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Direct Torque Control of an Induction Motor Based on Neurofuzzy

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ABSTRACT

The main objective of this work is to improve the speed and torque responses of three phase Induction Motor (IM) during different loads and speeds conditions. Induction Motor is most commonly used in different industrial applications, that require fast dynamic response and accurate control over wide speed ranges. Therefore, this work proposes Direct Torque Control (DTC). Particle Swarm Optimization (PSO) technique is used for optimal gains tuning of PI. The results show the improvement in the speed response of DTC, in terms of reducing steady state error, ripple reduction in the torque and speed responses. Neurofuzzy (ANFIS) controller is used to improve the performance of PI-PSO controller. ANFIS controller is trained by using PI-PSO data. The results of the ANFIS controller are better than PI-PSO in terms of torque ripple minimization, less steady state error in the speed response and more robustness. The simulation of the overall drive system is performed using MATLAB/Simulink program version 7.10 (R2010a).

Keywords: Induction Motor (IM), Direct Torque Control, PI controller, Particle Swarm Optimization (PSO) and Neurofuzzy (ANFIS).

السيطرة المباشرة على عزم المحرك الحثي بأستخدام تقنية هجينة من الشبكات العصبية والسيطرة الضبابية (Neurofuzzy)

الخـــلاصـــــــة

الهدف الرئيسي من هذا العمل هو تحسين أداء السرعة والعزم في المحرك الحثي ثلاثي الاطوار عند أحمال وسرع مختلفة. ويعد المحرك الحثي الأكثر شيوعا في التطبيقات الصناعية المختلفة, التي تتطلب إستجابة ديناميكية سريعة ودقة في السيطرة لمديات واسعة من السرعة, لذا تم في هذا العمل اقتراح استخدام تقنية السيطرة المباشرة على العزم **(DTC)**, والتي تعتبر من طرق السيطرة الاتجاهية لتحسين الاستجابة الديناميكية للمحرك. إستخدمت تقنية أفضلية الحشد الجزيئي **(PSO)** لأختيار القيم المغلى لقيم المتغيرات **(gains)**. وقد بينت النتائج التحسين الذي طرأ

على أداء تقنية السيطرة **DTC** في استجابة السرعة من حيث تقليل خطأ الحالة المستقرة و تقليل التموج في موجتي السرعة والعزم.إستُخدِم مسيطر **Neurofuzzy(ANFIS)** لتحسين أداء المسيطر **PI-PSO** دُرِبَ مسيطر **Neurofuzzy** بإستخدام المعلومات التي تم الحصول عليها من المسيطر **PI-PSO**. وبينت النتائج أن مسيطر **Neurofuzzy** هو أفضل من مسيطر **PI-PSO** من حيث تقليل التموج في موجة العزم وتقليل خطأ الحالة المستقرة في إستجابة السرعة وكذلك أكثر متانة.إستُخدِم لمحاكاة هذا العمل برنامج ماتلاب / سميولنك 7.10 (R2010a).

INTRODUCTION

Induction motors are asynchronous speed machines, operating under the synchronous speed. They are rugged, inexpensive to produce and easy to maintain when compared with the synchronous and DC machines. It can be operated at a nearly constant speed from zero to full load [1].

There are many different methods to drive IM; these methods can be mentioned as: scalar and vector control.

Scalar control known as V/f control .It assumes a constant relation between voltage and frequency. The structure is very simple and it is normally used without speed feedback [2, 3].

Vector control can be classified to: Field Oriented Control (FOC) and Direct Torque Control (DTC).

FOC was introduced for the first time by Blaschke in the early 1970s. FOC is widely used in high performance AC drives which transforms the motor equations into a coordinate system that rotates in synchronism with the rotor flux vector so the flux and torque of an AC machine can be controlled independently, as in a DC machine. The term of vector control refers to the control techniques that control both the amplitude and the phase of ac excitation voltage [4,5].

DTC was proposed in the middle of 1980 by I. Takahashi and Depenbrok [6,7]. DTC has emerged over the last two decades to become one possible alternative to the well-known vector control of induction machines [8,9,10].

The PI controller has been widely used in industry due to simple implementation, low cost and the ability to apply in a wide range of applications. It also improves the dynamic response of the system as well as reduces or eliminates the steady state error and the error sensibility. This is achieved by providing a proportional gain (K_p) for the error input term with an integral component correction (K_i) [11,12].

The PSO algorithm is one of the optimization techniques developed by Eberhart and Kennedy in 1995. This method has been found to be robust in solving problems featuring non-linearity and non-differentiability, which is derived from the social-psychological [13]. It was inspired by the social behavior of bird flocking and fish schooling, and has been found to be robust in solving continuous nonlinear optimization problems. PSO becomes a focus these days due to its simplicity and ease to implement [14].

