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Reduction of torque ripples of Direct Torque Controlled Permanent Magnet SM Using Neural Network

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Abstract— *recently there has been a fast growth in industrial application of the DTC technique, this due to its quick torque response. But, this technique suffers from a major disadvantage of steady state ripple in torque and flux. This paper proposes a direct torque control based on neural network to reduce this torque and flux ripples. Simulation results witch confirm the feasibility of this propose controller are presented.*

Key-Words— *Direct torque control, Neural Network, PM synchronous machine.*

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 light weight size, simple mechanical construction, easy maintenance, good reliability, and high efficiency [1].

In recent years significant advances have been made on the sensor less control of IM. One of the most well-known methods used for control of AC drives is the Direct Torque Control (DTC) developed by Takahashi in 1984 [2]. The DTC was first applied to asynchronous machines and later to synchronous machine. For high performance control of PMSM, many researchers have explored the DTC scheme [3]. 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 vector.

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The main advantage of DTC is its structure simplicity, since no coordinate transformations, current controllers and PWM are needed. Moreover the controller does not depend on motor parameters. DTC is considered to be a simple and robust control scheme which achieves quick and precise torque control response [4]. However, the classical DTC has some drawbacks, and one of these is the significant torque and current ripple generated in steady state operation [5]

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 Network (ANNs), Fuzzy Logic Control (FLC)) techniques [6]. The application of artificial neural network (ANNs) attracts the attention of many scientists from all over the world [7].

Artificial Neural Networks (ANNs) tend to imitate the human learning process in a very limited way by a computer program or electronic circuit. The main property of ANNs is their ability to recognize patterns or make input output mapping. The ANN does not require the mathematical model of the system; it just uses experimental or simulated input output data to be trained (to be trained refers to the process of adjusting the weights and biases of an ANN to reach the specific outputs) [8]. ANNs can be used to identify and control nonlinear dynamic systems because they can approximate a wide range of nonlinear functions to any desired of accuracy. Moreover, they can be implemented in parallel and, therefore, shorter computational time. Also, they have immunity from harmonic ripples and have fault-tolerant capability [9].

This paper is presented in first section a control strategy of DTC, in second section, is proposed the DTC with neural network controller which replaces the hysteresis controller and switching table. Finally, the simulation results on Matlab are presented and discussed.

II. Direct Torque Control

The main idea of Direct Torque Control (DTC) is to directly control the torque and flux produced by the machine, without current control, as it is the case in FOC [10], so basic principle of the DTC is to select proper voltage vectors using a per-defined switching table.

The selection is based on the hysteresis control of the stator flux linkage and the torque. In the basic form the stator flux linkage is estimated with:

$$\varphi_s = \int_0^t (V_s - Ri_s)dt \quad (1)$$

Lets us replace the estimate of the stator voltage with the true value (1) and write it as:

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

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 :[11]

$$i_s = \frac{2}{3}\left(i_a + ie^{\frac{j2\pi}{3}} + i_c e^{\frac{j4\pi}{3}}\right) \quad (3)$$

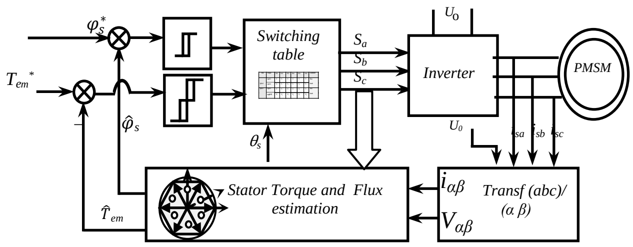

Fig1. Schematic diagram of DTC control strategy

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

$$\varphi_{s\alpha} = \int_0^t (V_{s\alpha} - Ri_{s\alpha})dt \quad (4)$$

$$\varphi_{s\beta} = \int_0^t (V_{s\beta} - Ri_{s\beta})dt \quad (5)$$

Stator Flux amplitude and phase angle are calculated in expression (6), (7):

$$\begin{cases} \varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} & (6) \\ \angle\varphi_s = arctg\,\frac{\varphi_{s\beta}}{\varphi_{s\alpha}} & (7) \end{cases}$$

(4)

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

$$T_{em} = \frac{3}{2}\, p\left(\varphi_{s\alpha}\, i_{s\beta} - \varphi_{s\beta}\, i_{s\alpha}\right) \quad (8)$$

In order to maintain the estimated stator flux and torque within the hysteresis bands.

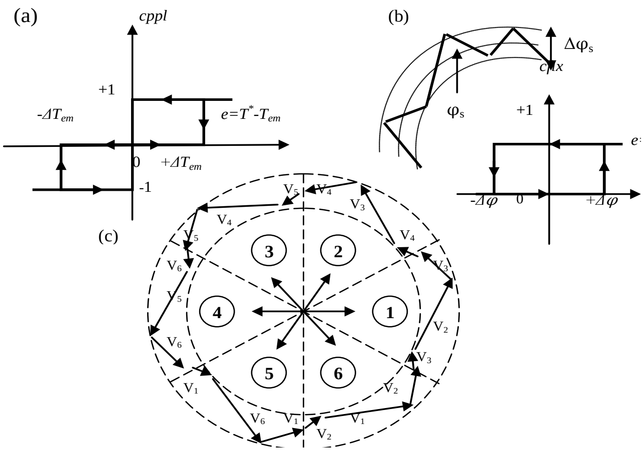

Fig2. (a) Torque hysteresis comparator (three-level)
(b) Flux hysteresis comparator (two-level)
(c) Vectors Selection corresponding to stator flux amplitude control

In particular the stator flux is controlled by two-level hysteresis comparator, whereas the torque by a three-level comparator [10], as shown in Fig2.

