Diyala Journal of Engineering Sciences

ISSN 1999-8716
Printed in Iraq

First Engineering Scientific Conference
College of Engineering –University of Diyala
22-23 December 2010, pp. 473-484

IMPROVEMENT OF DIRECT TORQUE CONTROL SYSTEM USING RADIAL BASIS FUNCTION NEURAL NETWORK AND FUZZY CONTROL TECHNIQUES

Mohammed Khalaf Masood[1] and Essam M. Abdul-Baki[2]
(1)Lecturer _ Diyala Education, Ministry of Education
(2)Engineering College , University of Al-Mustenseria

ABSTRACT:- Direct Torque Control (DTC) is one of the most effective and modern methods for speed control of three phase induction motors, but it suffers from some drawbacks, that it needs an estimator for the electromagnetic torque and stator flux, and the existence of inherent ripples in the output torque. So it needs to an improvement.

In this work a proposed DTC system supported by Radial Basis Function Neural Network (RBFNN) and a Fuzzy Controller (FC) are constructed to avoid the above drawbacks. The (RBFNN) is used as a rapid estimator for the electromagnetic torque and stator flux and the Fuzzy Controller is used instead of the hysteresis comparator for torque and flux errors in order to organize the switching state selector in a more accurate manner. After studying the (RBFNN) it is concluded that it will be more accurate to use it during training and simulation in the independent outputs mode for the torque, stator flux and the sector. Also, accurate results can be achieved from this network for the torque, stator flux by using different values for the spread spectrum in order to let the switching state selector acts regularly. The simulation of the proposed DTC system is done by using a (Matlab/Simulink) program. The proposed DTC system shows a considerable reduction in torque ripples, and best starting performance. This improvement leads to an ability to increase the sampling period four times the conventional one.

Keywords:- Induction Motor, Radial Basis Function Neural Network, Fuzzy Control, Direct Torque Control.

1- INTRODUCTION

The ac induction motor is rugged, low-priced and easy to maintain. In adjustable speed applications, ac motors are powered by inverters, in order to achieve variable speed operation. The high power inverters suffer from the switching losses due to the PWM strategy used to reduce the harmonic contents of the applied waveform.

A new technique for the torque control of induction motors was developed and presented in the middle of 1980's by I. Takahashi as Direct Torque Control (DTC) (1), and by M. Depenbrock as Direct Self Control (DSC) (2). In this method, the stator flux and torque are controlled directly by selecting the appropriate inverter state.

DTC is the first technology to control the "real" motor variables of torque and flux.This method reduces the switching losses to a considerable level in spite of its simplicity in control and fast electromagnetic torque response. The principle of the classical DTC is its decoupled control of stator flux and electromagnetic torque using hysteresis control of stator flux error and torque error and stator flux position. A switching look-up table is included for selection of voltage vectors feeding the induction motor by a voltage source inverter that does not require current regulator loops. However, the main problem is that when operating at steady state, the DTC produces high level of torque ripple, variable switching frequency of the inverter over a fundamental period, and stator flux droop during adjacent vector of a voltage vector change. Moreover, particularly when induction motor with DTC operates under heavy load condition in low speed region, distortion of the motor phase current is increased due to stator flux droop leading to reduced drive system efficiency (3).

In order to improve DTC performance by reducing torque and flux ripples, many control strategies have been presented since 1990's, one of these methods is by using Artificial Intelligent (AI) [Artificial Neural Networks (ANNs), Fuzzy Logic Control (FLC)] techniques. This control strategy can reduce torque and flux ripples considerably, consequently improve the steady performance of the drives, but this method still require further research in order to improve the controller performance.

This research will focus on proposed approach by using Radial Basis Function Neural Network (RBFNN) and fuzzy Logic Control (FLC) technique to improve the performance of the DTC. In this work the (RBFNN) will be used instead of the flux and electromagnetic torque estimator and the flux sector detector, while the (FLC) technique replaces the three levels hysteresis controller that used to determine the torque signal error, and the two levels hysteresis controller that is used to determine the flux error by using four membership function (negative large NL, negative small NS, positive small PS, positive large PL). The application of the above proposed DTC system provides a rapid and accurate determination of the switching angles suitable for the loading case of the induction motor. The obtained results show that evident improvements are obtained by using this proposed technique as compared with the conventional DTC system [4], [5].

