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A Novel Switching Tables of Twelve Sectors DTC for Induction Machine Drive Using Artificial Neural Networks

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Abstract: The direct torque control (DTC) is one of the actively researched control schemes of induction machines (IMs), which is based on the decoupled control of stator flux and electromagnetic torque. The traditional twelve sectors DTC control scheme of IM drive using hysteresis comparators and switching table has considerable electromagnetic torque ripple, stator flux ripple and harmonic distortion of voltage/current for IM drive. In order to ensure a robust twelve sectors DTC control scheme and minimize the harmonic distortion of stator current, a novel switching tables of twelve sectors DTC control scheme with the application of the artificial intelligence technique (artificial neural networks (ANNs)). The electromagnetic torque, stator flux and harmonic distortion of stator current are determined and compared with the traditional twelve sectors DTC control scheme. The simulation of the proposed switching tables were carried out in Matlab/Simulink software. A comparative study of the proposed switching tables is also presented to illustrate the merits of each of the switching table on the performance of the twelve sectors DTC control scheme.

Keywords: Direct Torque Control, Induction Motor, Neural Network, Twelve Sectors

1. Introduction

The recent years, IMs have for most industrial low to high speed application due to their reliability, affordable price, the rugged construction and efficiency in comparison with DC motors which suffer from the drawbacks of the brushes-collector, corrosion and necessity of maintenance. However, IMs are considered as non-linear, multivariable and highly coupled systems. For this reason, IMs have been used especially in closed-loop for variable speed application. Even the IM is possible for high precision torque and speed control through highly preserved control technique [1].

There are two most common as drives control schemes that are being widely researched. One of it is field oriented control (FOC) which was proposed by F. Blaschke. The second scheme is the DTC control which was proposed by I. Takahashi and T. Noguchi [2].

Since it has been introduced in the early 1980s, DTC strategy has gained its popularity in electrical drives research area [3]. The DTC strategy provides the very quick response with a simple control structure and hence [4]. Unlike FOC, DTC does not require any current regulator, coordinate transformation and PWM signals generator. In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained. The problem is to quantify how good the torque control is with respect to FOC. In addition, this controller is very little sensible to the parameters variations in comparison with FOC. FOC makes decoupling of stator current to produce independent control of torque and flux. FOC is very sensitive to flux variations, which is mainly affected by parameter variations. It is greatly influenced by the performance of induction motor. Instead of FOC, DTC directly controls stator flux and electromagnetic torque without depending on parameter variation [5]. However, the DTC technique presents the disadvantage of large stator flux and torque ripples. Consequently, this has opened a new and interesting area for academic research and industrial applications for nonlinear control techniques [6]. The higher current and torque ripple witch imply higher machine losses and noise, the inherent variable switching frequency and the lack of direct current control [7].

The basic concept of DTC is to control both electromagnetic torque and stator flux simultaneously by proper selection of optimum inverter switching states in accordance with the torque and flux errors [8]. The switching frequency of voltage source inverter is non-fixing. Non-fixing switching frequency capability of the inverter not to be used fully. Secondly, there is the sharp increase or decrease of torque because only one voltage vector works in a sampling period and the options of the vector is limited [7].

Due to advantages of artificial intelligence (AI) techniques like neural networks (NNs), fuzzy logic (FL), Genetic algorithms (Gas) are used to improve the performance of drive [9]. A NNs controller, are a set of nonlinear functions to build, by learning, a large family of models and non-linear connectors [10].

The technique of ANN control will also be introduced and used for performance improvement of proposed strategies for classical 12 sectors DTC. The model is then simulated on a Matlab/Simulink environnement.

