Proceedings of the 2nd International Conference on
Systems and Control, Marrakech, Morocco, June 20-22,
2012

Performance improvement for inverter fed Permanent Magnet SM with Direct Torque Neural Control

F.Hamidia, A.Larabi, and MS. Boucherit

Abstract— **This paper describes a neural direct torque control instead of the conventional DTC to reduce stator flux and electromagnetic torque ripples due to the hysteresis based scheme in open and closed loop. The results obtained from simulation confirmed the feasibility of the proposed technique compared to the conventional one.**

I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) fed by PWM inverters are widely used for industrial applications, especially servo drive application, in which constant torque operation is desired. In traction and spindle drives, on the other hand, constant power operation is desired. These machines have the advantages of compactness simple mechanical construction, easy maintenance, good reliability, and high efficiency [1]. In the past, AC drives were only used in small demanding applications, regardless of the advantages of AC motors as opposite to DC motors, since the high switching frequency inverters cost was rather competitive. With the developments in the power electronics area, the vector control methods, which use fast microprocessors and digital signal processing (DSP), made possible the use of induction motors in typically DC motors dominated areas, since the current components producing torque and flux are decoupled, achieving the system separately excited DC motor similar features[1].

Since Takahashi presented the DTC for an induction machine in 1986, the use of DTC techniques has spread in AC machine control, due to its high dynamic performance. Unlike FOC, DTC does not require any coordinate transformation, pulse-width modulation (PWM) or position sensors to achieve a decoupled control of flux and torque. The currents of the machine are controlled indirectly through torque and flux control. In addition, the DTC is not over-sensitive to parameter detuning in comparison with FOC. In spite of its simplicity, DTC permits good torque control in steady-state and transient operating conditions [2]. In the late 1990s, DTC techniques for PMSM machines have appeared [3]. Using hysteresis comparators and the switching vector table for both flux and torque control is the origin of its simple structure. However, a direct torque controlled motor suffers from great torque ripples due to the fast torque response. Many control algorithms have been proposed to reduce the torque ripple in DTC [4].

In order to improve DTC performance by reducing torque and flux ripples the authors in [5-11], propose a fuzzy controller to replace hysteresis comparators and switching table exist in classical DTC with different approaches. Artificial neural networks (ANN) are widely used in control engineering practice. The reason why ANN are gaining importance is the ability of representing complex nonlinear mappings. When the designer tries to minimize the ambiguities by the use of a detailed mathematical model, then the design becomes infeasible. Neuro-control architectures achieve controlling complex nonlinear models, and they are not as costly as the detailed mathematical models. Various neuro-control architectures are applied in order to solve this type of problems. The mapping properties of ANN have been analyzed by many researchers [12].

Neural networks are recently showing good promise for application in power electronics and motion control system [13]. Since the switching lookup table only depends on the electromagnetic torque error, stator flux error and the angle of the flux, and not on the parameters of the motor, it can be trained off-line. This means that once the neural network is trained it does not need to know anything of parameters of motor if its parameters have any change [13].

For this reason, this paper proposes the neural network controllers for permanent magnet synchronous motor to replace the hysteresis comparators and switching lookup table in open and closed loop.

II. PMSM MODEL

The transformation of PARK brings back to the equation stator in reference frame related to the rotor.

$$\begin{cases} V_d = R_s I_d + L_d \frac{dI_d}{dt} - \omega_r L_q I_q \\ V_q = R_s I_q + L_q \frac{dI_q}{dt} * \omega_r L_d I_d + \omega_r \varphi_f \end{cases} \tag{1}$$

Where R_s is the stator resistance, I_d is the d-axis current, φ_d is the total flux in the d-direction, φ_q is the total flux in the q-direction, and I_q is the q-axis current. Flux-linkage can also be expressed in d–q coordinates as follows:

$$\begin{cases} \varphi_d = L_d I_d + \varphi_f \\ \varphi_q = L_q I_q \end{cases} \tag{2}$$

Where L_d is the d-axis inductance, φ_f is the flux-linkage due to the permanent magnets, and L_q is the q-axis inductance. As d-axis is aligned with magnet's axis, there is no contribution of the magnets to q-axis magnetic flux-linkage φ_f.

