[1.]Habib BENBOUHENNI

NEW ZERO VOLTAGE VECTORS IN DIRECT TORQUE CONTROL OF INDUCTION MOTOR DRIVE USING INTELLIGENT CONTROLLERS

[1.] Ecole Nationale Polytechnique d'Oran, ALGERIA

Abstract: Direct Torque Control (DTC) is known to produce the quick and robust response in AC drives. However, during steady state, torque, flux and current ripple occur. An improvement of the electric drive can be obtained using a new zero voltage vectors in DTC scheme based on the intelligent controllers. This paper discusses the application of fuzzy logic and neural network in a torque and flux control loops respectively. Torque output has good dynamical and stable response, and stable torque ripple of traditional DTC can be improved.
Keywords: Fuzzy logic, neural network, Induction motor, Zero voltage

INTRODUCTION

The New conception of electrical drives was influenced by the development of semiconductor components which enabled the development of modern frequency converters as the practical realization of modern control methods of A.C. drives including the vector control in the field coordinates of motor and direct torque control methods [1].

In 1970s, field oriented control (FOC) scheme proved success for torque and speed control of induction motor. Decoupling of two components of stator currents (flux and torque producing components) is achieved as DC machines to provide independent torque control. Hence the scheme proves itself superior to the DC machine. The problem faced by FOC scheme is complexity in its implementation due to the dependence of machine parameters, reference frame transformation. Later DTC was introduced. The method requires only the stator resistance to estimate the stator flux and torque [2].

The direct torque control (DTC) method was proposed in the middle of 1980 by I. Takahashi, this method has become one of the high performance control strategies for AC machine to provide a very fast torque and flux control. The name direct torque control is derived from the fact that, on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits [3].

DTC method is characterised by its simple implementation and a fast dynamic response. Furthermore, the inverter is directly controlled by the algorithm, i.e. a modulation technics for the inverter is not needed. The main advantages of DTC are the absence of coordinate transformation and current regulator, the absence of separate voltage modulation block.

Since DTC was first introduced, several variations to its original structure were proposed to overcome the inherent disadvantages in any hysteresis-based controller, such as variable switching frequency, high sampling requirement for digital implementation, and high torque ripple. To solve this problem, various techniques have been proposed. Including the use of variable hysteresis bands, predictive control schemes, space vector modulation techniques, and intelligent control methods [4].

This paper proposes a novel scheme and tables of DTC drive for an induction motor based neural and fuzzy logic controller hysteresis has been developed using Matlab Simulink. Stator current, rotor speed, electromagnetic torque and flux plot which show the performance of DTC with. Neural and fuzzy logic controller's hysteresis DTC has also tracked the required speed and torque successfully which represents the successful design of the DTC drive.

INDUCTION MOTOR MODEL

The dynamic model of an induction motor in the stationary reference frame can be written in d-q frame variables. Stator voltage vector Vs of the motor can be expressed as follows [5]:

$$Vds = \frac{d\Phi ds}{dt} + Rs.iqs \tag{1}$$

$$Vqs = \frac{d\Phi qs}{dt} + Rs.iqs \tag{2}$$

The stator flux vector $\overline{\Phi_s}$ and components can be written as

$$\Phi ds = Lsids + Lm.idr \tag{3}$$

$$\Phi qs = Ls.iqs + Lm.idr \tag{4}$$

$$\overline{\Phi s} = Ls.\overline{is} + Lm.\overline{ir} \tag{5}$$

The rotor flux vector $\overline{\Phi_r}$ and components in the stator reference frame are:

$$\Phi dr = Lridr + Lm.ids \tag{6}$$

$$\Phi qr = Lr.iqr + Lm.ids \tag{7}$$

$$\overline{\Phi r} = Lr.\overline{ir} + Lm.\overline{is} \tag{8}$$

where V_{ds} and V_{qs} are the stator voltages, i_{ds} and i_{qs} are the stator currents, i_{dr} and i_{qr} are the rotor currents, Φ_{ds} and Φ_{qs} are the stator fluxes, Φ_{dr} and Φ_{qr} are the rotor fluxes, i_s and i_r are the stator and rotor currents vectors, R_s is the stator windings resistance., and L_s, L_r, L_m are stator, rotor self-inductance and mutual inductance respectively. The electromagnetic torque T_e developed by the induction motor in terms of stator and rotor flux vectors can be expressed as

$$T_e = \frac{3}{2} p \frac{Lm}{\sigma.Ls.Lr} .\left|\overline{\Phi s}\right|.\left|\overline{\Phi r}\right|.\sin(\delta) \tag{9}$$

where $\delta = 1 - \frac{Lm^2}{Ls.Lr}$ is the leakage factor, p is the number of pole pairs. From the above equation, clearly, the electromagnetic torque is cross vector product between the stator and rotor flux vectors. Therefore, generally torque control can be performed by controlling torque angle δ with constant amplitude of the stator and rotor fluxes [5].

TWO-LEVEL INVERTER

The voltage source inverter (VSI) is a static converter constituted by switching cells generally with transistors or IGBT for high powers (Figure 1). The operating principle can be expressed by imposing on the machine the voltages with variable amplitude and frequency starting from a standard network 791/1368v-60Hz. Voltages at load neutral point can be given by the following expression [3]:

$$\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \frac{E}{6}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} v_{Ao} \\ v_{Bo} \\ v_{Co} \end{bmatrix} \quad (10)$$

This modeling for the two converters that feed the induction motor.

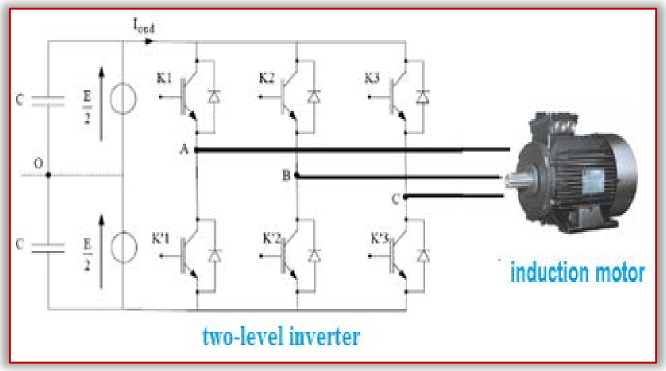


Figure 1. Voltage source inverter scheme

DIRECT TORQUE CONTROL WITH TWO-LEVEL INVERTER

The Direct Torque Control (DTC) method allows direct and independent electromagnetic torque and flux control, selecting an optimal switching vector [3]. The Figure 2 shows the schematic of the basic functional blocks used to implement the DTC of induction motor drive. A voltage source inverter (VSI) supplies the motor and it is possible to control directly the stator flux and the electromagnetic torque by the selection of optimum inverter switching modes [6].