2. Conventional DTC Control

The DTC control, as shown in Figure 1, consists of directly controlling the inverter switches turn OFF or ON, on the calculated value of the stator flux from relation (2) [11]. The reference frame related to the stator makes possible to estimate flux and torque on the one hand and the position of stator flux on the other hand. The aim of the switches control is to give the vector representing the stator flux the direction determined by the reference value [11].

$$\begin{cases} \Phi s\alpha = \int_0^t \left(V s\alpha - R_S \cdot i_{s\alpha}\right) dt \\ \Phi s\beta = \int_0^t \left(V s\beta - R_S \cdot i_{s\beta}\right) dt \end{cases} \tag{1}$$

$$\overline{\Phi_S}(k+1) \approx \overline{\Phi_S}(k) + \overline{V_S} \cdot T_E \rightarrow \Delta\overline{\Phi_S}(k) = \overline{V_S} \cdot T_E \tag{2}$$

Where: T_E is the sample time

The stator flux sector is determined by the components $\Phi s\alpha$ and $\Phi s\beta$. The angle between the referential and Φ_S is equal to [12]:

$$\theta = arctg\left(\frac{\Phi s\beta}{\Phi s\alpha}\right) \tag{3}$$

The electromagnetic torque is proportional to the vectorial product between the stator and rotor flux vector [13, 14]:

$$T_e = p \frac{L_m}{\sigma L_r L_s} \Phi_s \Phi_r \sin(\widehat{\overline{\Phi}_s \overline{\Phi}_r}) \tag{4}$$

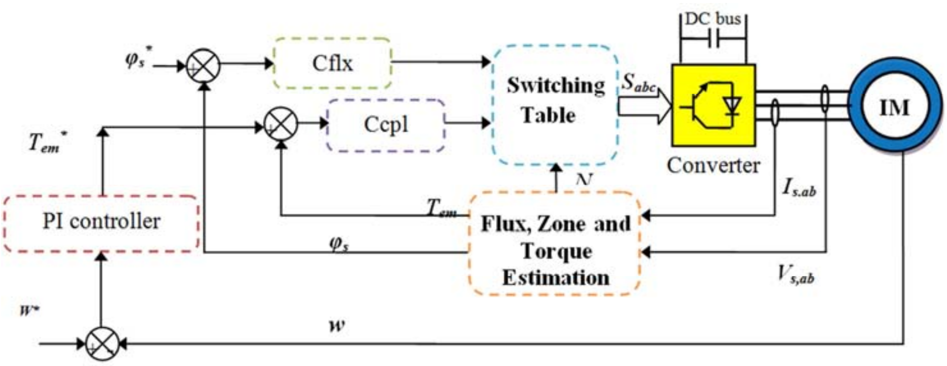


Figure 1. *Block diagram of conventional DTC control.*

Two levels classical inverter can achieve seven separate positions in the phase corresponding to the eight sequences of the voltage inverter [11]. The flux angle of the 6 sectors as shown in Figure 2.

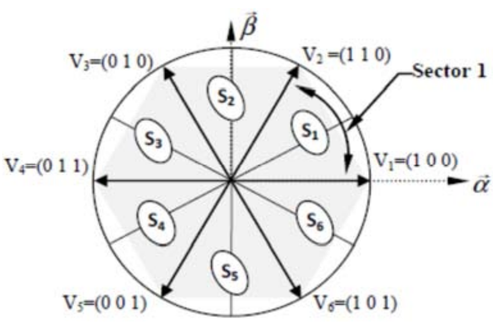


Figure 2. *Different vectors of stator voltages in case of table with 06 sectors.*

3. Twelve Sectors DTC Control

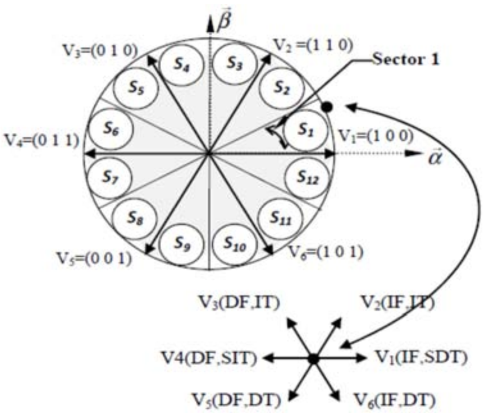


Figure 3. *Different vectors of stator voltages in case of table with 12 sectors.*

The 12 sectors method uses the same block diagram as shown in Figure 2, but the switching table now consists of 12 non null voltage vectors, to be selected [11]. The sectors division for 12 sectors is as shown in Figure 3. As indicated in the figure all the six vectors are used in all the sectors thus reducing the torque ambiguity which occurs in the case of six sectors DTC control [15].