2- THE CONVENTIONAL DTC SYSTEM

It has been mentioned that the DTC requires the flux and torque estimations, which can be performed as it is proposed in the schematic block diagram of the conventional DTC system shown in Figure (1), in normal operation, two of the motor phase currents and the DC bus voltage are simply measured, together with the inverter's switch positions (V_{sa},V_{sb}, V_{sc}).

Then the measured information from the motor is fed to the stator flux and torque estimators [6], [7].

The block of induction motor model (The parameters of the Induction Motor are given in Appendix-A) and the DTC controller structure was implemented using the design already available in the standard Simulink library. The only block that had to be constructed was the sector calculation block seen in Figure (2).

The simulation of the conventional DTC system with a DC voltage supply provides a number of worthwhile results; numerical simulation has been carried out by using Matlab/Simulink program for three different sampling times, [T_s=0.1 msec, T_s=25 μsec, T_s=10 μsec]. For simulation, reference torque is limited to (14.6 Nm) and reference stator flux is taken as (0.96 Weber) and changing load torque from (0-14-0 Nm) [8].

3- MODELLING OF THE PROPOSED DTC SYSTEM

RBFNN in the DTC system is used to perform the work of the conventional estimator in the same system. The input data used in the trained RBF networks are two of the motor phase currents (i_{sa}, i_{sb}) and the DC bus voltage (V_{dc}), together with the inverter's switch positions (V_{sa}, V_{sb}, V_{sc}), while the output data are the electromagnetic torque (T_e), stator flux (λ_s), and flux position sector (S_k) as shown in Figure (3).

The RBFNN estimator used to operate as stator flux and electromagnetic torque estimators of the DTC satisfactorily was designed and constructed for three different cases of the RBFNNs and, the best case was that using three independent outputs for electromagnetic torque, stator flux and sector, chosen for training and simulation of the RBFNNs [9], [10].

The Fuzzy Controller (FC) operates as hysteresis comparators and switch table selector (S_k), the input data used in fuzzy controller are the stator flux error ($E\lambda_s$), electromagnetic torque error(ET_e) by using four membership function (NL, NS, PS, PL), while the output pulses (V_{sa}, V_{sb}, V_{sc}) represent switching state of the inverter. Switching state of the inverter is a crisp value. The fuzzy controller schematic in Simulink/Matlab for DTC system fed inverter is shown in Figure (4).

It is more efficient for the fuzzy controller to use a set of differential equations written in m-files. These m-files will be accessed by Simulink through the S-function block, which can be run directly by built-in solvers with the graphical links to other Simulink blocks.
The entire Simulink model for proposed DTC system is shown in Figure (5).

4- SIMULATION RESULTS OF THE PROPOSED DTC SYSTEM

In this step the transient and the steady state response of the used motor in both conventional and proposed systems are studied at different loads (6, 10, 14 Nm), speeds (145, 100, 70 rad/sec)(i.e. frequencies 50, 30, 23Hz) and different sampling times (10, 25,100 µsec). A comparative study has been done with that of the conventional system in order to determine the improvements of the proposed system. Figure (6) represents one of these tests showing the starting and running operation at load of the motor during a time period of (0 to 1.8 sec), at the operating frequency of (23Hz), rotor speed (ω_r=70 rad/sec) using sampling period of (100 µsec). The stator flux locus λ_s in d-q plane, stator current i_{sa} (A), electromagnetic torque T_{em} (Nm), and the rotor speed ω_r (rad/sec) are plotted versus the time period of the proposed system and compared with that of conventional one. This case considered to be presented, in order to show the ability of this new system to increase the already commercially used sampling time of (25 µsec) to be (100 µsec) with an acceptable torque ripples. From the above results, a numerical data are extracted and tabulated to declare the improvement. Table (1) show that the reduction in the no-load starting time increases as the speed reduced, and table (2) shows that the reduction in the steady state torque ripples for certain load increases with speed reduction as compared with that of the conventional DTC.