Artificial Intelligent systems (AIS), means those systems that are capable of imitating the human reasoning process as well as handling quantitative and qualitative knowledge. The control rules and controller computation will grow exponentially with respect to a number of considered variables. Therefore, intelligent control strategy is gradually drawing attention [10]. Neurofuzzy

(ANFIS) is one the intelligent techniques combining between the merits of the artificial neural networks and fuzzy logic. ANFIS has gain a lot of interest over the last few years as a powerful technique to solve many real world problems. AIS when compared to conventional techniques, they own the capability of solving problems that do not have algorithmic solution. Neural networks and fuzzy logic technique are quite different, and yet with unique capabilities useful in information processing by specifying mathematical relationships among numerous variables in a complex system, performing mappings with degree of imprecision, control of nonlinear system to a degree not possible with conventional linear systems[15].

MATHEMATICAL MODEL OF IM

The mechanical representation of an IM can be depicted as a transformer with moving secondary winding, where the coupling coefficients between the stator and rotor phases change permanently with the change of rotor position [16, 17].

The mathematical model can be described by differential equation with time varying mutual inductances. Therefore, axis transformation is applied to convert the three phase parameters (voltage, current and flux) to two–axis frame called (dq-axis stationary frame or park transformation). Park transformation is applied to refer the stator variables to a synchronously rotating reference frame fixed in the rotor, by such transformation the stator and rotor parameters rotate in synchronous speed and all simulated variables in the stationary frame appear as DC quantities in the synchronously rotating reference frame [16,17].

The per-phase equivalent circuit diagrams of an I.M. in two- axis synchronously rotating reference frame.

From the circuit diagram the following equations can be written [16]:

- Stator equation:

$$V_{qs}{}^{e} = R_s i_{qs}{}^{e} + \frac{d\Psi_{qs}}{dt} + w_e \Psi_{ds} \quad \dots (1)$$

$$V_{ds}{}^{e} = R_s i_{ds}{}^{e} + \frac{d\Psi_{ds}}{dt} - w_e \Psi_{qs} \quad \dots (2)$$

- Rotor equation:

$$V_{qr}{}^{e} = R_r i_{qr}{}^{e} + \frac{d\Psi_{qr}}{dt} + (w_e - w_r)\Psi_{dr} \quad \dots (3)$$

$$V_{dr}{}^{e} = R_r i_{dr}{}^{e} + \frac{d\Psi_{dr}}{dt} - (w_e - w_r)\Psi_{qr} \quad \dots (4)$$

Where:

the superscript notation "*e*" referred to the synchronously rotating reference frame quantities.

The development torque by interaction of air gap flux and rotor current can be found as:

$$T_e=(3/2)(P/2)\overrightarrow{\Psi_m} \times \overrightarrow{I_r} \qquad ...(5)$$

By resolving the variables into d^e-q^e components:

$$T_e= (3/2)(P/2)\left(\Psi_{ds} i_{qs}^{\ e} - \Psi_{qs} i_{ds}^{\ e}\right) \qquad ...(6)$$

The dynamic torque equation of the rotor:

Where:

ω_r = is the rotor speed; P: no. of poles;

J= rotor inertia;

T_L= load torque

The stator current can be found by:

$$i_{ds}^{\ e} = \frac{\Psi_{ds} - \Psi_{qm}}{L_s} \qquad ... (7)$$

$$i_{qs}^{\ e} = \frac{\Psi_{qs} - \Psi_{qm}}{L_s} \qquad ... (8)$$

$$\Psi_{qm} = \frac{L_{m1}}{L_s}\Psi_{qs} + \frac{L_{m1}}{L_r}\Psi_{qr} \qquad ... (9)$$

$$\Psi_{dm} = \frac{L_{m1}}{L_s}\Psi_{ds} + \frac{L_{m1}}{L_r}\Psi_{dr} \qquad ... (10)$$

Where,

$$L_{m1} = \frac{1}{\left(\frac{1}{L_m} + \frac{1}{L_s} + \frac{1}{L_r}\right)} \qquad ... (11)$$

DIRECT TORQUE CONTROL

Direct Torque Control describes the way in which the control of torque and speed are directly based on the electromagnetic state of the motor, similar to a DC motor, but contrary to the way in which traditional PWM drives use input frequency and voltage. Direct torque control is the first technology to control the “real” motor controlled variables as torque and flux [18]. Figure (1) shows the block diagram of DTC.