With: SI(D)T: Small Increase (Decrease) of Torque

Thus twelve sectors DTC control consist of two level stator flux hysteresis comparators (Cflx) and four level torque hysteresis comparators (Ccpl) for reducing the repulsion in torque and stator flux [15]. Table 1 show the classical strategy 12 sectors DTC control.

Table 1. *Switching table for the classical 12 sectors DTC.*

N Cflx	 Ccpl	1	2	3	4	5	6	7	8	9	10	11	12
1	2	2	3	3	4	4	5	5	6	6	1	1	2
	1	2	2	3	3	4	4	5	5	6	6	1	1
	-1	1	1	2	2	3	3	4	4	5	5	6	6
	-2	6	1	1	2	2	3	3	4	4	5	5	6
0	2	3	4	4	5	5	6	6	1	1	2	2	3
	1	4	4	5	5	6	6	1	1	2	2	3	3
	-1	7	5	0	6	7	1	0	2	7	3	0	4
	-2	5	6	6	1	1	2	2	3	3	4	4	5

A Table 2 to 4 illustrates of modification switching table of classical 12 sectors DTC control for the IM drives.

Table 2. *Switching table for the strategy 1 of 12 sectors DTC.*

N Cflx	 Ccpl	1	2	3	4	5	6	7	8	9	10	11	12
1	2	2	3	3	4	4	5	5	6	6	1	1	2
	1	2	2	3	3	4	4	5	5	6	6	1	1
	-1	2	2	3	3	4	4	5	5	6	6	1	1
	-2	6	1	1	2	2	3	3	4	4	5	5	6
0	2	3	4	4	5	5	6	6	1	1	2	2	3
	1	4	4	5	5	6	6	1	1	2	2	3	3
	-1	4	4	5	5	6	6	1	1	2	2	3	3
	-2	5	6	6	1	1	2	2	3	3	4	4	5

Table 3. *Switching table for the strategy 2 of 12 sectors DTC.*

N Cflx	 Ccpl	1	2	3	4	5	6	7	8	9	10	11	12
1	2	2	3	3	4	4	5	5	6	6	1	1	2
	1	2	2	3	3	4	4	5	5	6	6	1	1
	-1	1	1	2	2	3	3	4	4	5	5	6	6
	-2	1	1	2	2	3	3	4	4	5	5	6	6
0	2	3	4	4	5	5	6	6	1	1	2	2	3
	1	4	4	5	5	6	6	1	1	2	2	3	3
	-1	7	5	0	6	7	1	0	2	7	3	0	4
	-2	7	5	0	6	7	1	0	2	7	3	0	4

Table 4. *Switching table for the strategy 3 of 12 sectors DTC.*

N Cflx	 Ccpl	1	2	3	4	5	6	7	8	9	10	11	12
1	2	2	2	3	3	4	4	5	5	6	6	1	1
	1	2	2	3	3	4	4	5	5	6	6	1	1
	-1	1	2	2	3	3	4	4	5	5	6	6	1
	-2	6	6	1	1	2	2	3	3	4	4	5	5
0	2	3	4	4	5	5	6	6	1	1	2	2	3
	1	3	3	4	4	5	5	6	6	1	1	2	2
	-1	7	5	0	6	7	1	0	2	7	3	0	4
	-2	5	6	6	1	1	2	2	3	3	4	4	5

4. Twelve Sectors DTC-ANN

The ANN controller are, as their name indicates, computation al networks which attempt to simulate, in a gross manner, the networks of the nerve cell (neurones) of the biological (human or animal) central nervous system. The NNs are composed of simple elements called neurones operating in parallel. As in nature, the connections between elements largely determine the network function [16]. ANN models have rising popularity in different kind of control systems due to their learning abilities, robust structures, beside their modeling success on non-linear and complex mathematical models [17]. The ANN has many models, but the usual model is the multilayer feed forward network using the error backpropagation algorithm. Such a NN contains three layers: input layers, hidden layers and output layers. Each layer is composed of several neurones. The number of the neurones in the input and output layers depends on the number of the selected input and output variables. The number of hidden layers and the number of neurones in each depend on the desired degree of accuracy [18].

The structure of the IM with 12 sectors DTC-ANN using a two-level inverter is represented by Figure 4.