The motor torque expression with d–q magnitudes is [14]:

$$C_{em} = p(\varphi_d I_q - \varphi_q I_d) \tag{3}$$

F.Hamidia is with the research laboratory of engineering and automatic, YF University, Ain D'heb 26000, Medea, Algeria (corresponding author, e-mail: fe_hamidia@ yahoo.fr).

A. Larabi, is with the Electrical Engineering Department, USTHB University, PB.32, Bab-Ezzouar, 16111,Algiers, Algeria.

MS. Boucherit is with the Electrical Engineering Department, National School ENP, 10 Pasteur avenue, Hassan Badi, BP182, El-Harrach, Algiers, Algeria.

III. DIRECT TORQUE NEURAL CONTROL (DTNC) IN OPEN LOOP

The basic principle of the DTC is to select proper voltage vectors according to the differences between the reference and actual torque and flux linkages [15].

Simplicity, high dynamic performance and quick torque response, as well as the fact that there is no need for co-ordinate transformation, voltage or current decoupling and no need for an encoder, are important advantages leading to remarkable commercial applications. Of course, there are some drawbacks besides the advantages mentioned above, mainly the variation of switching frequency, the torque ripple and the starting [15].

In the DTC, the stator flux vector is estimated by taking the integral of difference between the input voltage and the voltage drop across the stator resistance given by [16]:

$$\varphi_s = \int_0^t (V_{s-}R_s i_s)dt \tag{4}$$

Lets us replace the estimate of the stator voltage with the true value and write it as:

$$V_s(S_a, S_b, S_c) = \frac{2}{3}\, U_o(S_a + S_b e^{\frac{j2\pi}{3}} + S_c e^{\frac{j4\pi}{3}}) \tag{5}$$

S_a, S_b, S_c represent the state of the three phase legs 0 meaning that the phase is connected to the negative and 1 meaning that the phase is connected to the positive leg.

The stator current space vector is calculated from measured currents i_a, i_b, i_c: [17]

$$i_s = \frac{2}{3}(i_a + i_b e^{\frac{j2\pi}{3}} + i_c e^{\frac{j4\pi}{3}}) \tag{6}$$

The component α and β of vector φ_s can be obtained:

$$\begin{aligned} \varphi_{s\alpha} &= \int_0^t (V_{s\alpha-}R_s i_{s\alpha})dt \\ \varphi_{s\beta} &= \int_0^t (V_{s\beta-}R_s i_{s\beta})dt \end{aligned} \tag{7}$$

Stator Flux amplitude and phase angle are calculated in expression (8):

$$\begin{cases} \varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \\ \angle\varphi_s = arctg\,\frac{\varphi_{s\beta}}{\varphi_{s\alpha}} \end{cases} \tag{8}$$

Once the two components of flux are obtained, the electromagnetic torque can be estimated from the relationship cited below:

$$T_{em} = \frac{3}{2}\, p(\varphi_{s\alpha}\, i_{s\beta} - \varphi_{s\beta}\, i_{s\alpha}) \tag{9}$$

The voltage plane is divided into six sectors so that each voltage vector divides each region into two equal parts.

These vectors are shown in fig1, where six active vectors of same magnitude are presented and two remaining vectors are zero.

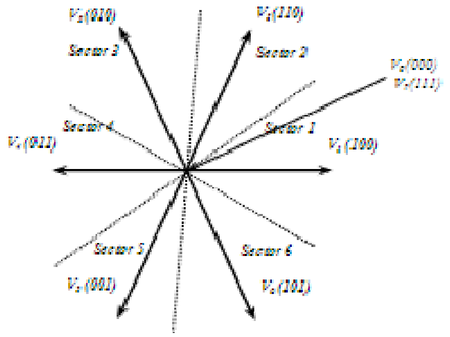

Figure 1. Spatial voltage vectors as function of the state inverter

The DTC is based on selecting one of the voltage vectors that maximizes the necessary change to correct the flux and torque error producing the smallest number of commutations in the bridge inverter.