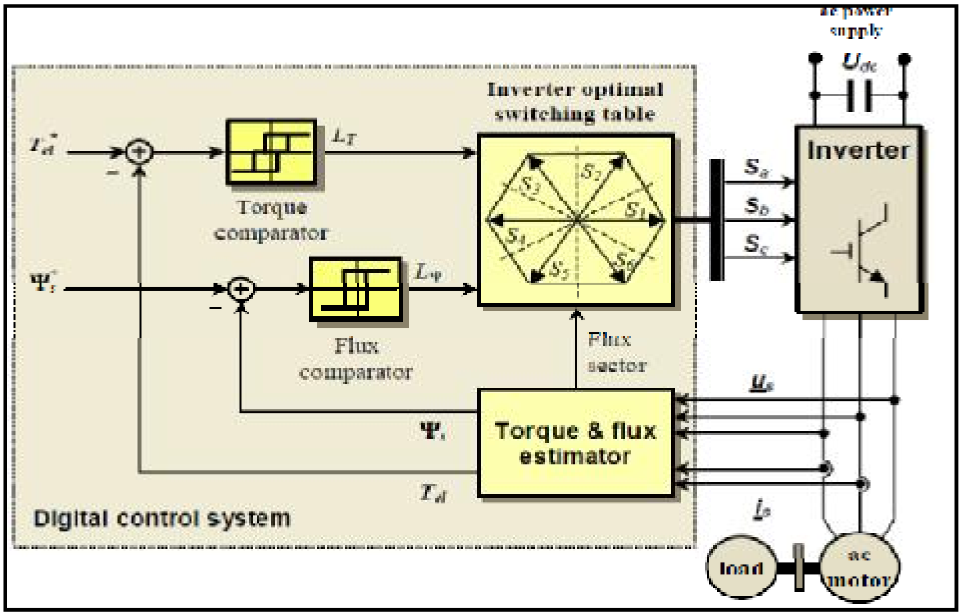


Figure (1) DTC block diagram.

Generally, in a symmetrical three phase induction motor, the instantaneous electromagnetic torque is proportional to the cross product of the stator flux linkage space vector and the rotor flux linkage space vector [19].

$$T_e = \left(\frac{3P}{2}\right)\psi_s\psi_r\sin\delta \qquad \dots(12)$$

Whereψ_s , is the stator flux linkage space vector , ψ_r is the rotor flux linkage space vector referred to stator and δ is the angle between the stator and rotor flux linkage space vectors.
The estimator equations for stator flux (ψ_s), stator flux position(θ_s)and torque are:

$$\psi_s = \sqrt{\psi_{qs}^2 + \psi_{ds}^2} \qquad \dots(13)$$

$$\theta_s = \tan^{-1}\left(\frac{\psi_{qs}}{\psi_{ds}}\right) \qquad \dots(14)$$

$$T_e = \left(\frac{3p}{2}\right)(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \qquad \dots(15)$$

NEUROFUZZY

Fuzzy systems allow to transfer the vague fuzzy form of human reasoning to mathematical systems. The use of IF–THEN rules in fuzzy systems gives us the possibility of easily understanding the information modeled by the system. In most of the fuzzy systems the knowledge is obtained from human experts. However this method of information acquisition has a great disadvantage given that not every human expert can and/or wants to share their knowledge [14]. Figure (3) shows a block diagram of neurofuzzy controller.

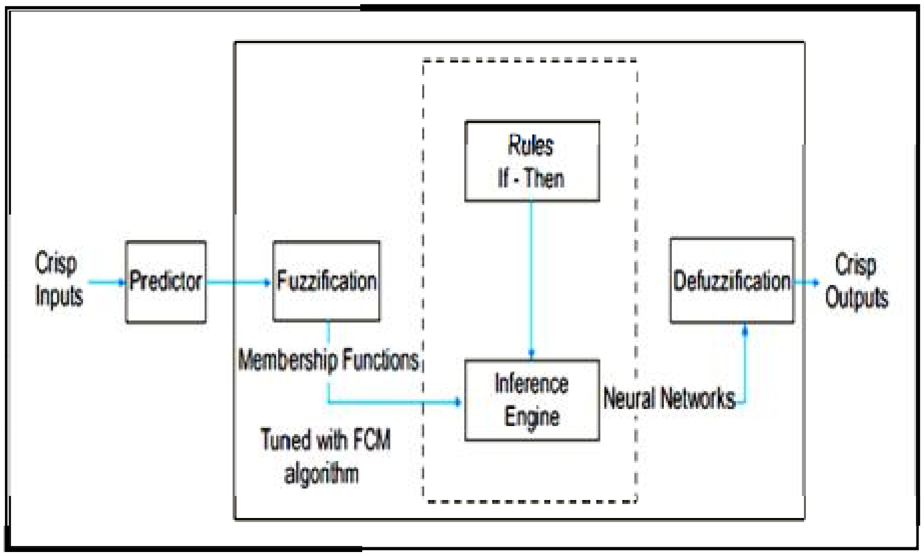


Figure (2) Neurofuzzy controller block diagram.

SIMULATION AND RESULTS

The values of the electrical design parameters for 3 phase squirrel cage IM used in the simulation are shown in the appendix A and the look up table that used for optimum switching states is shown in appendix B. Figure (3) shows the MATLAB/ Simuink circuit of the conventional DTC.

