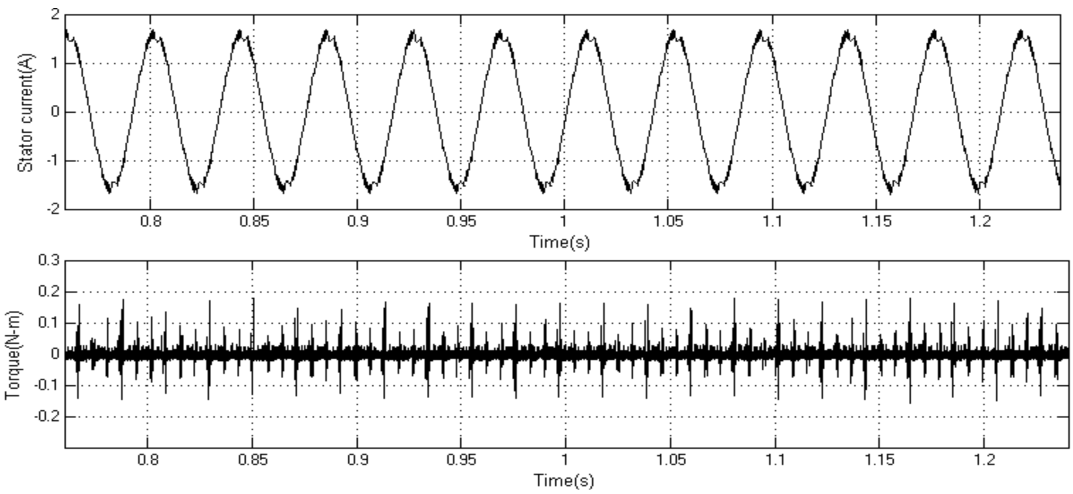

Figure 11. Typical PMSM DTC configuration: current for stator and ripple for torque

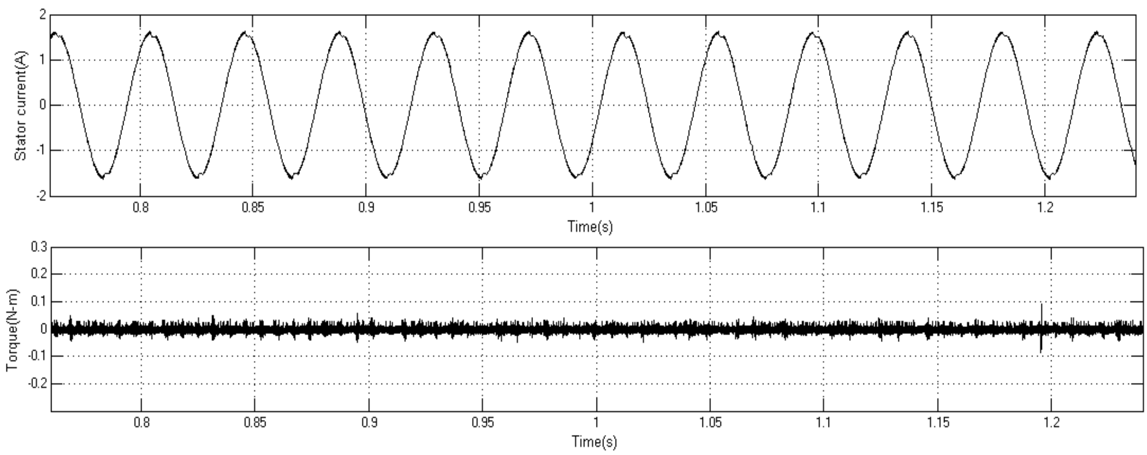

Figure 12. PMSM DTC with fuzzy logic for current for stator and ripple for torque

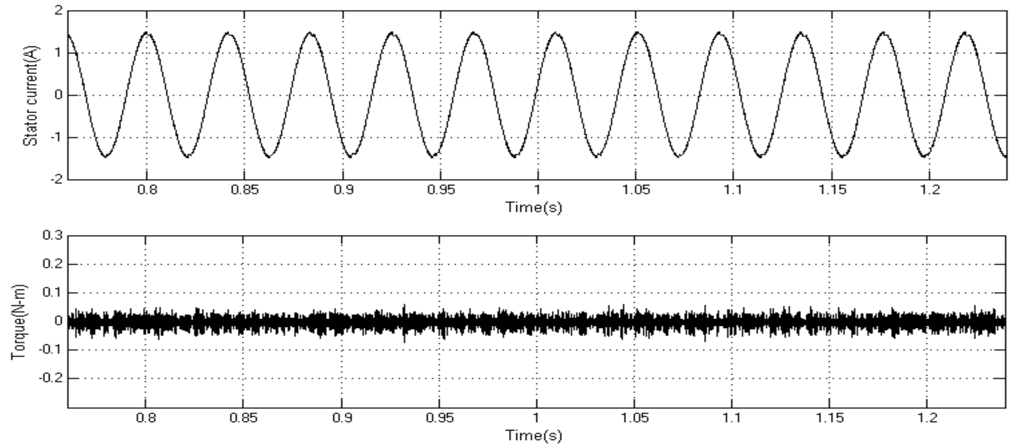

Figure 13. PMSM DTC using a neural network that accounts for current for stator and ripple for torque

Table 3. Comparison of ripple for torque and current for stator total harmonic distortion attained using different PMSM DTC techniques

PMSM	Stator current THD	Torque ripple (p-p)(Nm)
Basic method	4.375%	0.35
Fuzzy controller	1.756%	0.12
Neural controller	0.94%	0.12

6. CONCLUSION

In order to enhance the DTC of PMSM's functionality, fuzzy and neural network controllers are introduced in this paper. To improve the efficiency of the PMSM's basic DTC scheme, the error and change in error of flux are processed in a fuzzy controller. Recurrent neural networks process the flux and torque defects in neural network controllers to improve the performance of the fundamental DTC of PMSM. The suggested remedy offers an effective response with reduced harmonics in the torque ripple and stator current. When compared to the basic DTC scheme of the PMSM, the stator current THD% value in steady state is improved by the use of fuzzy and neural network controllers.

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