Table (3) which deals with the starting operation at load, shows that the percent reduction of the starting time increased as the load increased, such that the conventional DTC system fail to start at a load torque more than (6.1Nm), while the proposed DTC still has the ability to start over this value. It is clear that, the peak values of the starting torque in all of these cases are approximately the same.

The FFT gives a numerical representation of the improvements by calculating the Total Harmonic Distortion (THD) in the stator current and the average value of the harmonics content in the waveform of the electromagnetic torque ripples(T_{av}) as follows [11] :

$$THD = \sqrt{\frac{\sum_{n=3,5,...}^{\infty} I_n^2}{I_{s1}^2}} \qquad (1)$$

$$I_n^2 = I_3^2 + I_5^2 + I_7^2 + ...+ I_{nth}^2 \qquad (2)$$

where (I_{s1}) is the rms value of the fundamental component, and (I_n) is the rms value of n^{th} harmonic components.

Table (4) shows the THD factor for the current waveforms calculated according to equation (1) for different speeds, at load torque equal to (14 Nm) and (T_S=100µsec). It is clear that the percent reduction in THD increased with speed reduction also, and this value of THD being acceptable by the authorities of electricity suppliers in spite of the increase the sampling time or the sampling period from (25 µsec) (which is considered commercially by ABB) to (100 µsec).

The average value of the harmonics content in the waveform of the electromagnetic torque ripples T_{av} , is calculated by the following equation:

$$T_{av} = \frac{\sum_{n=1}^{n=30} T_n}{n} \qquad (3)$$

where T_n is; the peak value of the n^{th} harmonic in the spectrum of the electromagnetic torque ripples.

Table (5) shows a comparison in T_{av} values between conventional DTC system and the proposed, at different speeds, when T_L=14 Nm and T_S=100µsec.

5- CONCLUSIONS

The simulation of the proposed DTC system and the obtained results declare the improvement achieved. The rapid RBFNN estimator for stator flux and torque, and an accurate FC technique used to furnish the suitable triggering pulses improve the performance of the driver. The improvement accomplishes the increase in the percent reduction of the torque ripples, the harmonic content in the motor line current (THD), and in the starting time, and the increase in the starting torque capability. The tabulated data show the other aspects of the improvement describing the regularity of the performance and gives a numerical evaluation of the proposed system improvement. This improvement leads to the ability of increase the sampling time four times of that of the conventional DTC. This will reduce the switching losses in the inverter used as a driver.

REFERENCES

1- I.Takashi and T. Noguch, (1986), "Anew Quick-Response and High-Efficiency Control Strategy of an Induction Motor", IEEE transaction on industry applications, vol. IA-22, No. 5, sep. /oct..
2- M. Depenbrok, (1988), "Direct Self-Control (DSC) of Inverter-Fed Induction Machine", IEEE transaction on power electronics, vol. 4, October..
3- Y. Kumsuwan et al., (2008), "Modified direct torque control method for induction motor drives based on amplitude and angle control of stator flux", Elsevier/Electric Power Systems Research 78, pp. 1712–1718. .
4- N. Delannayy1, F. Rossi, B. Conan-Guez, M. Verleysenz1, (2004), "Functional Radial Basis Function Networks (FRBFN)", Published in ESANN'04 Proceedings.
5- Z. Kovaˇci´c and S. Bogdan, (2006), "Fuzzy Controller Design Theory and Applications", Published by CRC press, Taylor &Francis Group.
6- Asea Brown Boveri Ltd (ABB), (2002), "Direct Torque Control- Technical Guide No.1", ABB Automation Group Ltd, Finland.
7- A. A. Pujol, (2000), "Improvements in Direct Torque Control of Induction Motors," PhD. Thesis Submitted to University of Politeqnique of Catalunya (UPC), Terrasa.
8- M. K. Musso`ud, (2009), "Direct Torque Control of Induction Motor By Using Radial Basis Function Neural Network and Fuzzy Control Techniques" PhD. Thesis Submitted to the Department of Electromechanical Engineering/ University of Technology, Iraq.
9- H. Demuth, M. Beale, (2002), "Neural Network Toolbox for Use with Matlab" User's Guide, Version 4.
10- M. K. Musso`ud, E. M. Abdul-Baki, (2010), " A Proposed Estimator for a Direct Torque Control System Using Radial Basis Function Neural Network Technique", a paper accepted to be published in Diyala Journal of Engineering Sciences.
11- M. H. Rashid, (2004), "Power Electronics Circuits, Drives & Applications", Third Edition by Pearson Education, Inc., Pearson Prentice Hall.
12- M. Hinkkanen, (2004), "Flux Estimators for Speed-Sensorless Induction Motor Drives", Ph.D. Thesis Submitted to Helsinki university of technology, Espoo, Finland.