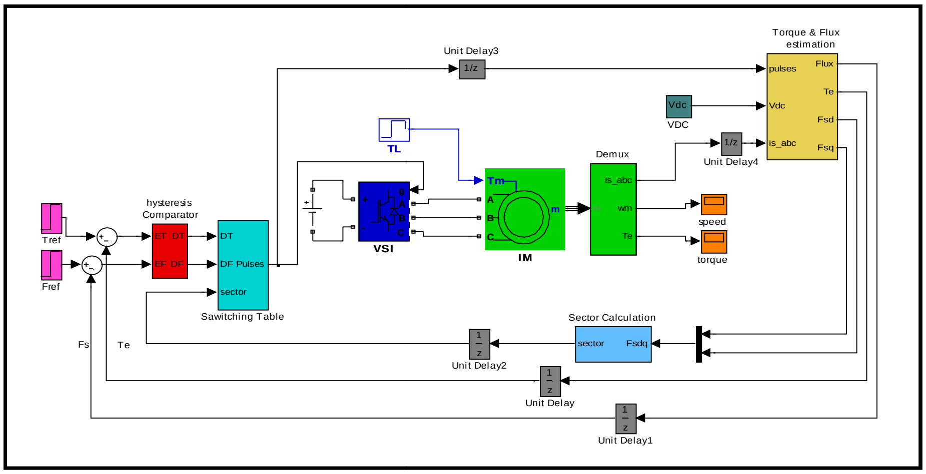


Figure (3) Conventional DTC Matlab/Simulink circuit.

The DTC with PI-PSO controller Matlab/Simulink circuit is shown in Figure (4)

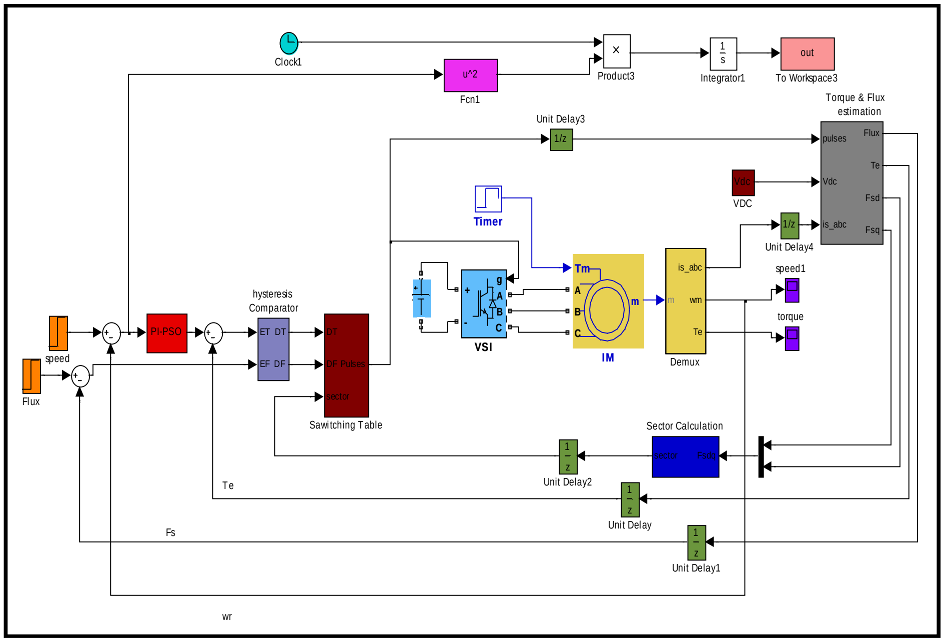


Figure (4) DTC with PI-PSO Matlab/Simulink circuit

The PSO tuning method in this work depends on ITAE performance index. The gains of PI controller which are obtained by using PSO technique are kp= 4.663, ki=1.957, Speed and torque responses of IM for conventional DTC and DTC with PI-PSO controller at different loads(no load at (0-0.3)sec., 14 N.m.at (0.3-0.7)sec. , and 7N.m. at (0.7-1)sec.) are shown together in Figures (5), (6) ,(7) and (8).

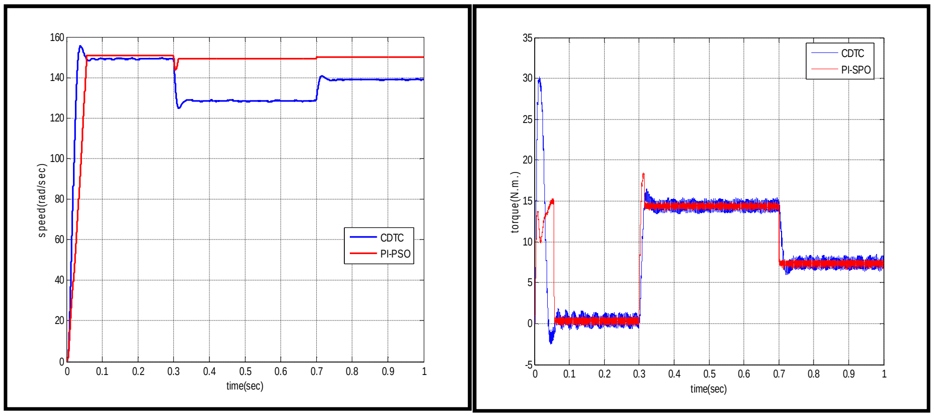


Figure (5) Speed and torque responses at ω=149 rad/sec, T_L= (0-14-7)N.m. where CDTC is conventional DTC