The structure of the neural network to perform the 12 sectors DTC applied to IM satisfactorily was a NN controller with 3 linear input nodes, 30 neurones in the hidden layer, and 3 neurones in the output layer, as shown in Figure 5.

The structure interne of the NN controller as shown in Figure 6, the architecture of layer 1 is shown in Figure 7, and layer 2 is shown in Figure 8 respectively.

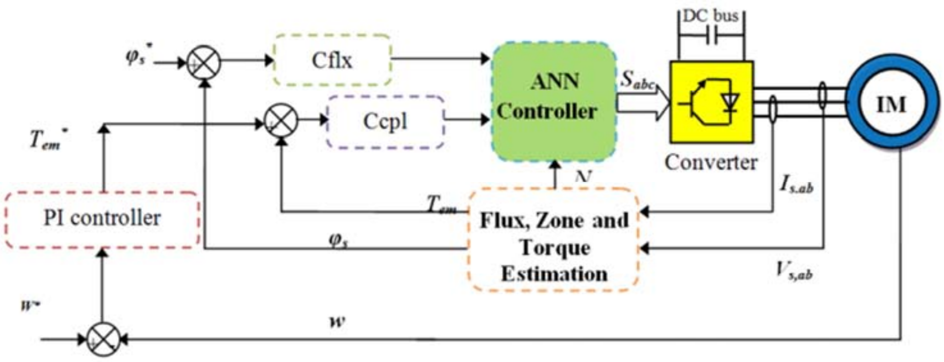


Figure 4. *Twelve sectors DTC-ANN scheme for sensorless IM drive.*

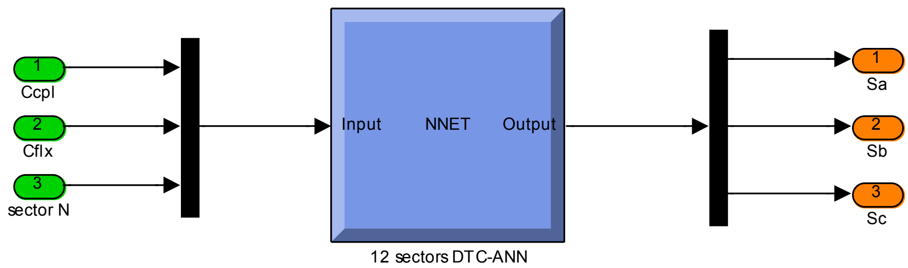


Figure 5. *Neural network structure for 12 sectors DTC.*

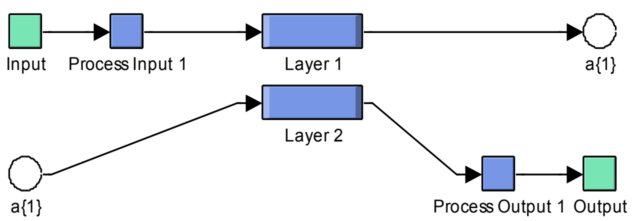


Figure 6. *Architecture of multilayer neural network for 12 sectors DTC control.*

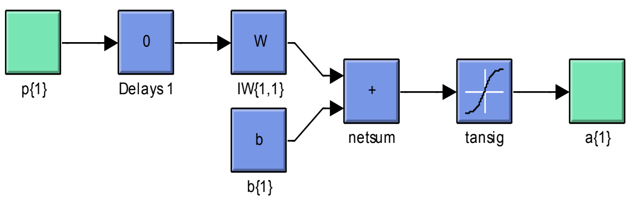


Figure 7. *Architecture of layer 1.*

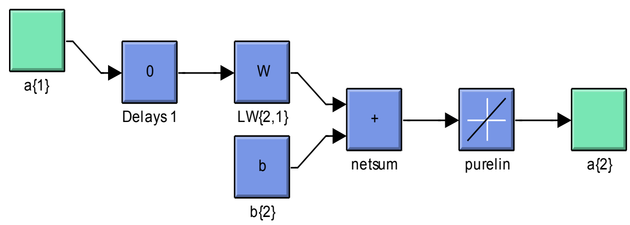


Figure 8. *Architecture of layer 2.*

5. Simulation Results

The simulation results of proposed strategies of 12 sectors DTC with ANN of the IM drive are compared with conventional DTC with ANN controller. The controls system was tested under deferent operating conditions such as sudden change of load torque (Tr).