Table (1): No-load results at different speeds.

Rotor Speed Rad/sec	Starting time (t_{st}) (sec)			P-P torque ripples(T_{pp}) (Nm)		
	Conv.	Prop.	% red.	Conv.	Prop.	% red.
145	0.3	0.27	10	4	4	0
100	0.45	0.35	22.2	17	8	52.9
70	0.6	0.4	33.3	22	9	59.1

Table (2): Load results at different speeds and loads.

Rotor speed (rad/sec)	Load torque (Nm)	P-P of torque ripples (Nm)		
		Conv.	Prop.	% red.
145	6	8	4	50
	14	11	6	45.5
100	6	15	7	53.3
	14	17	7.5	55.9
70	6	20	8	60
	14	23	9	60.1

Table (3): The starting at load performance.

Load Torque (Nm)	Starting time (sec)		Peak Value of the Starting Torque (Nm)	
	Conv. DTC	Prop. DTC	Conv. DTC	Prop. DTC
1	0.3	0.27	17	17
3	0.4	0.35	17	17
5	0.65	0.5	18	17.7
6.1	2.6	0.9	18.5	18
6.5	fail	1.63	fail	18

Table (4): THD of motor current **.**

Speed (rad/sec.)	THD Conv.	THD Prop.	% Reduction
145	0.1915	0.1506	21.36 %
100	0.2177	0.1282	41.11 %
70	0.3495	0.1395	61.12 %

Table (5): Average torque **.**

Speed (rad/sec.)	T_{av} Conv.	T_{av} Prop.	% Reduction
145	0.3133	0.1746	44.3 %
100	0.4382	0.1460	66.7 %
70	0.6633	0.1763	73.4 %

APPENDIX-A

Squirrel–Cage Induction Motor (ABB M2AA 100LA 3GAA102001-ADA), 3-phase, 400 volt, 50 Hz, 2.2 KW [12].

Table (A-1): The motor parameters.

Parameters	Symbol	Value
Stator Resistance	r_s	3.67 Ω
Rotor Resistance	r_r	2.10 Ω
Stator Leakage Inductance	L_{ls}	0.0209 H
Rotor Leakage Inductance	L_{lr}	0.0209 H
Magnetizing Inductance	L_m	0.224 H
Number of Pole	p	4
Moment of Inertia	J	0.0155 kg.m^2
Viscous Friction Coefficient	β	0.0025 Nm.s
Rated Speed	ω_m	1430 r/min.
Rated Torque	T_{ref}	14.6 Nm
Rated Current per Phase	I_{rat}	5.0 Amp.
Rated Power	P_r	2.2 KW
Rated Power Factor	cosθ	0.81