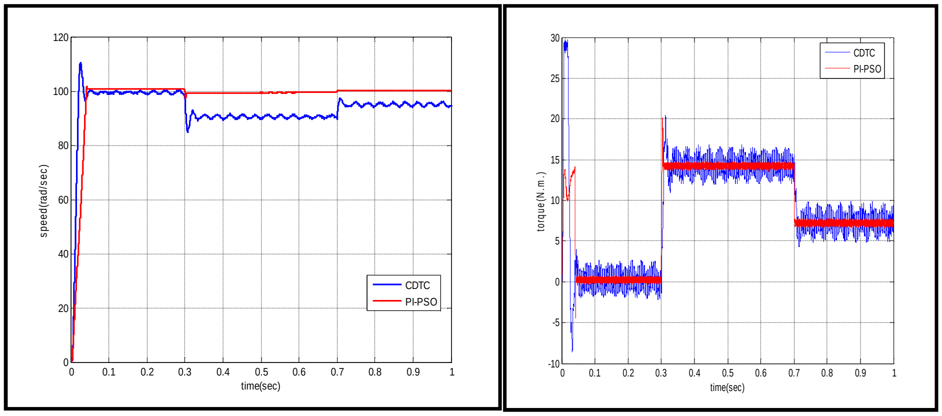


Figure (6) Speed and torque responses at ω=100rad/sec, T_L= (0-14-7)N.m.

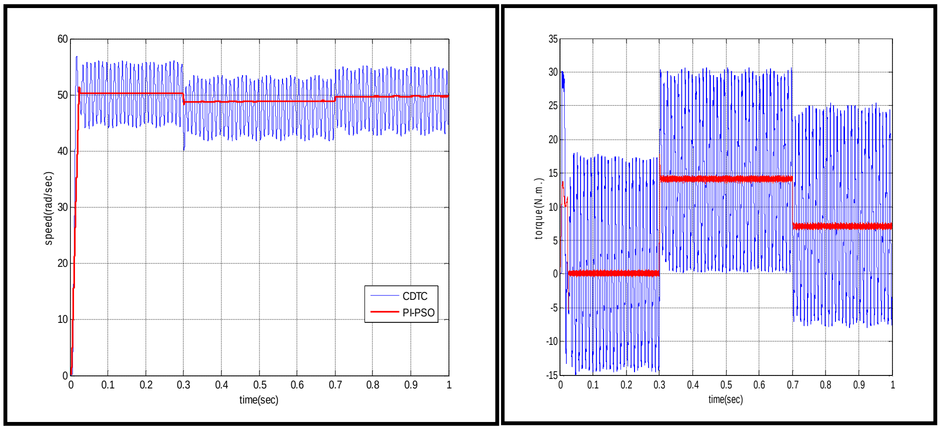


Figure (7) Speed and torque responses at ω=50 rad/sec, T_L= (0-14-7)N.m.

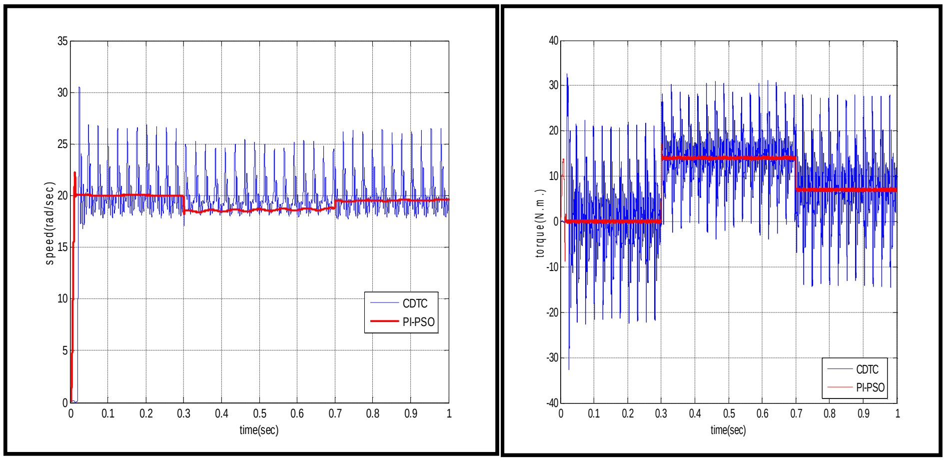
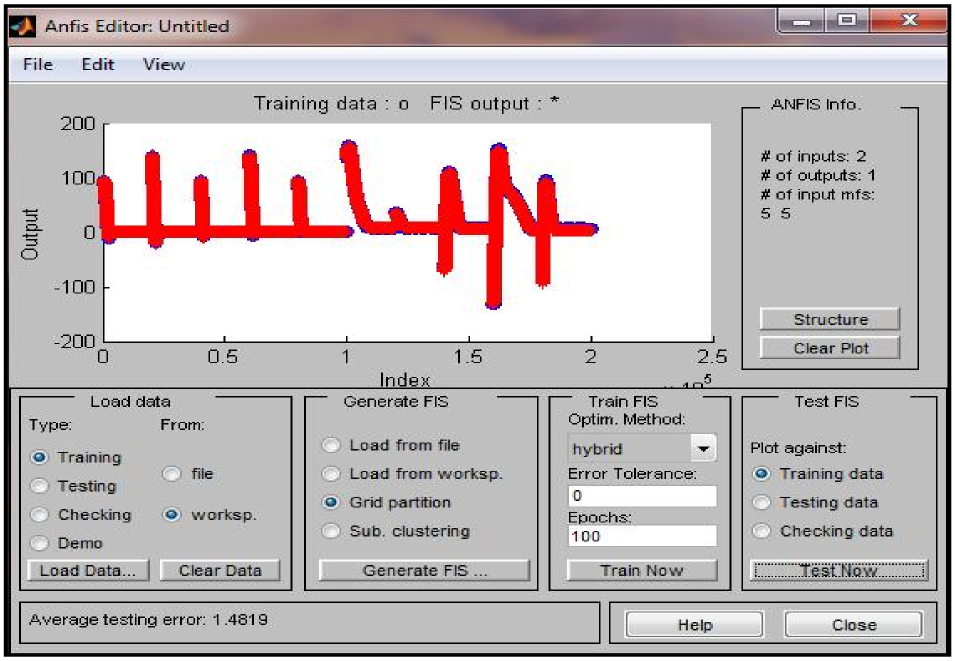