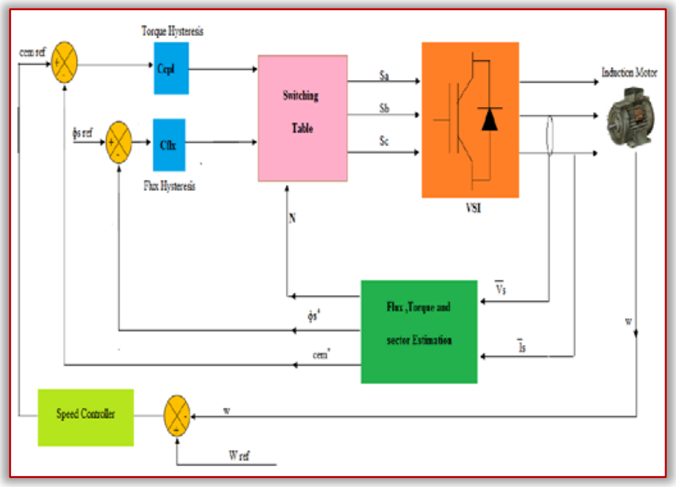


Figure 2 Basic direct torque control scheme for induction motor

— Vector model of inverter output voltage

In the PWM voltage source inverters, considering the combinations of the states of switching functions inverter switching state functions (C_1, C_2, and C_3) which can take either 1 or 0, the voltage vector becomes [7]:

$$v_s = U_0 \cdot \sqrt{\frac{2}{3}}\left(C_1 + C_2 e^{j\frac{2\Pi}{3}} + C_3 e^{j\frac{2\Pi}{3}}\right) \quad (11)$$

In the classical DTC method the plane is divided for the six sectors (Figure 3).

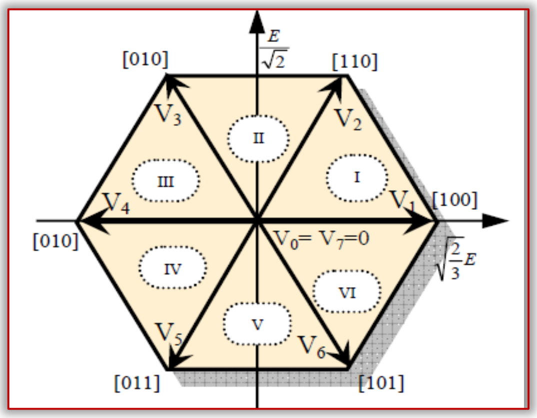


Figure 3. Partition of the αβ Plane into 6 Angular Sectors

— Stator flux and torque estimation

The components of the current ($I_{s\alpha}$, $I_{s\beta}$), and stator voltage ($V_{s\alpha}$, $V_{s\beta}$) are obtained by the application of the transformation given by (12) and (13) [7]:

$$\begin{cases} I_{s\alpha} = I_{sA}\sqrt{\frac{2}{3}} \\ I_{s\beta} = (I_{sB} - I_{sC})\sqrt{\frac{2}{3}} \end{cases} \quad (12)$$

$$\begin{cases} v_{s\alpha} = U_0 \cdot \left[C_1 - \frac{1}{2}(C_1 + C_2)\right] \cdot \sqrt{\frac{2}{3}} \\ v_{s\beta} = \frac{1}{\sqrt{2}} U_0 (C_2 - C_3) \end{cases} \quad (13)$$

The components of the stator flux ($\Phi_{s\alpha}$, $\Phi_{s\beta}$) given by (14):

$$\begin{cases} \bar{\Phi}_{s\alpha} = \int_0^t (\bar{v}_{s\alpha} - R_s I_s) dt \\ \bar{\Phi}_{s\beta} = \int_0^t (\bar{v}_{s\beta} - R_s I_s) dt \end{cases} \quad (14)$$

The stator flux linkage phase is given by (15).

$$\Phi_s = \sqrt{\Phi_{s\beta}^2 + \Phi_{s\alpha}^2} \quad (15)$$

The electromagnetic couple be obtained starting from the estimated sizes of flux $\Phi_{s\alpha}$, $\Phi_{s\beta}$ and calculated sizes of the current $I_{s\alpha}$, $I_{s\beta}$

$$c_{em} = \frac{3}{2} p\left[\Phi_{\alpha s} i_{\beta s} - \Phi_{\beta s} i_{\alpha s}\right] \quad (16)$$

The choice of one of the null vectors is performed having in mind the reduction of simultaneous commutations and consequently, the switching loses in the inverters legs. As the necessary further inverter's topology and therefore the voltage vector is determined at each sampling period, it is obviously that the last must be as small as possible in order to achieve a convenient switching frequency. In simulation it is possible to choose a fixed step size as small as we needed, but for the real time control, the limitations of the control system must be considered [8].

The switching Table allows to select the appropriate inverter switching state according to the state of hysteresis comparators of flux (Cflx) and torque (Ccpl) and the sector where is the stator vector flux (Φ_s) in the plan (α, β), in order to maintain the magnitude of stator flux and electromagnetic torque inside the hysteresis bands. The above consideration allows construction of the switching Table as presented in Table 1 [3].

Table 1 .Switching table for classical DTC

Cflx	N / Ccpl	1	2	3	4	5	6
1	1	2	3	4	5	6	1
	0	7	0	7	0	7	0
	-1	6	1	2	3	4	5
0	1	3	4	5	6	7	8
	0	0	7	0	7	0	7
	-1	5	6	1	2	3	4

The voltage vector table receives the flux level, the torque level and the sector number and generates appropriate control for the inverter from a look-up table as in Table 1[9].

Tables 2 to 4 illustrates of modification tables of classical DTC with a voltages zeros.

Table 2. Switching table for strategy 1 of classical DTC

Cflx	N / Ccpl	1	2	3	4	5	6
1	1	2	3	4	5	6	1
	0	2	3	4	5	6	1
	-1	7	0	7	0	7	0
0	1	3	4	5	6	1	2
	0	0	7	0	7	0	7
	-1	0	7	0	7	0	7

Table 3. Switching table for strategy 2 of classical DTC

Cflx	N / Ccpl	1	2	3	4	5	6
1	1	2	3	4	5	6	1
	0	7	0	7	0	7	0
	-1	7	0	7	0	7	0
0	1	3	4	5	6	1	2
	0	3	4	5	6	1	2
	-1	0	7	0	7	0	7

Table 4. Switching table for strategy 3 of classical DTC

Cflx	N / Ccpl	1	2	3	4	5	6
1	1	2	3	4	5	6	1
	0	1	2	3	4	5	6
	-1	7	0	7	0	7	0
0	1	3	4	5	6	1	2
	0	0	7	0	7	0	7
	-1	0	7	0	7	0	7

DIRECT TORQUE CONTROL USING REGULATORS HYSTERESIS BASED ON NEURAL AND FUZZY LOGIC

Since none of the inverter switching vectors is able to generate the exact stator voltage required to produce the desired changes in torque and flux, torque and flux ripples compose a real problem in DTC induction motor drive. Many solutions were proposed to improve performances [4].

According to the principle of operation of DTC, the torque presents a pulsation that is directly related to the amplitude of its hysteresis band. The torque pulsation is required to be as small as possible because of its causes vibration and acoustic noise.

A small flux hysteresis bands should be preferred when high switching speed semiconductor devices are utilized because their switching losses are usually negligible with respect to state losses. In this way, the output current harmonic can be strongly reduced.

In this paper, a neural and Mamdani-type FLC is developed to adapt the flux and torque hysteresis band in order to reduce the ripples in the motor developed torque.