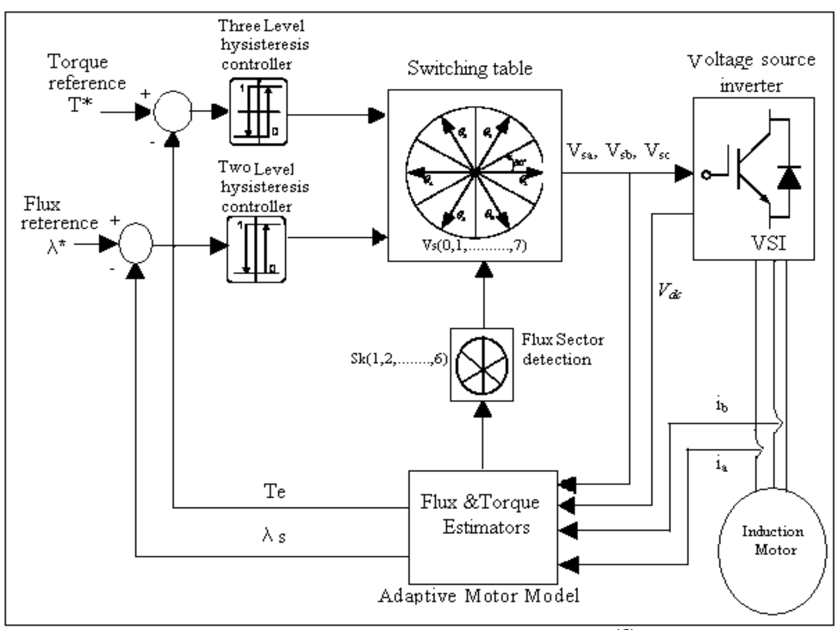


Fig.(1): Basic scheme of the DTC [6].

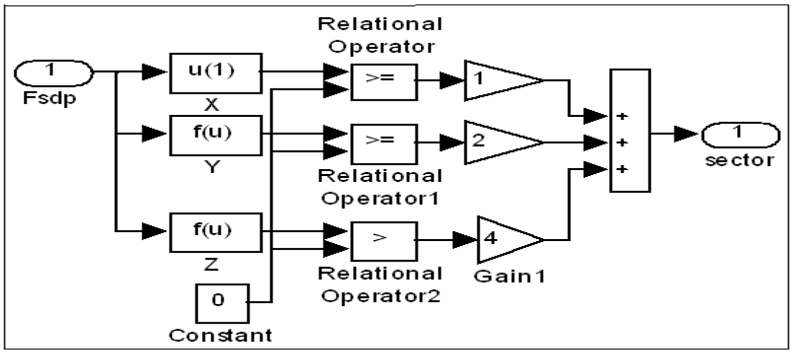


Fig.(2): Sector calculation block.

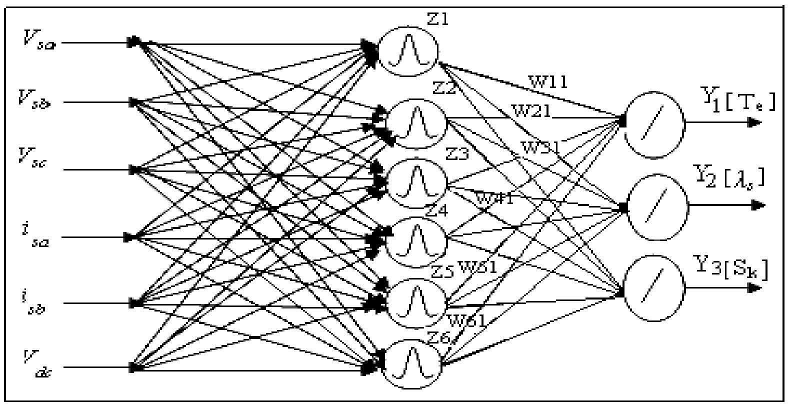


Fig. (3): RBFNN estimator has six inputs and three outputs.

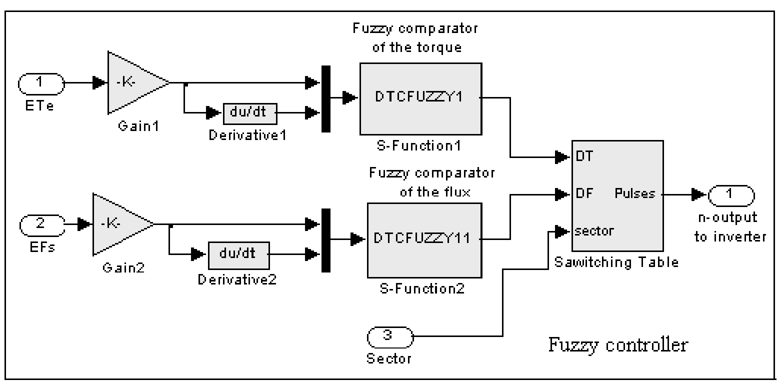


Fig.(4): Fuzzy controller.