Figure (8) Speed and torque responses at ω=20 rad/sec, T_L= (0-14-7)N.m.

The DTC with neurofuzzy controller Matlab/Simulink circuit is the same as the circuit in Figure (4) except that the PI controller is replaced by a neurofuzzy controller.

The obtained results from the DTC with PI-PSO are trained by using ANFIS editor as shown in Figure (9).



Anfis Editor: Untitled

Training data : o FIS output : *

ANFIS Info.

# of inputs: 2
# of outputs: 1
# of input mfs:
5 5

Load data
Type:
● Training
○ Testing
○ Checking
○ Demo
From:
○ file
● worksp.

Generate FIS
○ Load from file
○ Load from worksp.
● Grid partition
○ Sub. clustering

Train FIS
Optim. Method: hybrid
Error Tolerance: 0
Epochs: 100

Test FIS
Plot against:
● Training data
○ Testing data
○ Checking data

Average testing error: 1.4819

Figure (9) ANFIS training editor screen

Speed and torque responses of IM for Neurofuzzy controller at different loads are shown in Figures (10), (11) and (12).

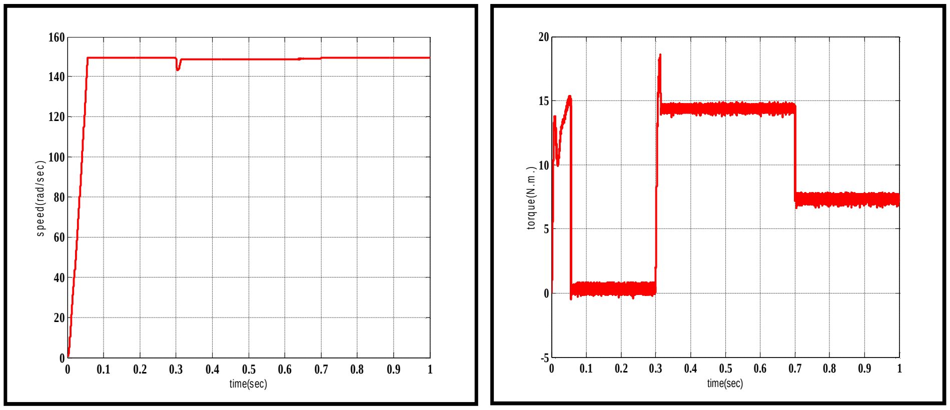


Figure (10) Speed and torque responses at ω=149 rad/sec, T_L= (0-14-7)N.m.

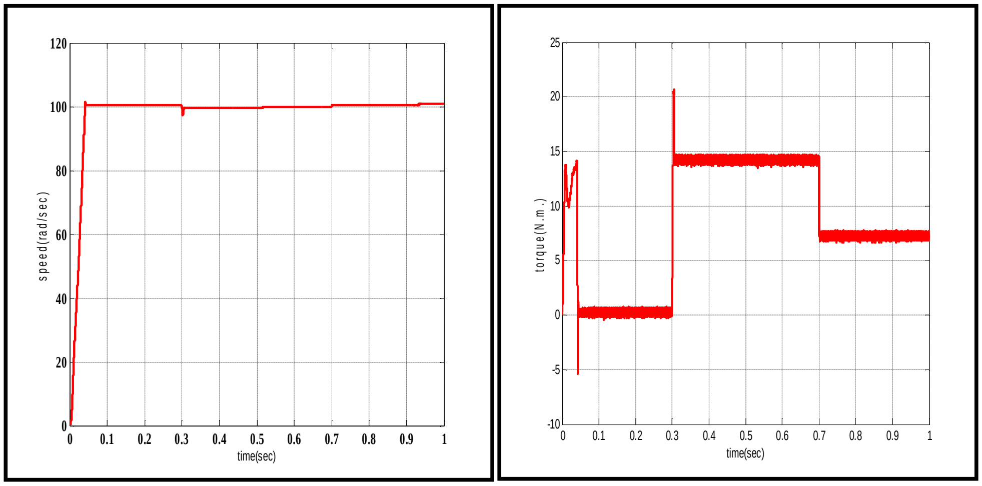


Figure (11) Speed and torque responses at ω=100 rad/sec, T_L= (0-14-7)N.m.