The Neural network controller is designed to have the following procedure:

Three input variables and three control variable (as shown in fig.2) for achieving constant torque and flux control respectively defined as:

The first variable is the difference between the command stator flux and the estimated stator flux.

$$E_\varphi = \varphi_s^* - \varphi_s \tag{10}$$

The second variable is the difference between the command electromagnetic torque and the estimated electromagnetic torque.

$$E_{Te} = T_e^* - T_e \tag{11}$$

The third variable is the angle between the stator flux and reference axis (stator flux angle)

The output is the Boolean switching controls (S_a, S_b, S_c).

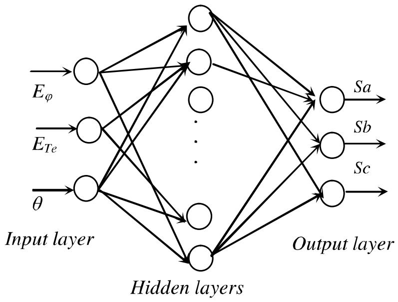

Figure 2. Architecture of neural controller replacing hysteresis comparators and switching table

In this case back-propagation algorithm was used to train the 3-15-3 neural network structure using tansig activation function type. In this step, we execute several tests and analyzing the performance of our system.

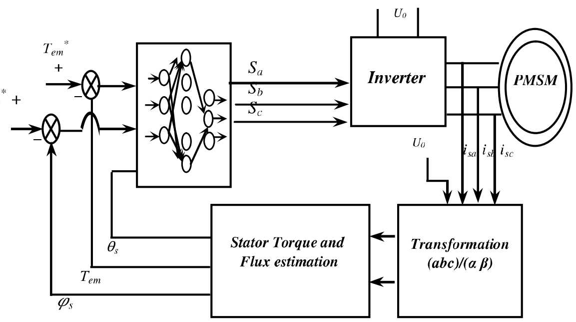

Figure 3. Schematic diagram of DTNC strategy

In Table I is presented the DTC selection algorithm.

TABLE I. SWITCHING TABLE

Flux	Torque	N1	N2	N3	N4	N5	N6	Controller
cflx= 0	*ccpl=1*	V_3	V_4	V_5	V_6	V_1	V_2	**Two Levels**
	ccpl=0	V_0	V_7	V_0	V_7	V_0	V_7	
	ccpl=-1	V_5	V_6	V_1	V_2	V_3	V_4	**Three levels**
cflx= 1	*ccpl=1*	V_2	V_3	V_4	V_5	V_6	V_1	**Two Levels**
	ccpl=0	V_7	V_0	V_7	V_0	V_7	V_0	
	ccpl=-1	V_6	V_1	V_2	V_3	V_4	V_5	**Three levels**

IV. DIRECT TORQUE NEURAL CONTROL (DTNC) IN CLOSED LOOP

Traditional direct torque control system of permanent magnet synchronous motor introduces conventional PI regulator in closed loop control.

In this section, we replace the PI conventional speed regulator by a neuronal speed controller with the objective of increasing the response time period of the system; from the reference speed ω^* and measurement speed ω, the proposed Speed Controller provides the desired electromagnetic torque.

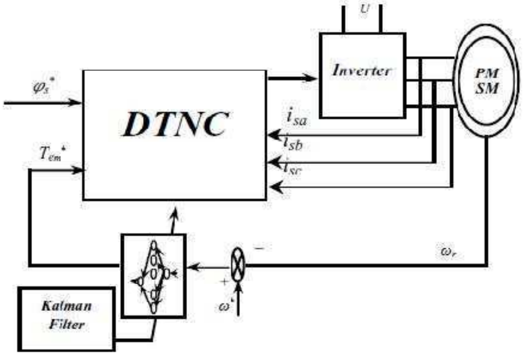

Figure 4. Schematic diagram of DTC-PMSM control with neural Speed Controller

In this work, the used neural network is a single layer neural network with fourteen neurons in hidden layer and single input/single output. The proposed controller is obtained by learning neural network based on data inputs/outputs of Kalman filter as shown fig4 and the learning algorithm used is back-propagation.