The performance analysis is done with torque, stator flux, and stator current. The dynamic performance of the classical 12 sectors DTC with ANN control of the IM is shown Figure 9. Figure 10 shows the performance of the strategy 1 with ANN controller. Figure 11 shows the performance of the strategy 2 with ANN, Figure 12 shows the performance of the strategy 3 with ANN controller. Figures 13 and 14 shows the comparison between proposed strategies with ANN and classical 12 sectors DTC with ANN controller.

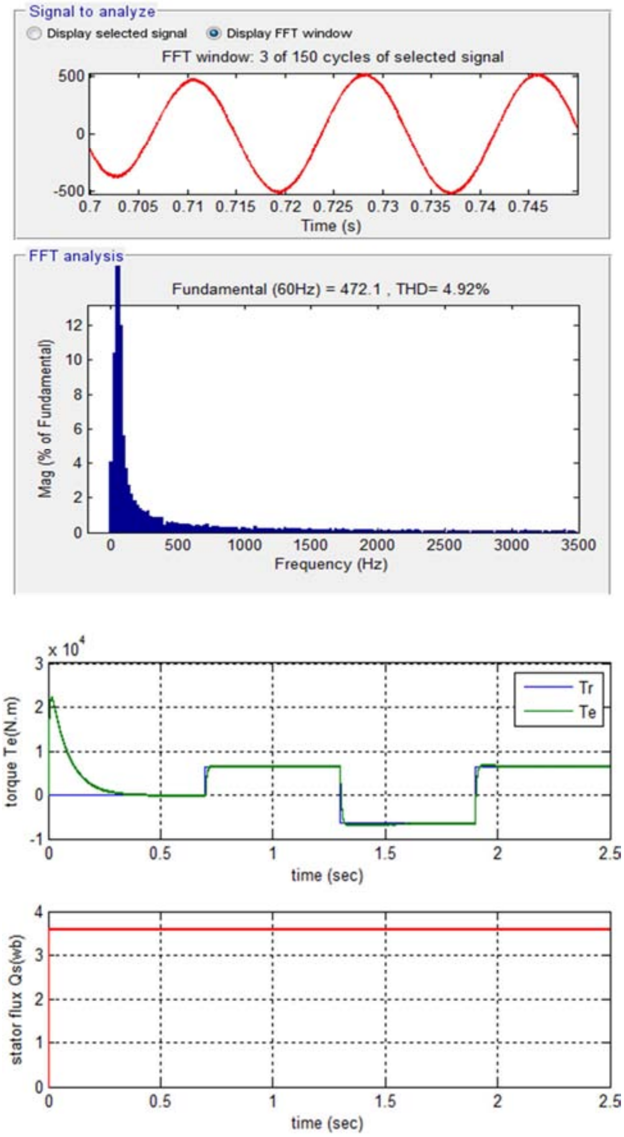


Figure 9. Performances of classical 12 sectors DTC with ANN for induction motor.