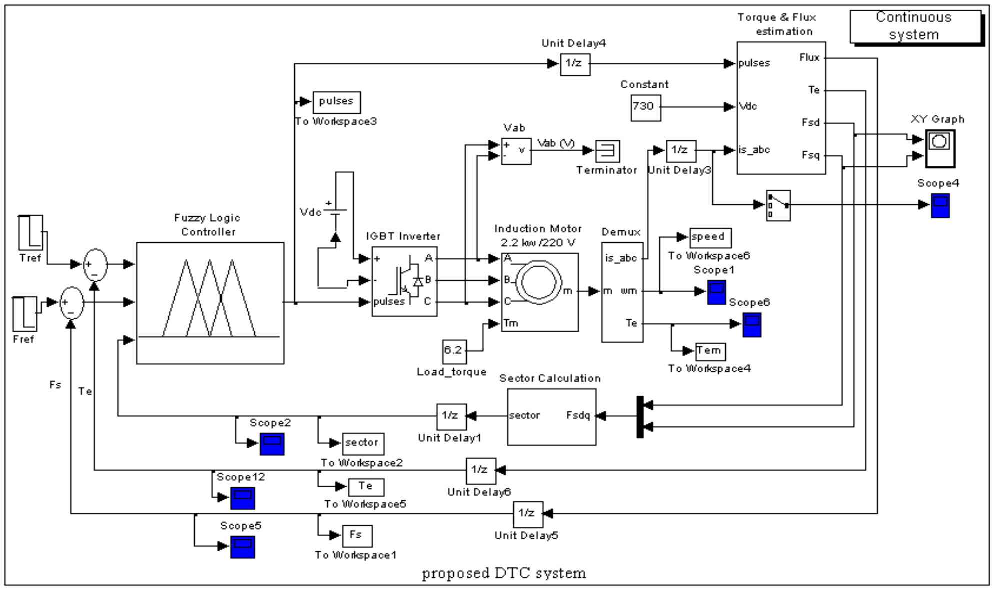
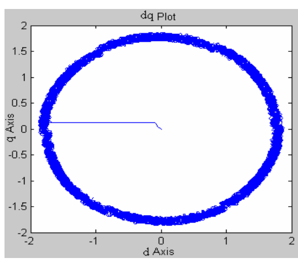


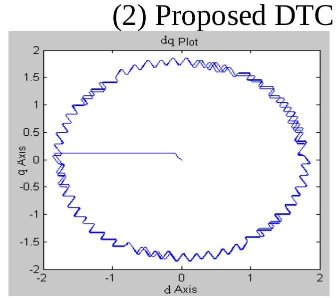
Fig. (5): Simulink model of the proposed DTC system.