We have used the Kalman Filter to training the ANN because it can give us better performance.

V. RESULTS AND DISCUSS

The proposed method has been tested by simulation, in order to evaluate the performances of PMSM. The parameters of permanent magnet synchronous machine are given in table II.

Table II:

Parameters of PMSM setting		
R_s	Stator resistance	1.5 ohm
L_d	d-axis inductance	0.05H
L_q	q-axis inductance	0.05 H
j	Inertia	0.0030Kg.m^2
f	Friction Coefficient	0.0009Nm/rad/s
φ_f	Magnetic flux linkage	0.314wb
P	Poles	2

Fig.5 presents different responses of electromagnetic torque, stator flux and current with a load torque applied (2N.m) and constant command flux of 0.314Wb using direct torque neural control and classical direct torque control. It appears in these figures that torque and flux tracks its references and stator flux locus is circular.

It can be seen in fig5 and fig7, the torque and current ripples is less by using neural control than responses obtained by classical DTC.

Fig.6 presents different responses of electromagnetic torque, stator flux and current with a changing load torque applied from 3Nm to 1Nm (between 0.7s and 1.5) and with inversion of torque (-2Nm). Fig.7 shows clearly that the rotor speed follows the desired reference and neural speed controller rejects the load disturbance quickly with no overshoot compared to classical DTC.

Fig 8, 9 respectively presents different responses of electromagnetic torque, stator flux and current in closed loop with a load torque and speed command changing.

VI. CONCLUSION

Direct torque control scheme based on artificial neural network controller has been presented in this paper.

By analyzing the torque waveforms, it shows that torque ripples can be reduced with and without rotor speed regulation. The rotor speed follows the desired reference without overshoot and rejects the load disturbance quickly and efficiently.

So the obtained results were very successful and confirm the validity of proposed techniques.