The principle of fuzzy logic and neural direct torque control (DTC) is similar to traditional DTC. The difference is using a fuzzy logical controller to replace the torque hysteresis loop controller, and the neural controller to replace the flux hysteresis loop controller. As shown in Figure 4.

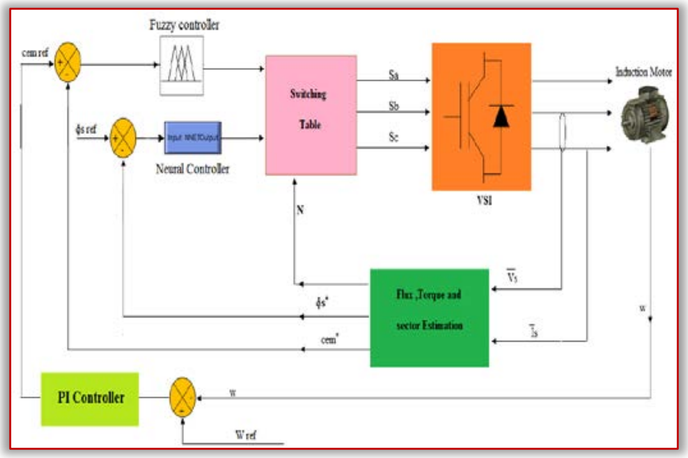


Figure 4. DTC with regulators hysteresis based on neural and fuzzy logic

— Design of neural for flux ripple

Artificial neural networks use a dense interconnection of computing nodes to approximate nonlinear functions. Each node constitutes a neurone and performs the multiplication of its input signals by constant weights, sums up the results and maps the sum to a nonlinear activation function g, the result is then transferred to its output.

A feed forward ANN is organized in layers: an input layer, one or more hidden layers and an output layer [7]. Multilayer Perceptron (MLP) is the most used neural network model. MLP utilizes a learning algorithm (back propagation) for training the network, MLP are capable to separate data that are not linearly separable. The MLP structure is shown in Figure 5 [10]. It includes a summer and a nonlinear activation function g [7].

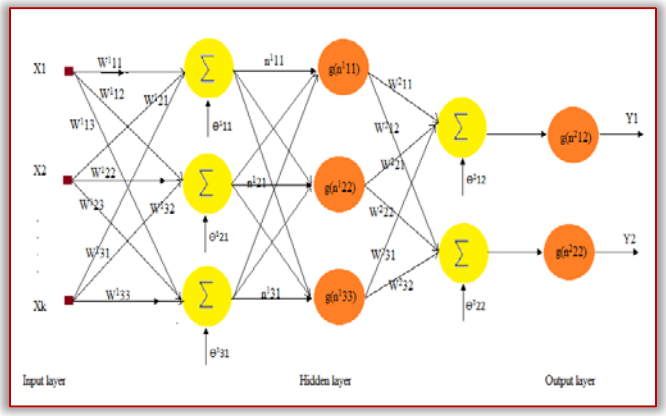


Figure 5. A Multilayer perceptron network with one hidden layer

The inputs xk, k = 1...K to the neuron are multiplied by weights wki and summed up together with the constant bias term θi. The resulting in is the input to the activation function g. The activation function was originally chosen to be a relay function, but for mathematical convenience a hyperbolic tangent (tanh) or a sigmoid function are most commonly used. The mathematical model of a neuron is given by (17) [7]:

$$y_i = g_i = g(\sum w_{ji} x_j + \theta_i) \tag{17}$$

The ANN is trained by a learning algorithm which performs the adaption of weights of the network iteratively until the error between target vector and the output of ANN is less than an error goal. The most popular learning algorithm for complex networks the back propagation algorithm and its variants. The later is implemented by many ANN software packages such as neural network tool box from MATLAB [11, 12].

In this paper, neural is developed to adapt the flux hysteresis band in order to reduce the ripples in the motor. The neural controller design is based on intuition and simulation. Figure 6 shows the block neural network controller of flux hysteresis band.

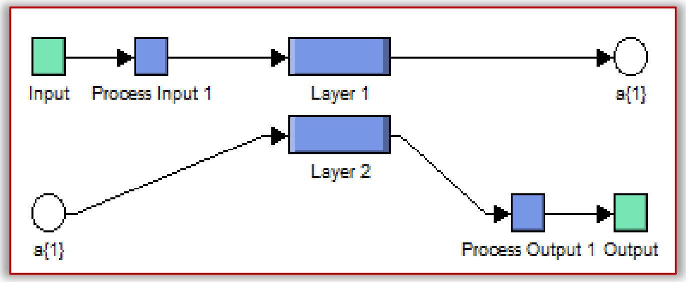


Figure 6. Block neural network controller of flux hysteresis band

— Design of FLC for torque ripple optimization

Fuzzy logic controller is online control. Recently, the fuzzy logic has been utilized for various control applications including motor speed control techniques. The fuzzy logic has made the control of complex nonlinear dynamic systems as simple as possible [13].

The principle of fuzzy logic direct torque control is similar to traditional DTC. The difference is using a fuzzy logical controller to replace the torque hysteresis loop controller. As shown in Figure 4.

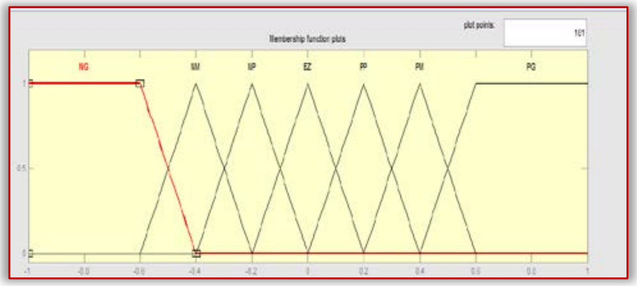
In this paper, an FLC is developed to adapt the torque hysteresis band in order to reduce the ripples in the motor developed torque. In conventional DTC technique, The amplitude of the torque hysteresis band is fixed. However, in this proposed scheme, the FLC controls the upper and lower limits. The fuzzy systems are universal function approximators. The FLC is used as a nonlinear function approximator producing a suitable change in the bandwidth of the torque hysteresis controller in order to keep the torque ripples minimum.

The fuzzy controller design is based on intuition and simulation. For different values of motor speed and current, the values reducing torque and flux ripple were found. These values composed a training set which is used to extract the table rule U (Δe, e). The shapes of membership functions (Figure 7 and Figure 8) are refined trough simulation and testing.

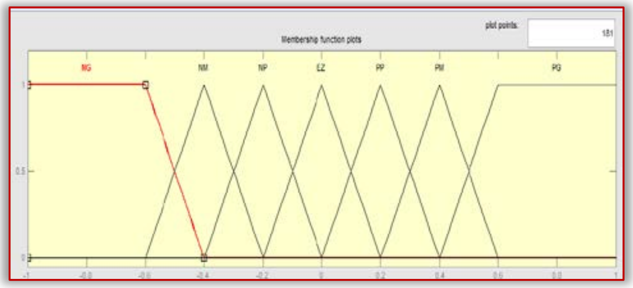
Figure 7 and 8 show the membership functions of input and output variables respectively. The fuzzy control rules are illustrated in Table 5.