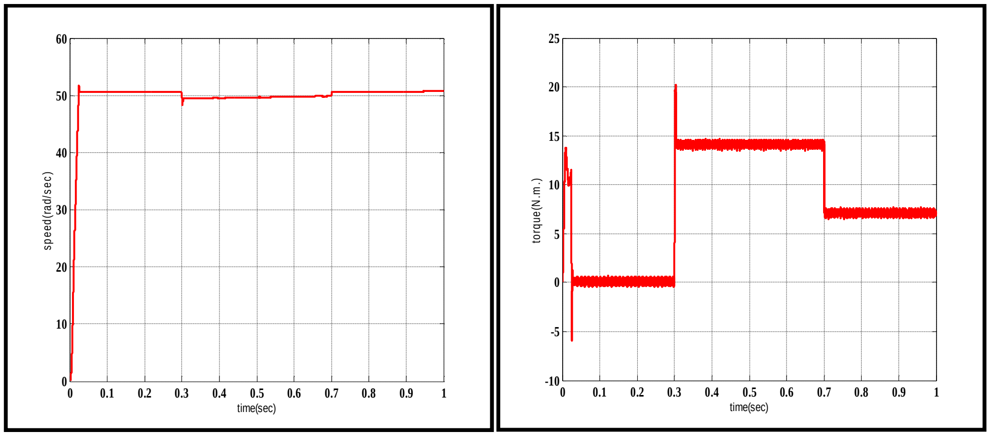


Figure (12) Speed and torque responses at ω=50 rad/sec, T_L= (0-14-7)N.m.

The zoomed speed responses of IM at different loads (no load, 14, 7) N.m , for DTC with PI-PSO controller and DTC with neurofuzzy controller are shown together in figures(13),(14),(15) and(16) .

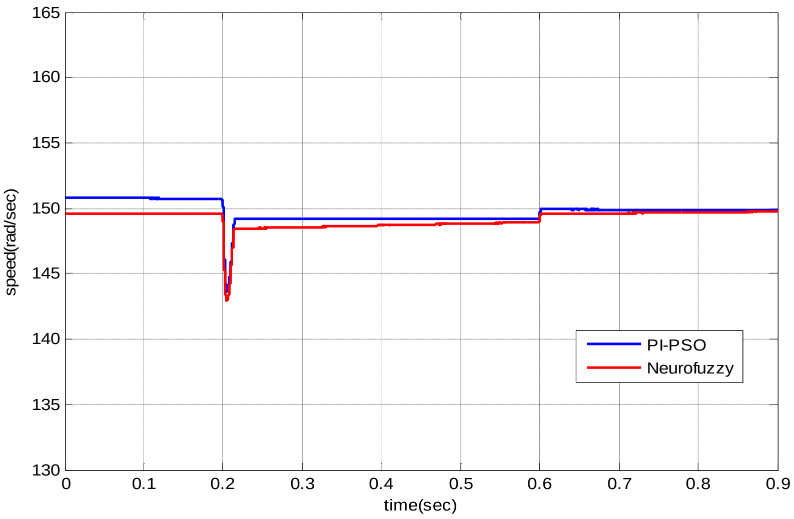


Figure (13) Speed responses at ω= 149 rad/sec.

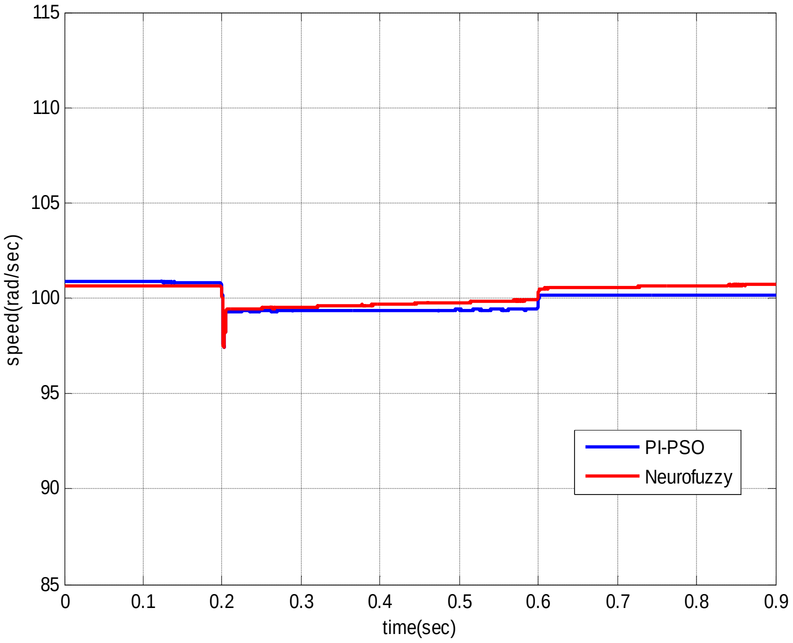


Figure (14) Speed responses at ω=100 rad/sec.