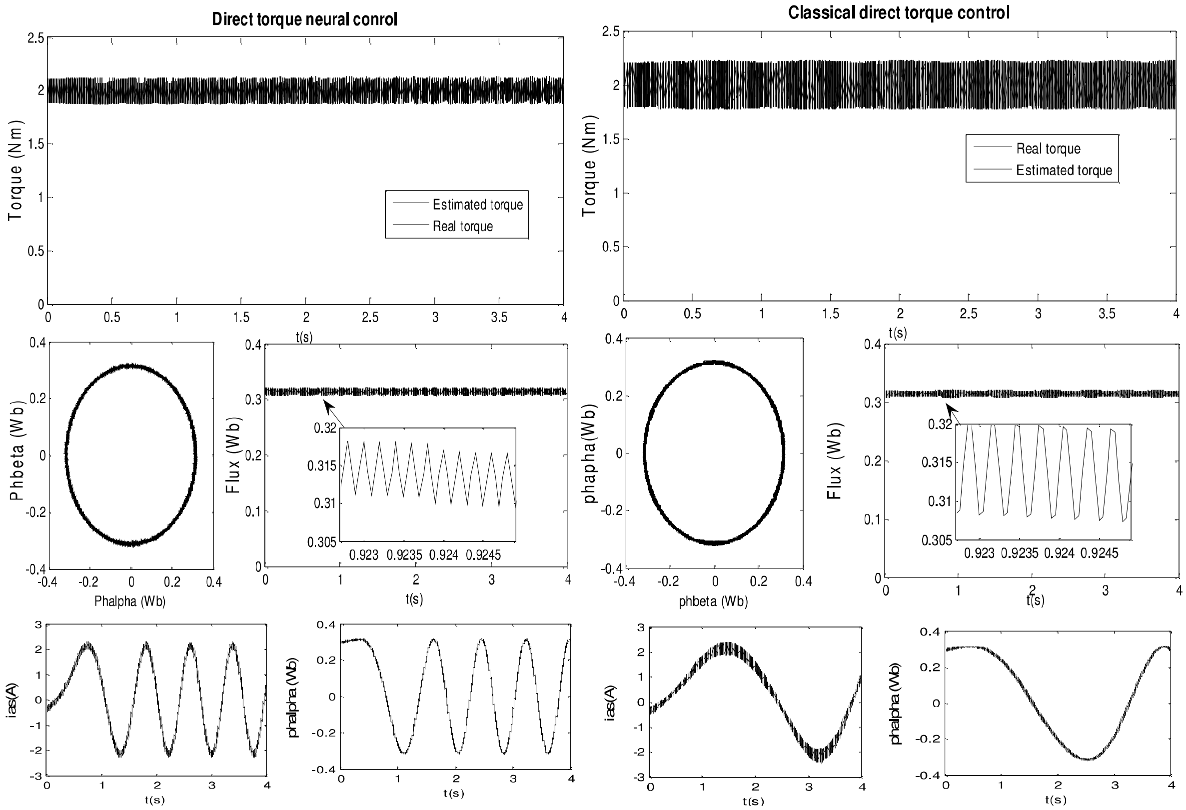

Figure 5. Performances of PMSM based on conventional and neural network control (in open loop)