Table 5. Fuzzy rules of torque hysteresis controller

e Δe	NL	NM	NP	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NP	EZ
NM	NL	NL	NL	NM	NP	EZ	PS
NP	NL	NL	NM	NP	EZ	PS	PM
EZ	NL	NM	NP	EZ	PS	PM	PL
PS	NM	NP	EZ	PS	PM	PL	PL
PM	NP	EZ	PS	PM	PL	PL	PL
PL	EZ	PS	PM	PL	PL	PL	PL



a)



b)

Figure 7. Input variable membership functions

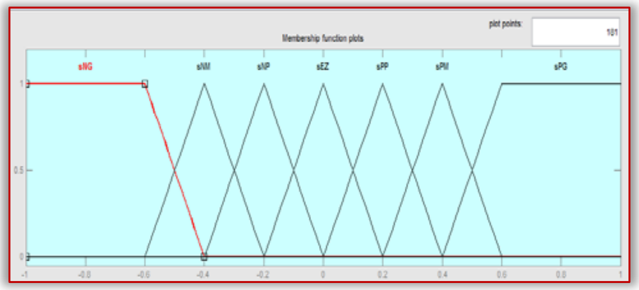


Figure 8. Output variable membership function

SIMULATION RESULTS

The motor parameters are Power = 1MW, Rated voltage = 791V, Poles = 3, Frequency=60Hz, Stator resistance = 0.228ohm, Rotor resistance = 0.332ohm, Stator inductance = 0.0084H, Rotor inductance = 0.0082H, Moment of inertia = 20 Kg.m2, Magnetizing inductance = 0.0078H.

Reference speed is chosen as 1000 r.p.m, and external load torques of 6500 N.m are applied at 0.8 sec with conventional DTC and DTC proposed.