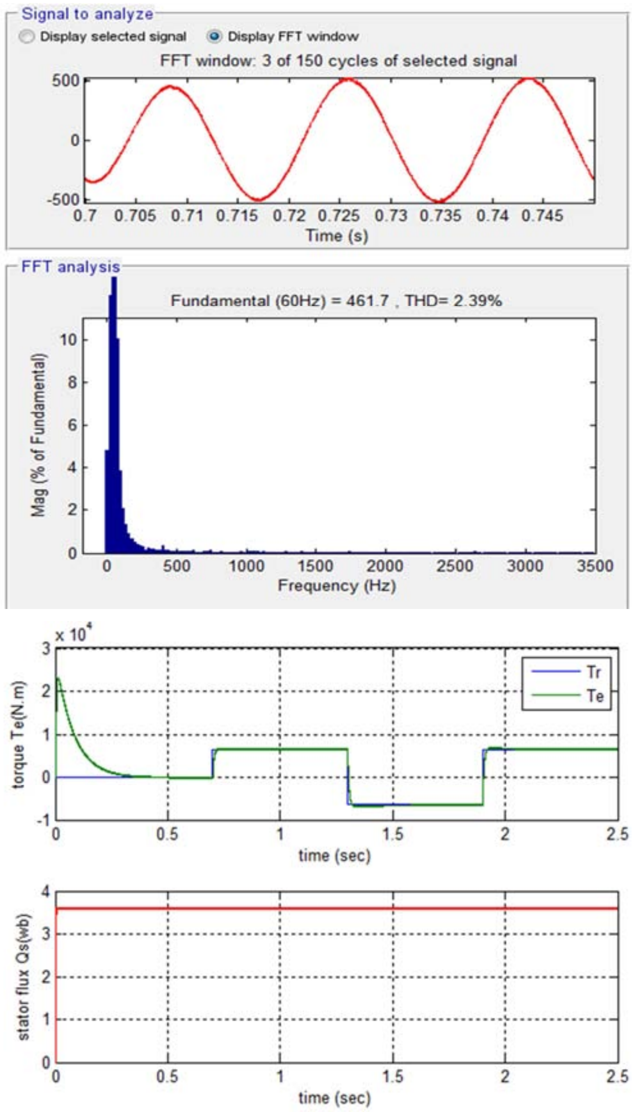
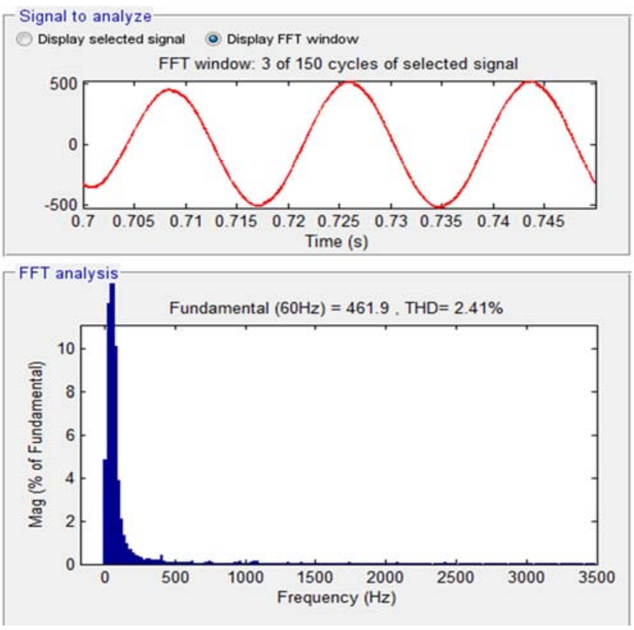


Figure 10. Performances of Strategy 1 with ANN for Induction Motor.



From the simulation results presented in Figures 9-12 it is apparent that the harmonic distortion (THD) value of stator current for the strategy 1 proposed utilizing ANN is considerably reduced. Table 5 shows the comparative analysis of THD value for stator current.

Table 5. Comparative analysis of THD value for stator current.

	Classical strategy	Strategy 1	Strategy 2	Strategy 3
Ias THD (%)	4.92	2.39	2.41	6.00