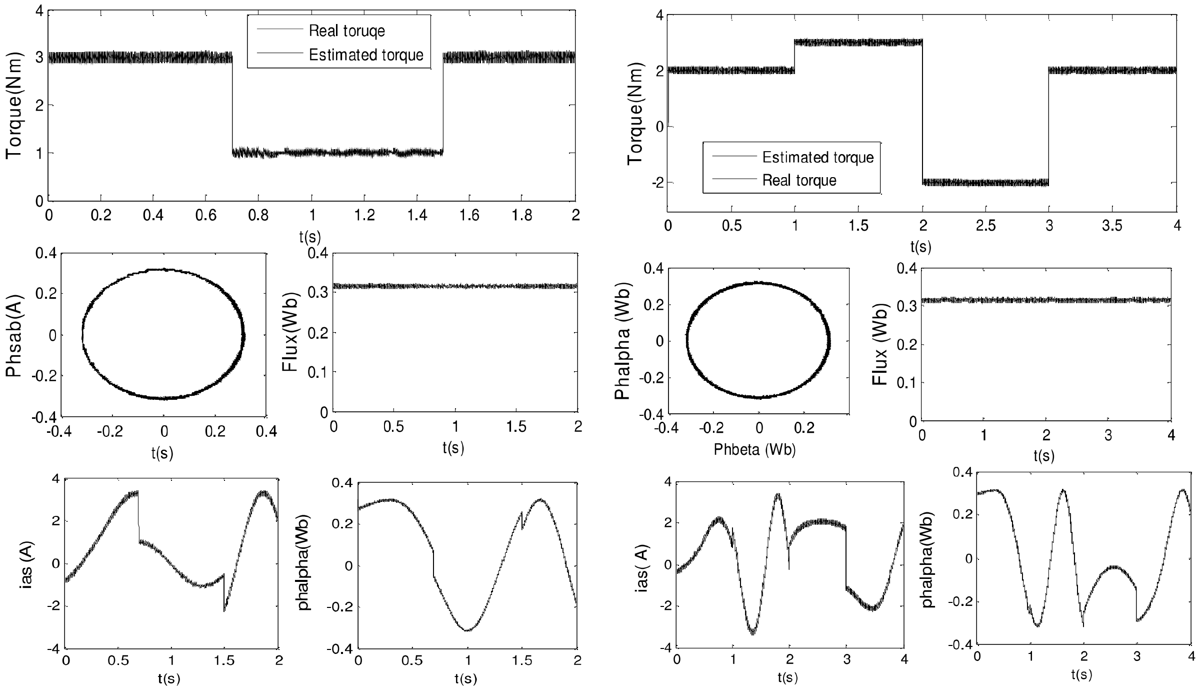

Figure 6. Performances of PMSM based on neural network control

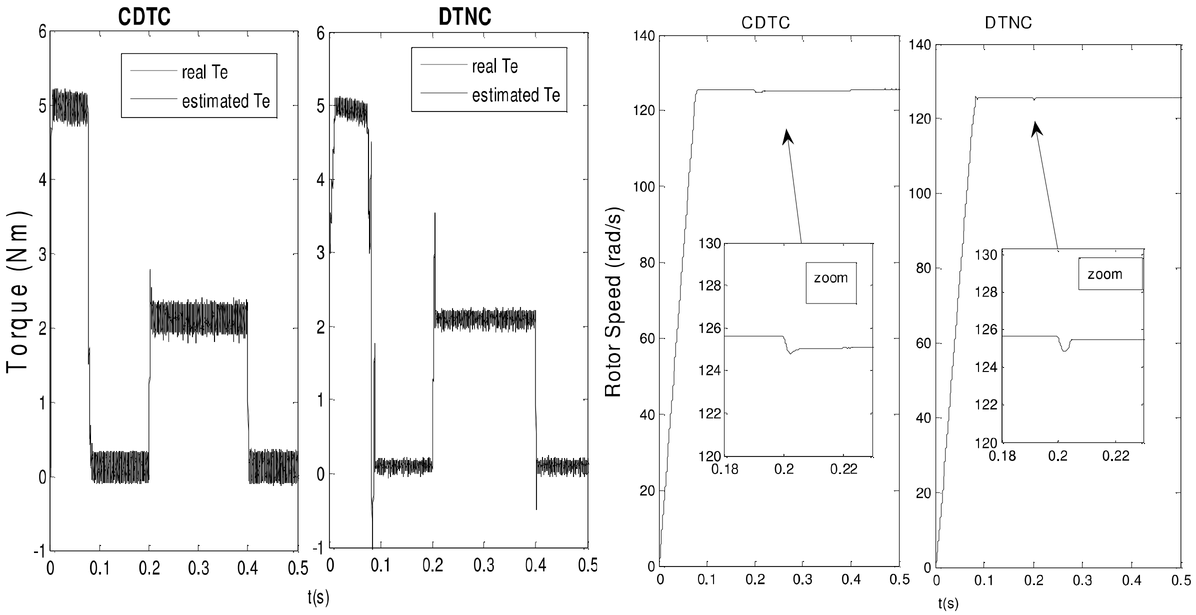

Figure 7. Performances of PMSM based on conventional and neural network control with speed regulation