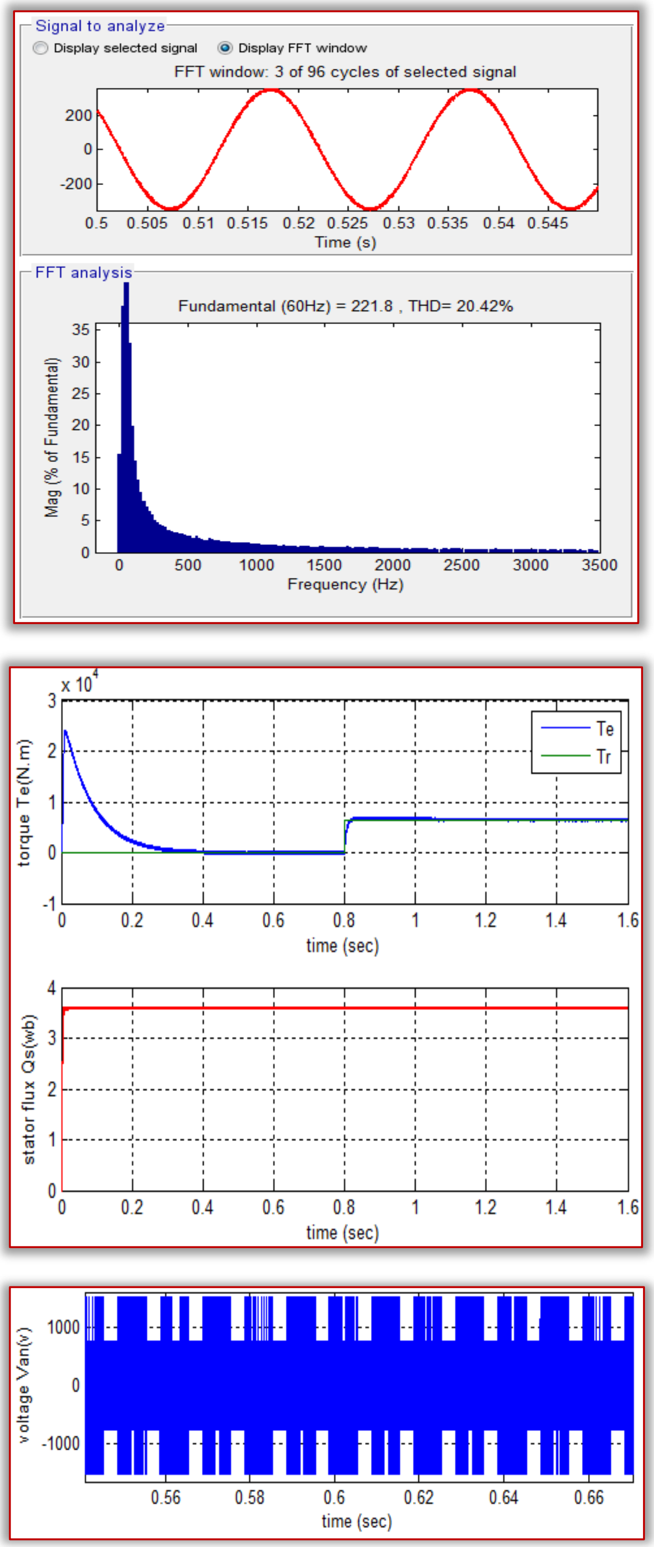


Figure 9. Performances of classical DTC

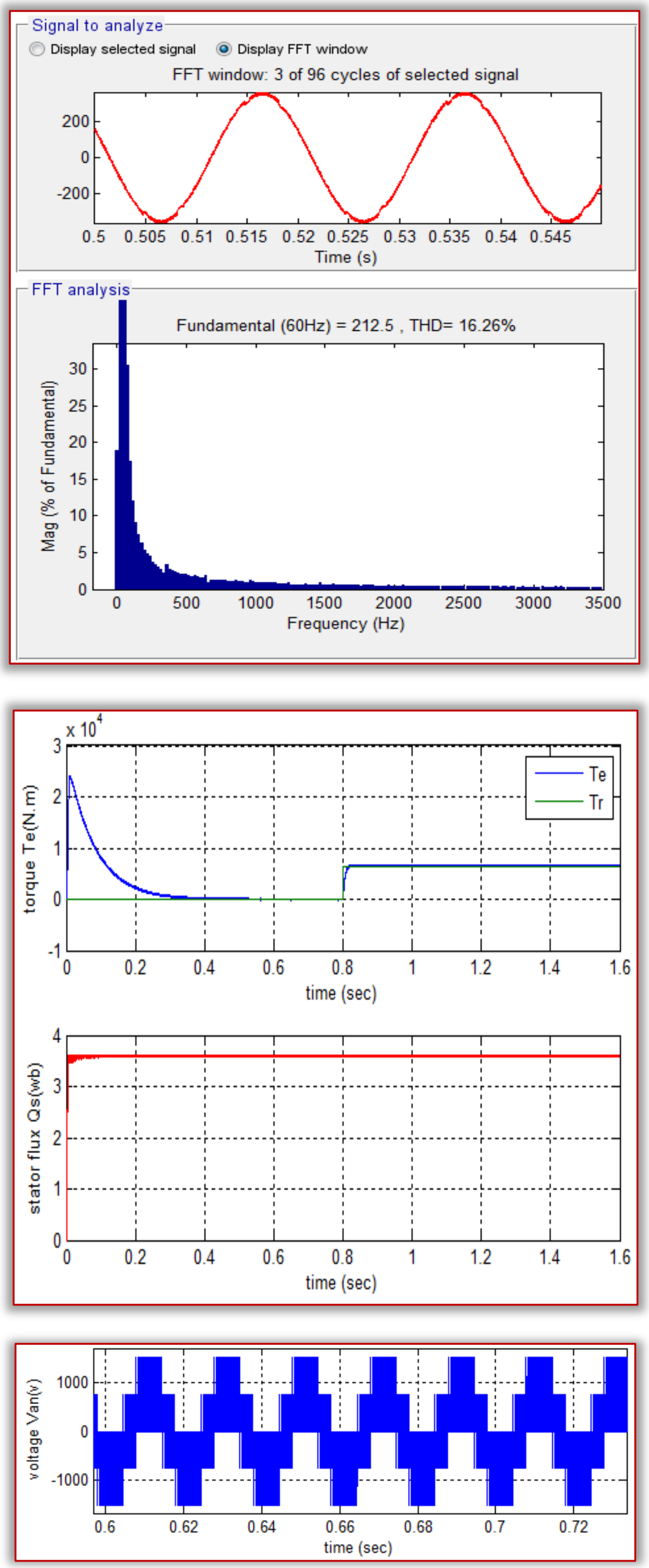
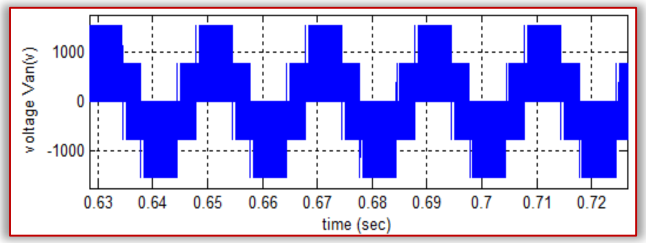
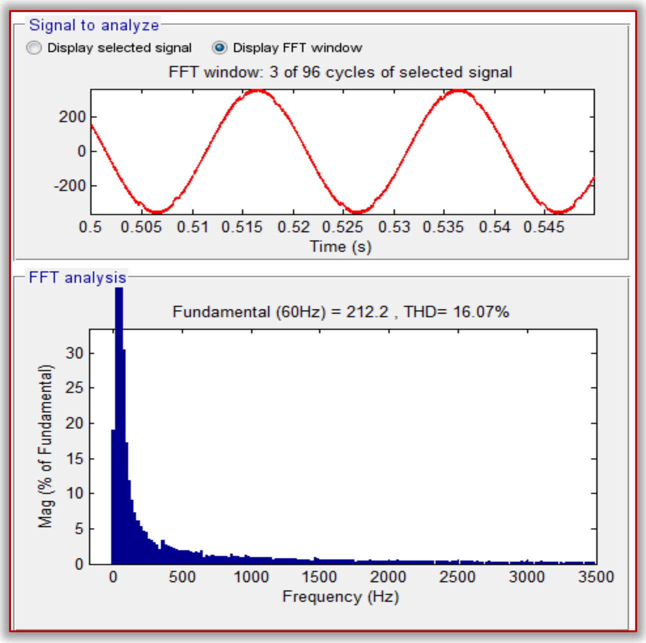


Figure 10. Performances of strategy 1 for classical DTC





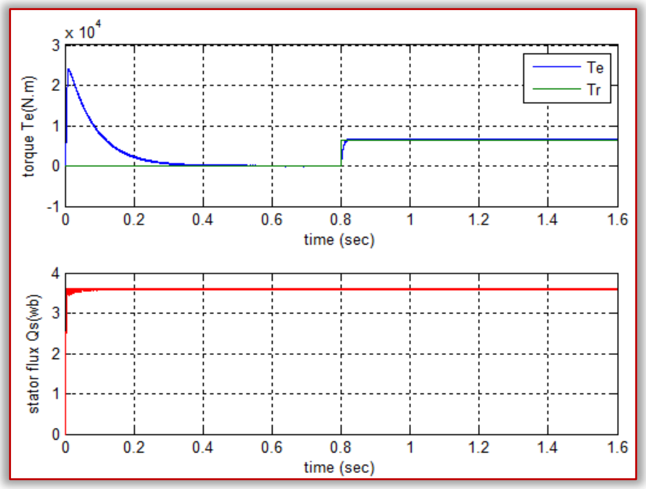
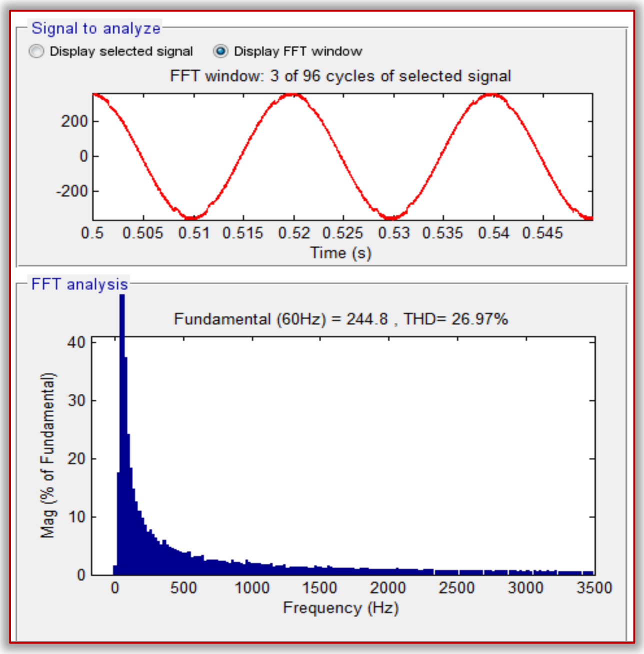
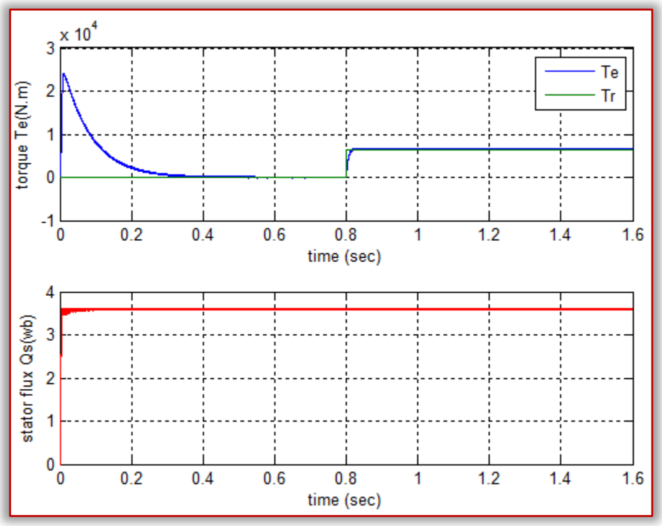