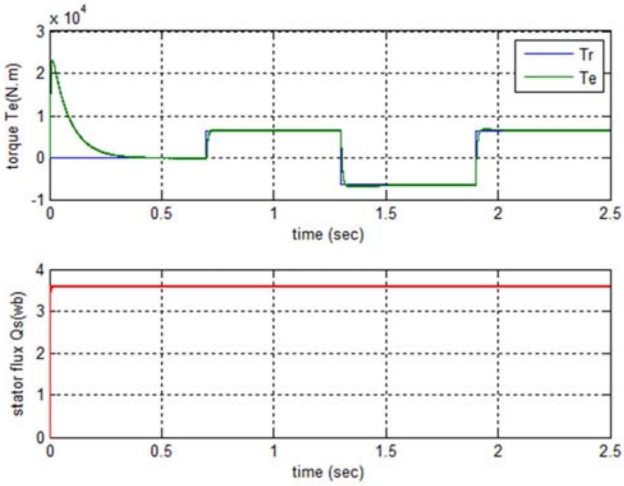
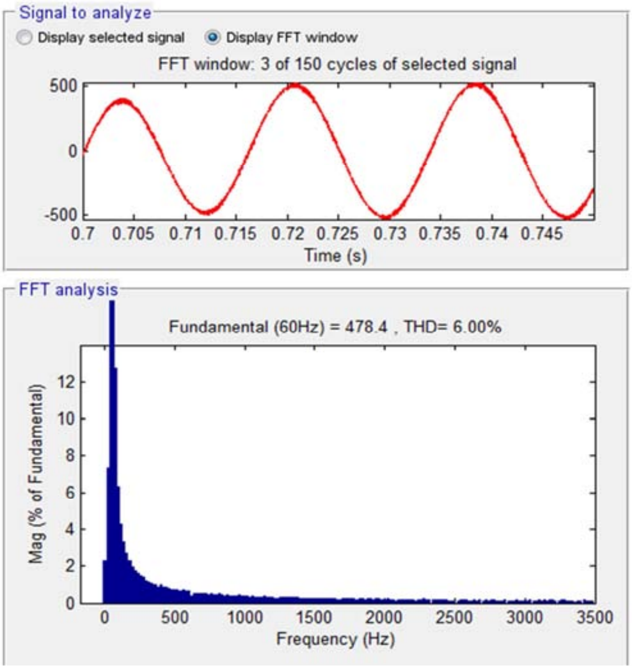


Figure 11. *Performances of Strategy 2 with ANN for Induction Motor.*



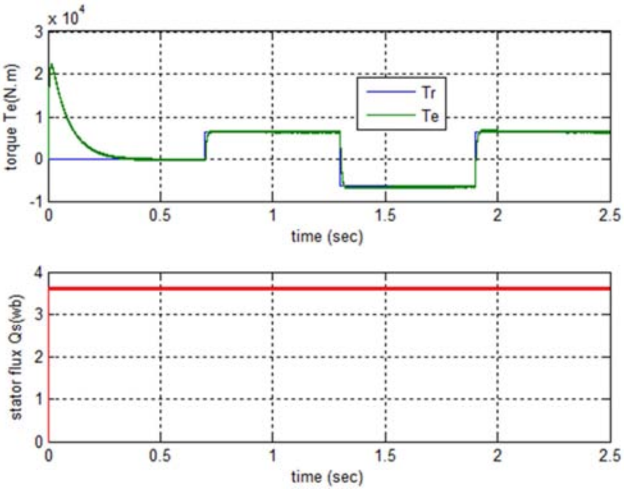
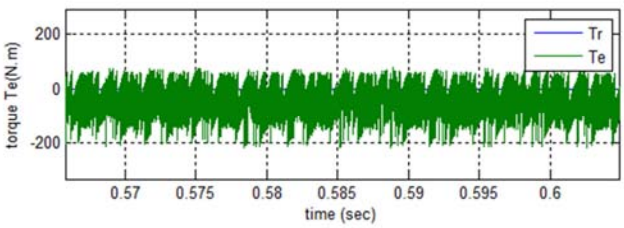


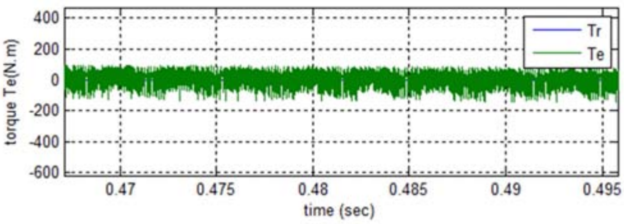
Figure 12. *Performances of strategy 3 with ANN for induction motor.*

Torque response comparing curves are shown in Figure 13.

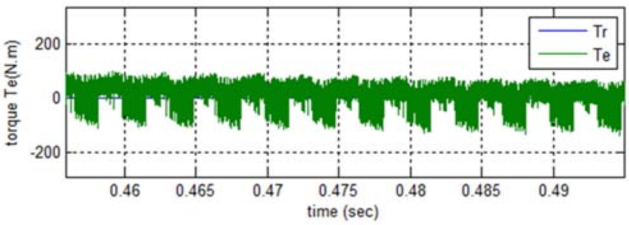
See Figure the torque ripple is significantly reduced when the strategy 1 proposed is in use.