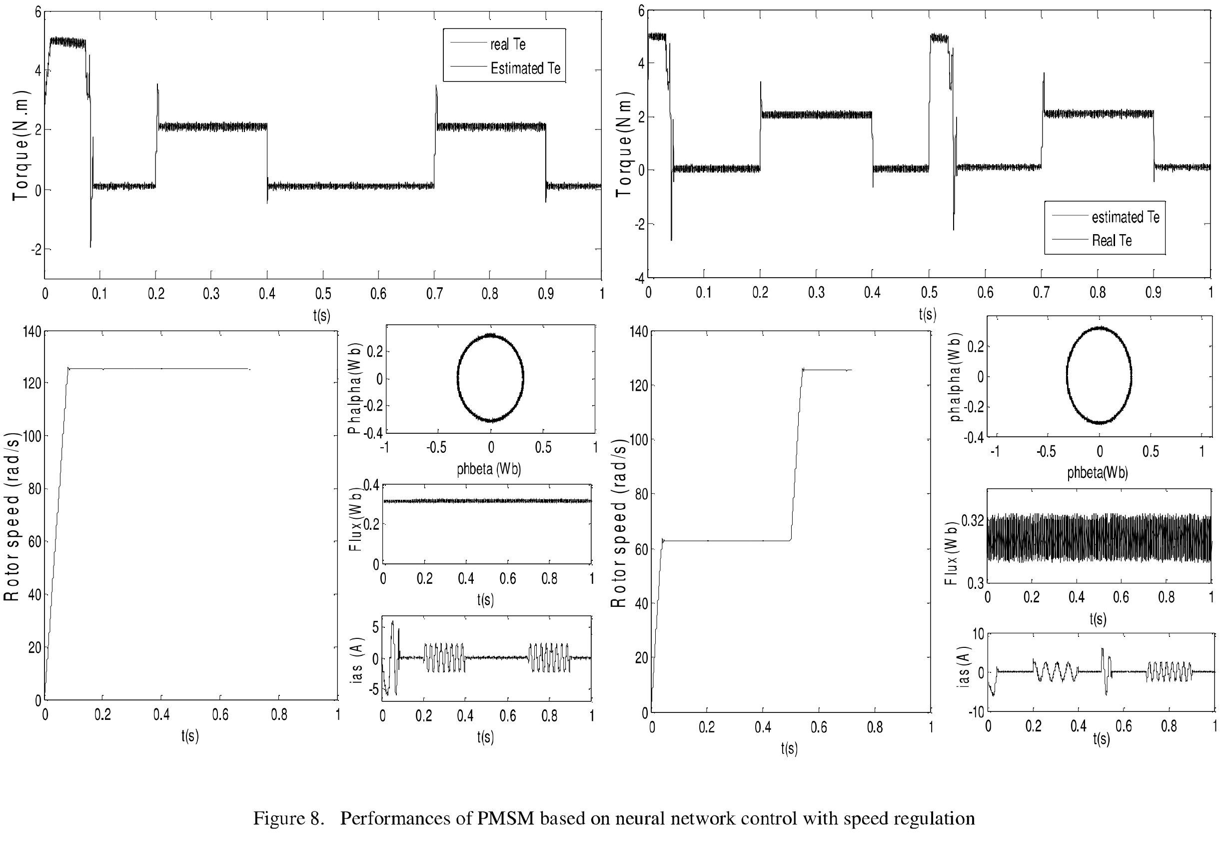

Figure 8. Performances of PMSM based on neural network control with speed regulation

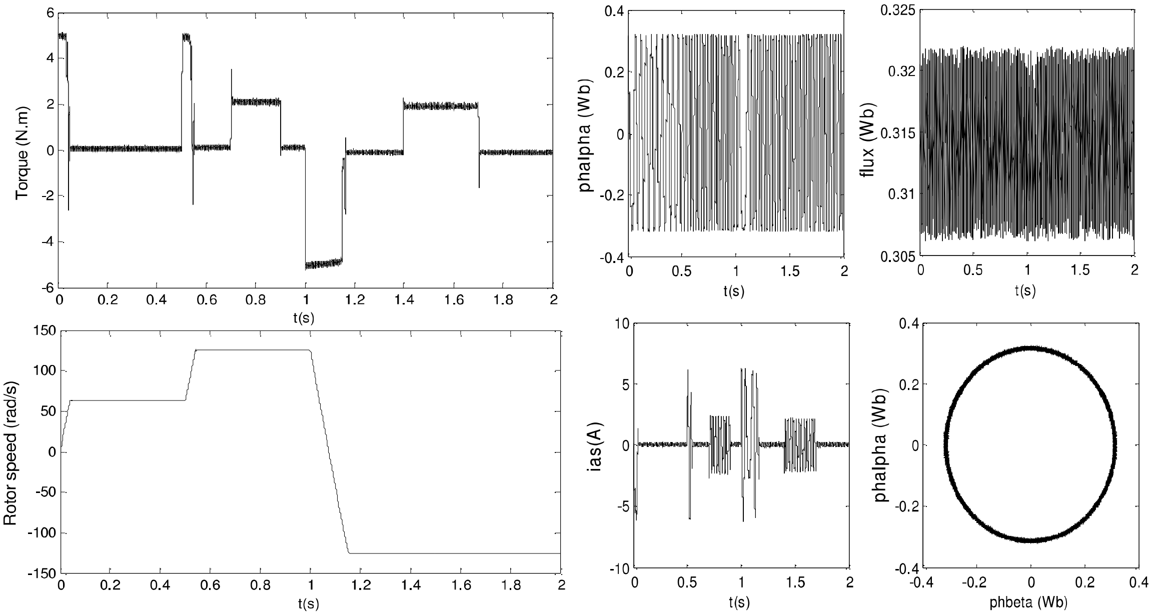

Figure 9. Performance of direct torque neural control with reverse rotor speed under load torque change

REFERENCES

[1] T. Sarasolath, J. Poza, M.A. Rodriguez, and G. Abad, "Direct torque control design and experimental evaluation for the brushless doubly fed machine," *Energy conversion and Management 52,* pp. 1226–1234, 2011.