Figure 11. Performances of strategy 2 for classical DTC





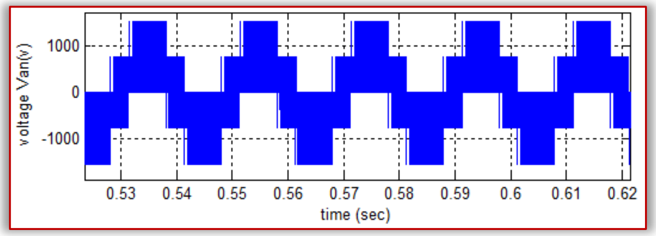
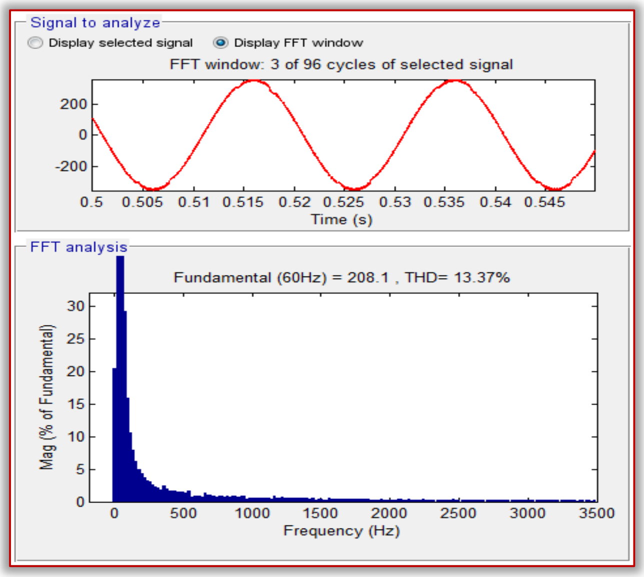
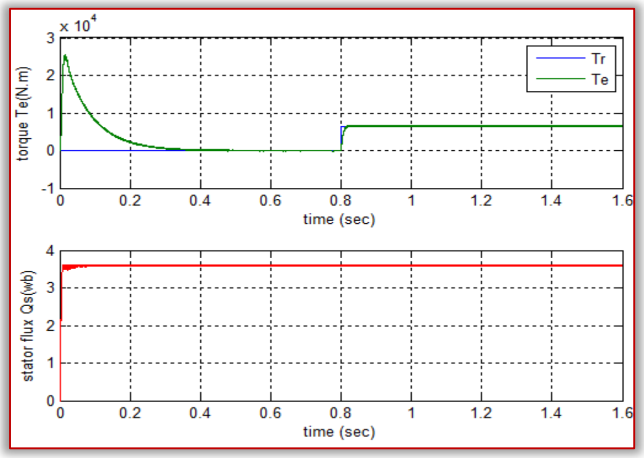


Figure 12. Performances of strategy 3 for classical DTC





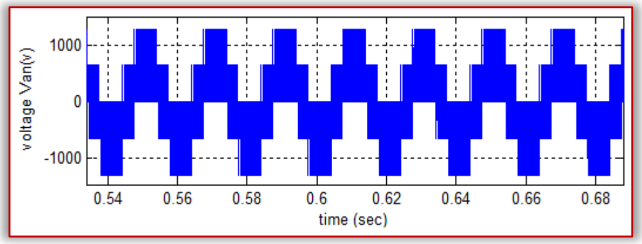
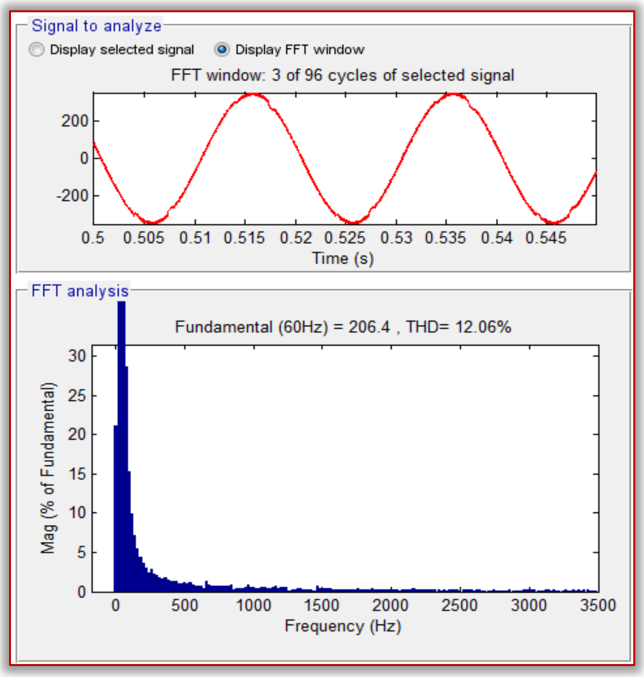
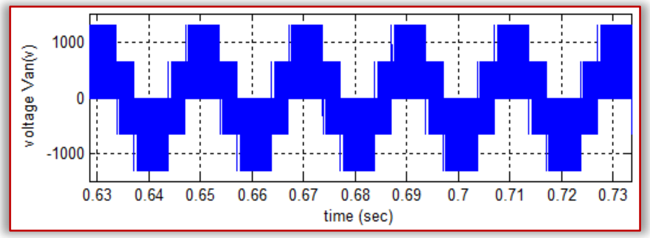


Figure 13. Performances of classical DTC with neural and fuzzy controllers





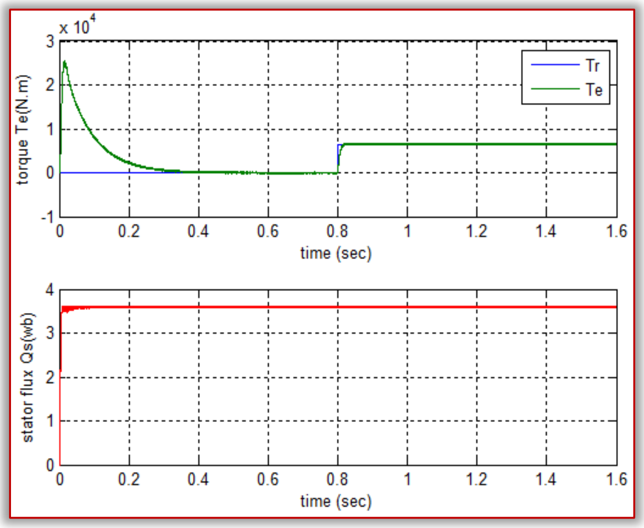
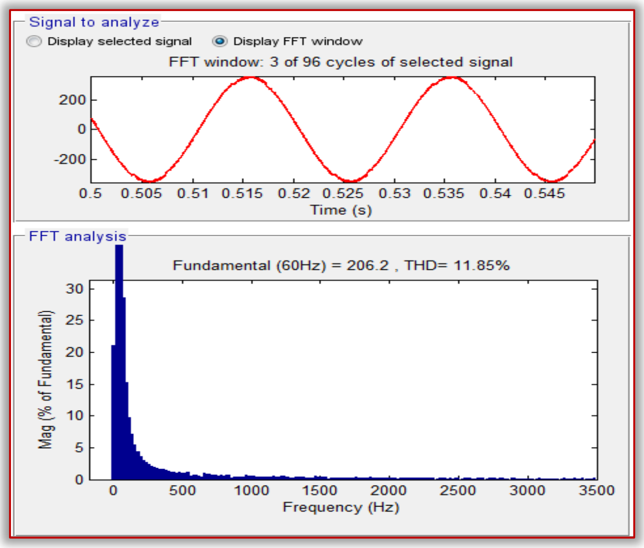
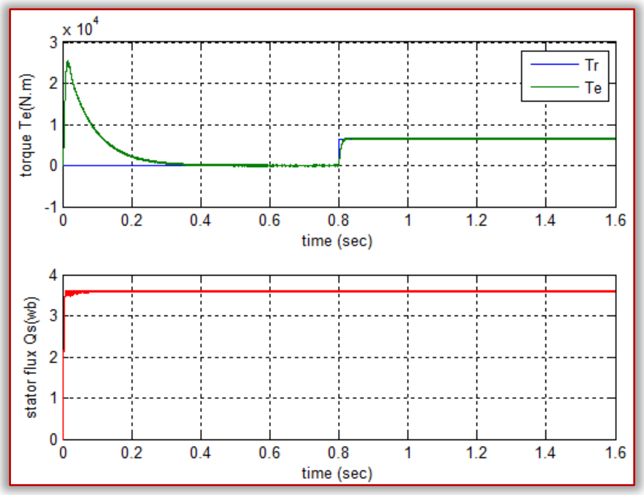