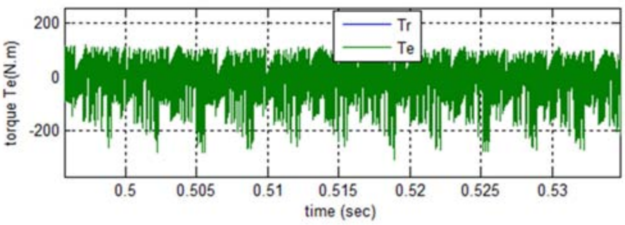
a) Classical 12 sectors DTC with ANN



b) Strategy 1 with ANN



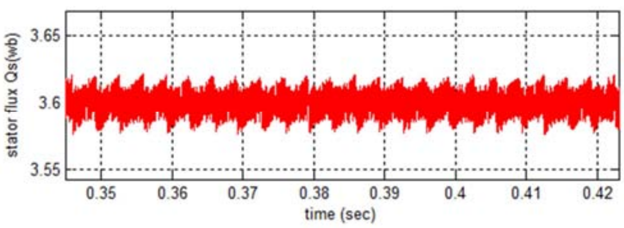
c) Strategy 2 with ANN



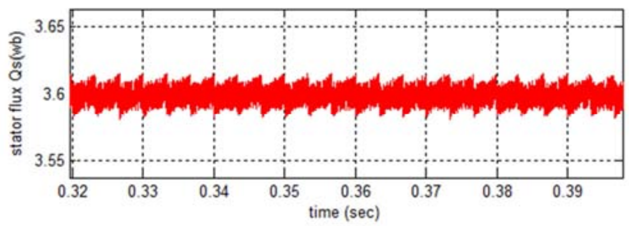
d) Strategy 3 with ANN

Figure 13. *Zooms in the torque.*

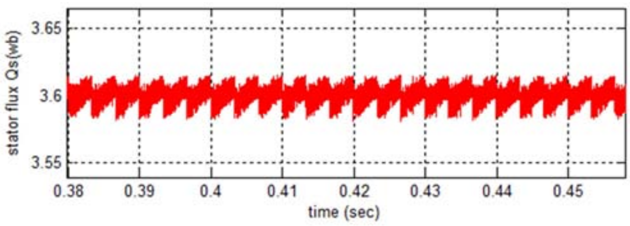
Figure 14 shows the stator flux responses of both the conventional 12 sectors DTC control and proposed strategies of 12 sectors with ANN controller. It is found that the strategy 1 of 12 sectors DTC scheme exhibited smooth response and lesser ripple in stator flux as compared to the conventional 12 sectors DTC and proposed strategies.



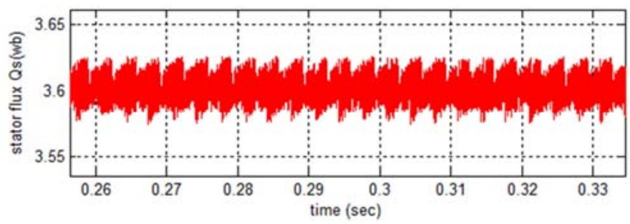
a) Classical 12 sectors DTC with ANN



b) Strategy 1 with ANN



c) Strategy 2 with ANN



d) Strategy 3 with ANN

Figure 14. *Zooms in the stator flux.*

6. Conclusion

In this paper, a new switching tables of twelve sectors DTC strategy is presented and it is shown that with neural networks controller for a two-level inverter. The simulation results obtained for the proposed strategy 1 illustrate a considerable reduction in electromagnetic torque ripple, stator flux ripple and THD value of stator current compared to the other strategies of DTC control with 12 sectors.

Appendix

The parameters of 3 phase IM employed for simulation purpose is given below [19, 20]:

Table 6. *Implementation parameters.*

Parameters	**Values**
Nominal power	1 Mw
Line to line voltage	791 V
Frequency	60 Hz
Stator resistance	0.228 Ω
Stator inductance	0.0084 H
Rotor resistance	0.332 Ω
Rotor inductance	0.0082 H
Mutual inductance	0.0078 H
Inertia	20 Kg.m^2
Friction	0.008 N.m.s
Number of poles	3

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