[2] M.T Lazmin, MJ. M. Al-khishali, and A.I. Al-Shawi, "Space Vector Modulation Direct Torque Speed Control Of Induction Motor", The 2nd International Conference on Ambient Systems, Networks and Technologies, *Procedia Computer Science 5* (2011) 505–512..

[3] A.Tlemçani,O.Bouchhida, K.Benmansour, D. Boudana and MS.Boucherit, "Direct Torque Control Strategy (DTC) Based on Fuzzy Logic Controller for a Permanent Magnet Synchronous Machine", *Journal of Electrical Engineering & Technology*, Vol.4, pp.66-78, 2009.

[4] Sh.Kaboli, M. R. Zolghadri, S. Haghbin and P. Eskandari, "Investigation on the flux-based torque-ripple behavior in dtc based induction motor drives", *Iranian Journal of Science & Technology, Trans. A*, Vol.32, No.A1 Winter, pp.7-16, 2008.

[5] R.Toufouti, S.Meziane and H.Benalla, " Direct Torque Control for Induction Motor using intelligent technique", *Journal of Theoretical and Applied Information Technology,* (2007):35-44.

[6] Milan ˇZalman, Ivica Kuric, "Direct Torque and flux Control of Induction Machine and fuzzy controller", *Journal of Electrical Engineering,* Vol.56, No.9-10, (2005):278-280.

[7] Sayeed A. Mir, Donald S. Zinger, Malik E. Elbuluk, "Fuzzy Controller for Inverter Fed Induction Machines", *IEEE Trans on industry application,*Vol.30, No.1, (1994):78-84.

[8] Jia-Qiang Yang, Jin Wang, "A New full-speed range direct torque control strategy for induction machine", *Proceedings of the Third International Conference on Machine Learning and Cybernetics, Shanghai*, 26-29 August 2004, pp.568-573.

[9] Zaimeddine Rabah, "Contrôle Direct du Couple d'une Machine Asynchrone Alimentée par des Onduleurs Multi-niveaux", doctorat Thesis, ENP Algiers, Algeria 2007.

[10] Xin Wei, Dayue Chen, Chunyu Zhao, "Minimization of torque ripple of direct-torque controlled induction machines by improved discrete space vector modulation", *Electric Power Systems Research 72* (2004) 103–112.

[11] Chiraz. Ben Jabeur-Seddik, Farhat. Fnaiech, "Hysteresis and Fuzzy Based Nonlinear Controllers for a Direct Torque Control of An Induction Machine", *2004 IEEE International Conference on Industrial Technology (ICIT),* pp.38-43.

[12] Ertu˘grul Akbas, E. Murat Esin, "A simulation comparison of intelligent control algorithms on a direct drive manipulator", *Robotics and Autonomous Systems 49* (2004) 235–244.

[13] A. L. Orille, G.M.A. Sowilam, "Application of neural networks for direct torque control", *Computers & Industrial Engineering 37* (1999) 391-394.

[14] H.M. Hasanien, "Torque ripple minimization of permanent magnet synchronous motor using digital observer controller", *Energy Conversion and Management 51* (2010) 98–104.

[15] Md. Enamul Haque,Limin Zhong, and Muhammed Fazlur Rahman*,* "A sensorless Initial Rotor Position Estimation Scheme for a Direct Torque Controlled Interior Permanent Magnet Synchronous Motor Drive", *IEEE Trans on Power Electronics,* Vol.18, No.6, pp.1376-1383. 2003.

[16] Ralph Kennel, Elwy E. El-kholy, Sabry Mahmoud, Abdou El-refaei, Farouk Elkady, "Improved direct torque control for induction motor drives with rapid prototyping system", *Energy Conversion and Management 47*, pp. 1999–2010, 2006.

[17] M.S. Merzoug and F.Naceri, "Comparison of Field-Oriented Control and Direct Torque Control for Permanent Magnet Synchronous Motor (PMSM)", *World Academy of Science, Engineering and Technology 45*, 2008.