Figure 14. Performances of strategy 1 for classical DTC with neural and fuzzy controllers





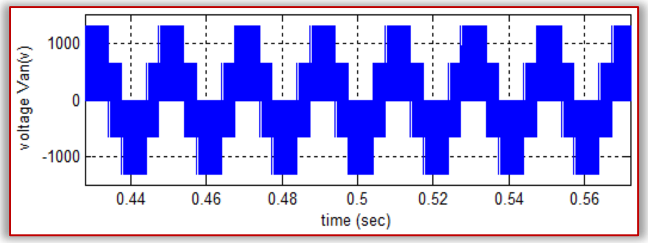
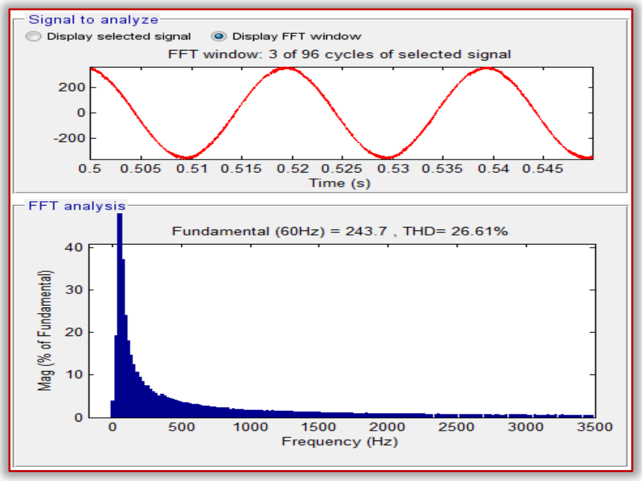


Figure 15. Performances of strategy 2 for classical DTC with neural and fuzzy controllers



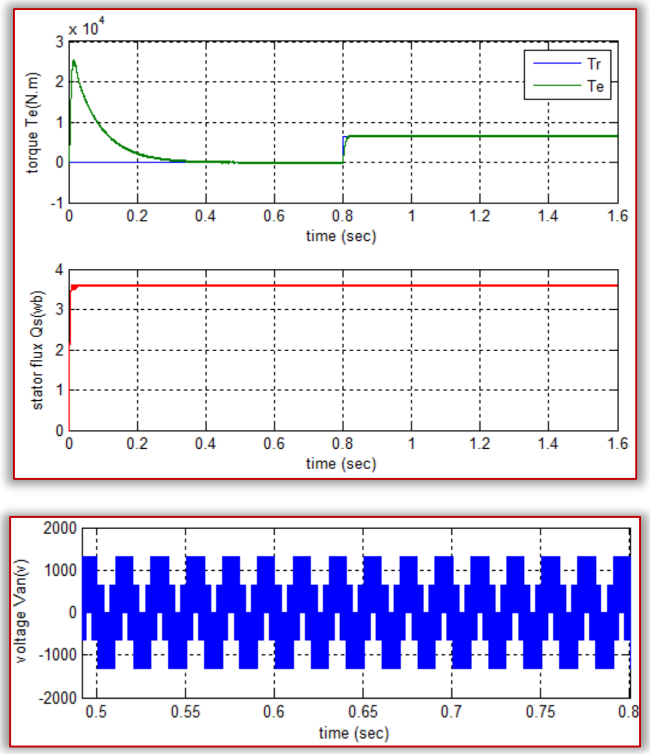
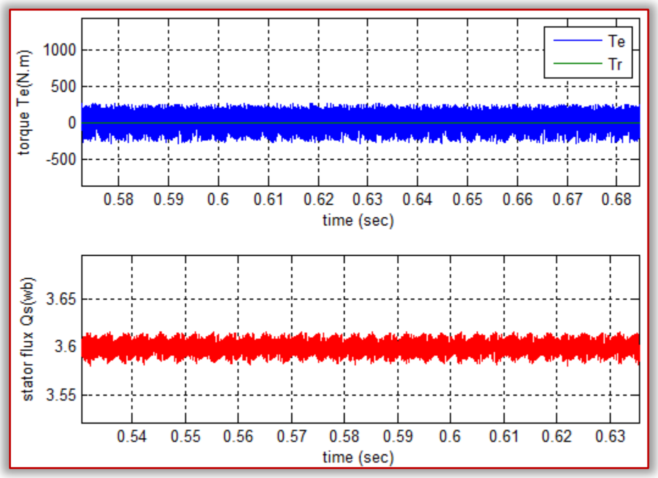
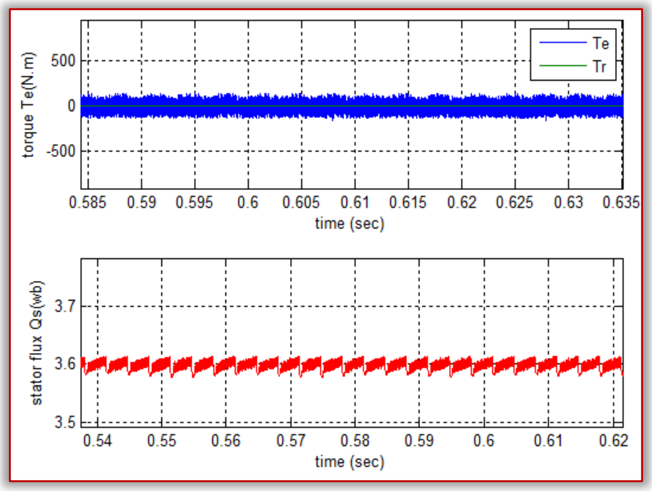


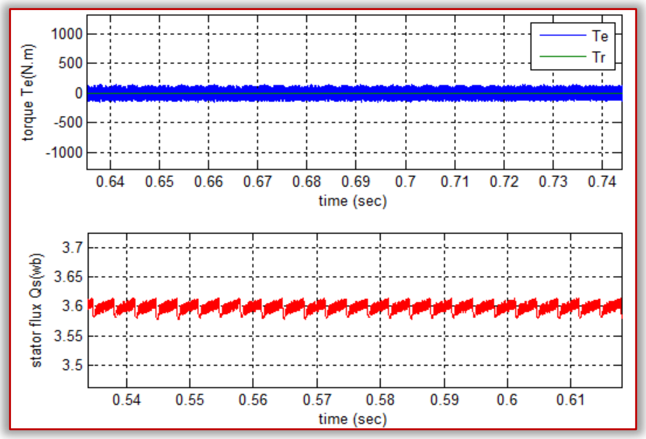
Figure 16. Performances of strategy 3 for classical DTC with neural and fuzzy controllers