(1)Conventional DTC

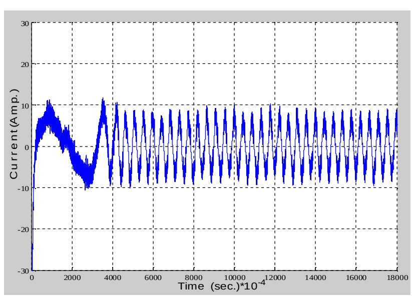
(2) Proposed DTC



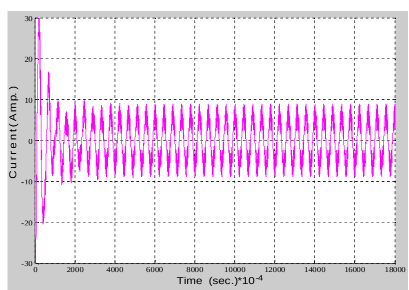
(a) λ_s in d-q plane



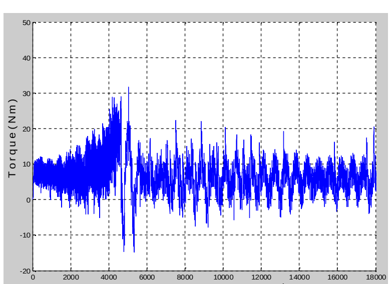
(b) λ_s in d-q plane



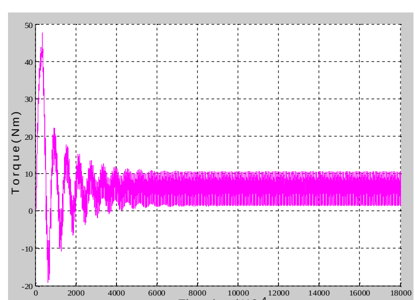
(c) i_{sa}



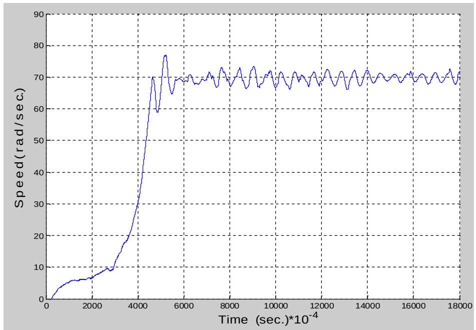
(d) i_{sa}



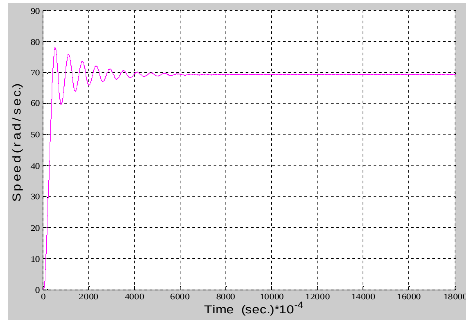
(e) T_{em}



(f) T_{em}



(g) ω_r

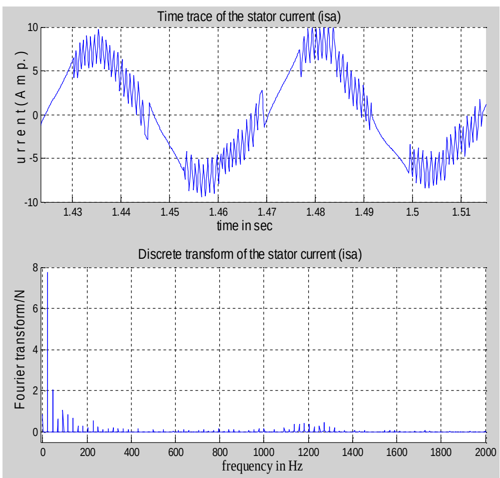


(h) ω_r

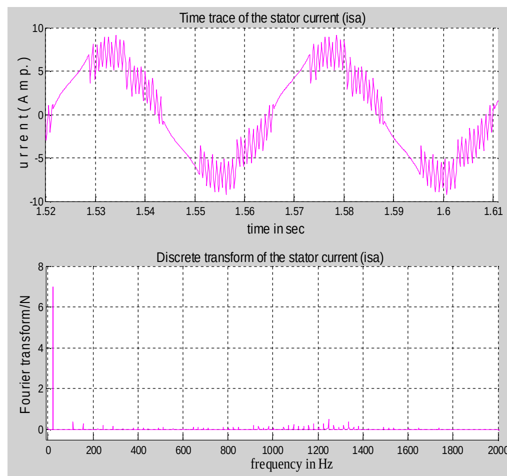
Fig. (6): ω_r = 70 rad/sec at (T_L=6 Nm) case.