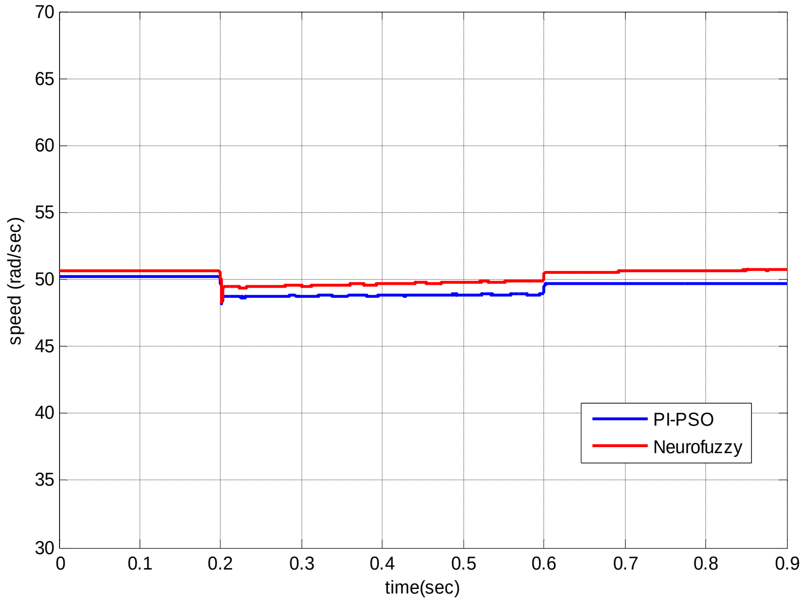


Figure (15) Speed response at ω=50 rad/sec.

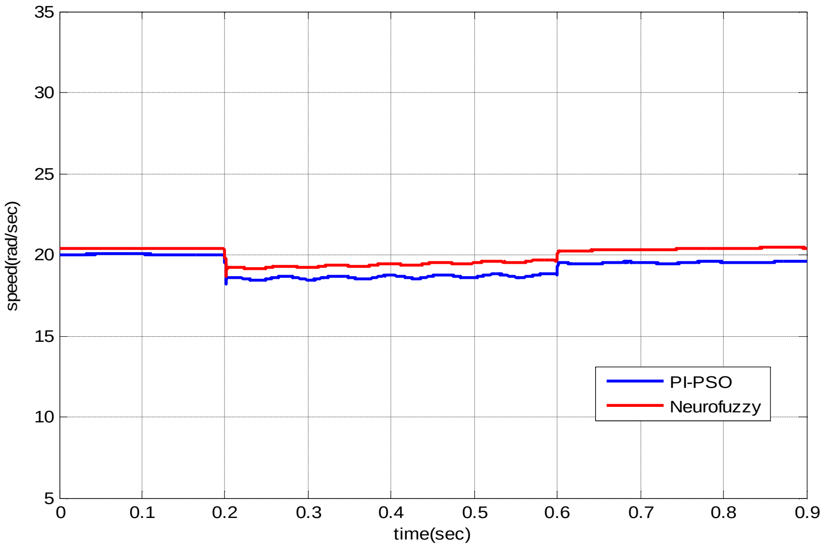


Figure (16) Speed response at ω=20 rad/sec.

CONCLUSIONS

PI-PSO controller improve the performance of conventional DTC in terms of less steady state error at different loads, very small overshoot and less torque ripple as depicted in the Figures (5), (6) ,(7) and (8).

Neurofuzzy technique is a hybrid technique, merges between the features of artificial neural networks and fuzzy logic control, where the neurofuzzy technique showed a simplicity in the training method when compared with the neural networks and simplicity of choosing the number and shapes of the membership functions when compared with the fuzzy logic. ANFIS controller has advantages over PI-PSO in terms of less steady state error, less torque ripple and more robust to the speed and load changes as shown in Figures (13), (14), (15) and (16).

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Appendix A

Motor design parameters

Item	**Value**
Rated power	2.2Kw
Nominal frequency	50Hz
Rated voltage	400V
No. of pole pairs	2
Rated speed	1430rpm
Stator resistance	2.3 Ω
Rotor resistance	3.14 Ω
Stator inductance	0.0136 H
Rotor inductance	0.0136 H
Mutual inductance	0.3 H
Moment of inertia	$4.5*10^{-3}$ Kg.m^2 /sec

Appendix B

The used lookup table for optimum switching state .

Flux error	**Torque error**	**Flux sectors**					
		S1	**S2**	**S3**	**S4**	**S5**	**S6**
1	1	001	011	010	110	010	100
	0	000	000	111	000	111	111
	-1	010	100	001	011	101	110
0	1	011	101	110	010	100	001
	0	111	111	000	111	000	000
	-1	110	010	100	001	011	101