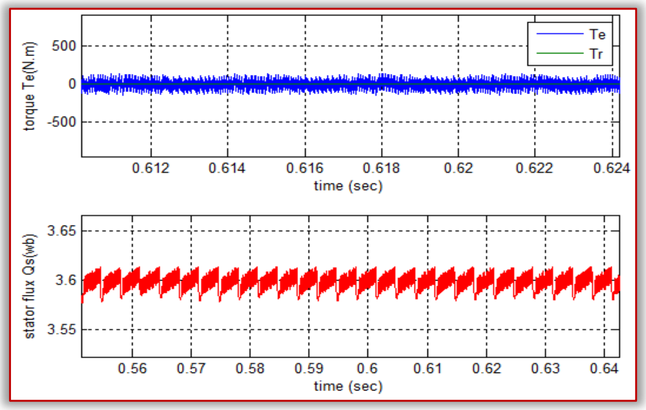
a) Classical DTC



b) Strategy 1

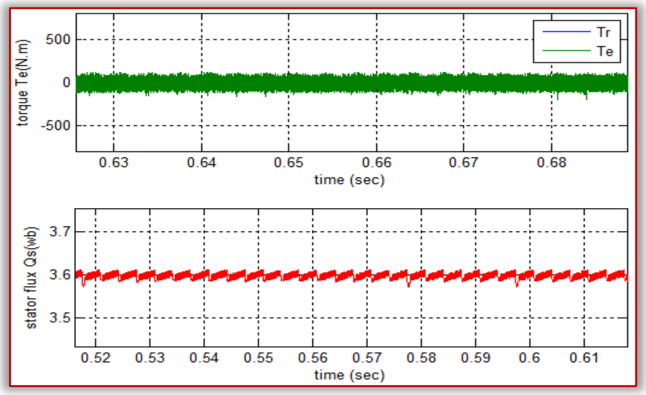


c) Strategy2

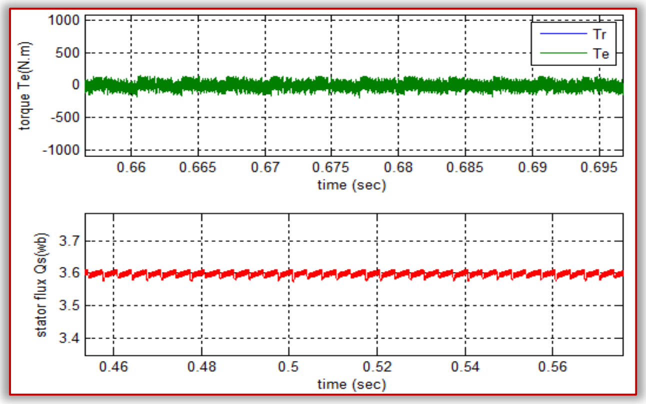


d) Strategy 3

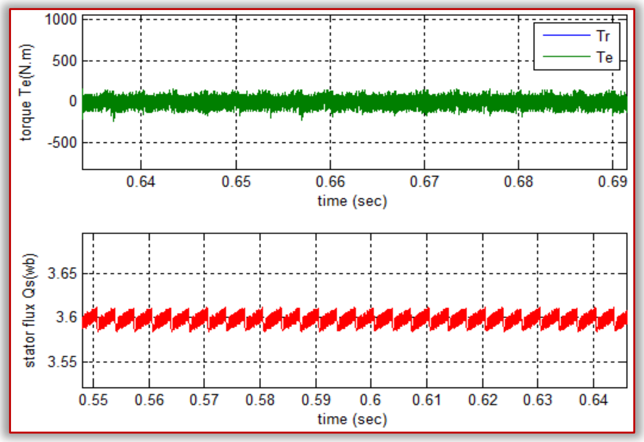
Figure 17. Comparison between classical and proposed strategy of DTC



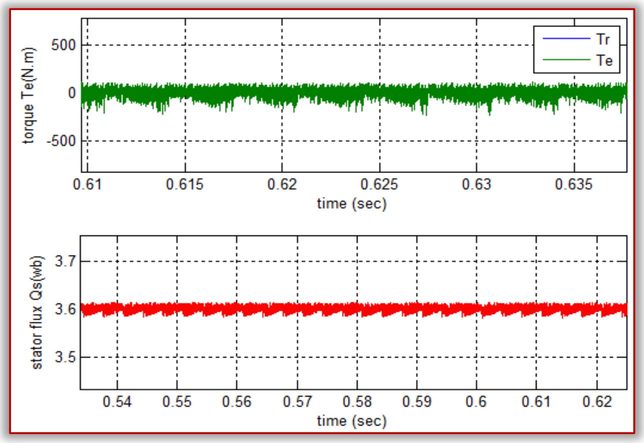
a) Classical DTC with neural and fuzzy controllers



b) Strategy 1 with neural and fuzzy controllers of classical DTC



c) Strategy 2 with neural and fuzzy controllers of classical DTC



d) Strategy 3 with neural and fuzzy controllers of classical DTC

Figure 18. Comparison between the classical and proposed strategy of DTC with neural and fuzzy controllers

In Table 5, we summarize the simulation results obtained by conventional DTC and the proposed strategies.

Table 5. Comparison results

Strategy	I_{as} THD (%)
Classical DTC	20.42
Strategy 1	16.26
Strategy 2	16.07
Strategy 3	26.97
Classical DTC with neural and fuzzy controllers	13.37
Strategy 1 with neural and fuzzy controllers	12.06
Strategy 2 with neural and fuzzy controllers	11.85
Strategy 3 with neural and fuzzy controllers	26.61

To compare with classical DTC and DTC proposed a voltage zeros for induction motor using fuzzy logic and artificial neural networks controller's is simulated. See figures the torque ripple is significantly reduced when neural and fuzzy controllers are in use.

In Table 5 the value of THD for stator current is significantly reduced when DTC proposed. On the other hand, we note that the strategy 2 of the classical DTC given good result compared to the best strategy 1 and 3, and classical DTC.

The speed reaches its reference without overrunning at the empty start for all strategies. And the torque flows the load torque.

The dynamics of the components of the stator flux are not affected by the application of these load guidelines.

CONCLUSION

This paper proposes new tables and novel scheme to improve the drive performance. Fuzzy logic and neural networks controller's of direct torque control (DTC) is used to improve dynamic response performance and decrease the torque ripples. It can be seen from the simulation results above for the simulation model given and the parameters mentioned above that flux, torque and current ripples is reduced remarkably for the proposed method (strategy 2). The simulation results show that the torque has a very good dynamic response for the mentioned DTC methods. Applying ANN and Fuzzy to replace controller's result in reducing the over and under shoots and lead to swift speed response as shown in simulation results. Therefore using the proposed method results in improving the motor performance.

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