(1) Conventional DTC

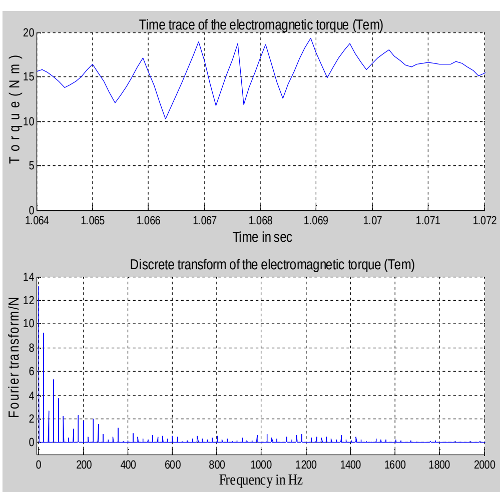
(2) Proposed DTC



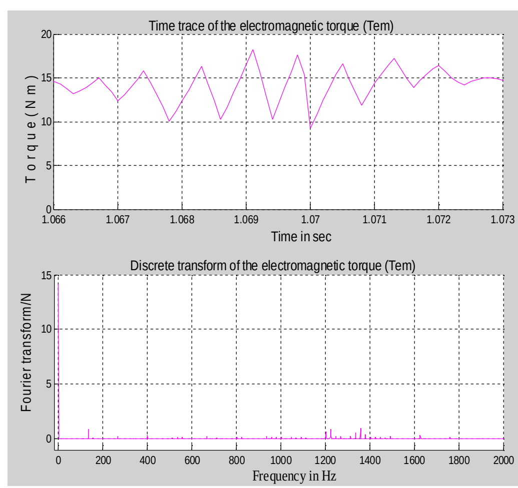
(a) ω_r=70 rad/sec, $f_o \approx 23$Hz.



(b) ω_r=70 rad/sec.



(a) ω_r =70 rad/sec.



(b) ω_r =70 rad/sec.

Fig.(7): the FFT analysis for the waveforms of both the stator current and the electromagnetic torque.

تحسين نظام السيطرة المباشر على العزم باستخدام تقنيات شبكة دالة الأساس الشعاعي العصبية والسيطرة المضببة

د. محمد خلف مسعود
مدرس
تربية ديالى _ وزارة التربية

د.عصام محمود عبد الباقي
أستاذ مساعد
كلية الهندسة_ الجامعة المستنصرية

الخلاصة

إن طريقة السيطرة المباشرة على العزم (DTC) تعد من أحدث الطرقِ وأكثرها فاعليةِ للسيطرةِ على سرعةِ محرك حثي ثلاثي الطور، لَكنَّها تَعاني مِنْ عدة عوائقِ كحاجتهاُ إلى مخمّنِ للعزم الكهرومغناطيسيِ ولفيض الساكن، والى وجود تموج متأصل في عزم الخرج. عليه فقد تم في هذا العمل تزويد منظومة السيطرة المباشرة على العزم (DTC) بشبكة دالة الأساس الشعاعي العصبية (RBFNN) وتقنية السيطرة المضببة (FC) لتَتفادى العوائقَ أعلاه.

إن شبكة دالة الأساس الشعاعي العصبية (RBFNN) استعملت كمخمن سريع لكل من العزم الكهرومغناطيسيِ وفيض الساكن بدلاً مِنْ المخمّن التقليديِ. أما تقنية السيطرة المضببة (FC) فقد استعملت كبديل أدق لمقارن الهسترة المستخدم لتحديد قيم أخطاءِ فيض الساكن والعزم لكي ينتظم عمل مُنتخب حالة الاقلدة (Switching State Selector). بعد دراسة عمل شبكة دالة الأساس الشعاعي العصبية تبين لدينا بأنها سوف تعطي نتائج دقيقه أذا ماصممت للعمل في حالة المخارج المستقلةِ لكُلّ من العزم وفيض الساكن والقطاعات (Sectors) أثناء التدريب والمحاكاةِ، باستخدام قيم مختلفة لثابت الانتشار (Constant Spread) للشبكة العصبية لكُلّ من العزم وفيض الساكن والقطاعات مما يؤدي إلى الحُصُول على نَتائِجِ أكثر دقة. إنّ محاكاةَ المنظومة المقترحة تمت باستعمال برنامج (Matlab/Simulink)، وا شارت النتائج المستحصلة إلى تخفيض جدير بالاعتبار في تموج العزم ، وأداء بدء أفضل. إن هذا التحسينِ قادنا إلى المقدرةِ على زيَاْدَة زمنِ العينة(period Sampling) أربع مراتَ بقدر الزمنِ التقليديِ المستخدم.