The voltage plane is divided into six sectors so that each voltage vector divides each region into two equal parts. In fig3 these vectors are shown, where six active vectors of same magnitude are presented and two remaining vectors are zero.

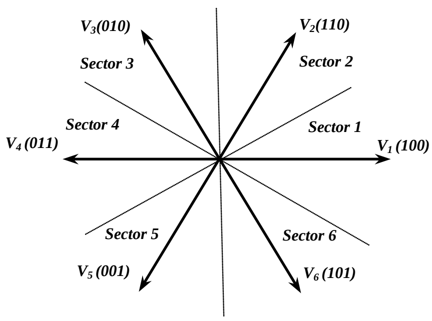

Fig3. Spatial voltage vectors as function of the state inverter

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

Depending on the area where the stator flux vector is, each vector will have a different effect. In table I, is presented the DTC selection algorithm. [12][13][14].

Flux	*Torque*	N=1	N=2	N=3	N=4	N=5	N=6	*Controller*
cflx=0	***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***
cflx=1	***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***

Table I. Switching table

III. NEURAL DIRECT TORQUE CONTROL

In recent years, neural f networks have become a popular research topic. They are widely applied in fields such as time series prediction, control problem, and pattern recognition.

To get better performance and to reduce the torque and flux ripples, a neural network controller has been introduced in this paper to replace the hysteresis controller and switching table with as shown fig4.

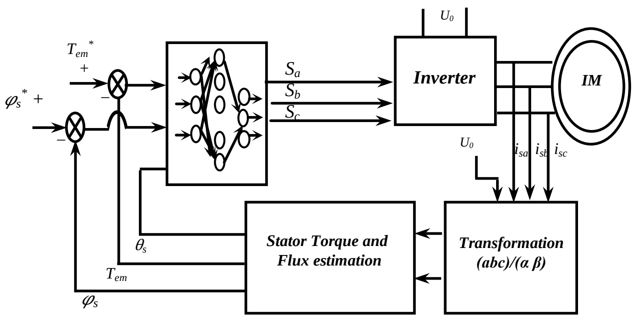

Fig4. Schematic diagram of neural DTC control strategy

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

Three input variables and three control variable (as shown in fig.5) for achieving constant torque and flux control respectively defined as:

$$E_\varphi = \varphi_s^* - \varphi_s$$

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

$$E_{Te} = T_e^* - T_e$$

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

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)

In the case of a multi-layer preceptor, the number of hidden layers and hidden neurons is not known a priori. Furthermore, there is no general rule for predicting the number of hidden neurons necessary to achieve a specified performance of the model. This 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.

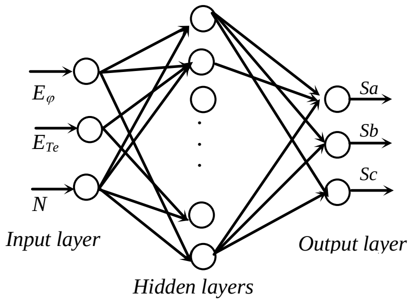

Fig5. Architecture of neural network controller

III. Simulation Result

To verify the approaches proposed in this paper, digital simulation based on Matlab/Simulink have been implemented.

This simulation was carried out to verify the function on the proposed estimators where the parameters of the Permanent Magnet Synchronous motor used in this paper are listed 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

In first part, the results of simulations of Neural Direct Torque Controlled Magnet Permanent Synchronous Motor is shown in fig6, presents different responses of electromagnetic torque, stator flux and current with a load torque applied .

It can be seen that stator flux vector describes a trajectory almost circular and the decoupling between flux and torque is maintained.

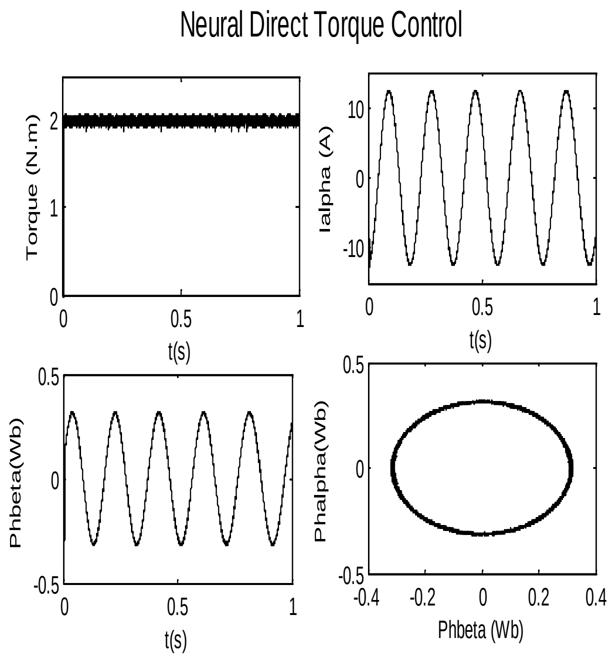

Fig6. Flux, torque and stator current using neural estimator with a load torque applied (2N.m)

In second part results of comparison using Neural Direct Torque Control and Classical Direct Torque Control is shown in fig7, 8 present responses torque and stator flux with a load torque applied. Fig.9 present responses torque using neural and classical DTC with a load torque applied (2N.m) and changing torque (1N.m) between (t=0.2s and t=0.4s). It can be noticed in these figures that the electromagnetic torque tracks its reference using neural network controller but with less torque ripples compared with classical DTC.

Neural DTC　　　　　　　　　　　　　Classical DTC

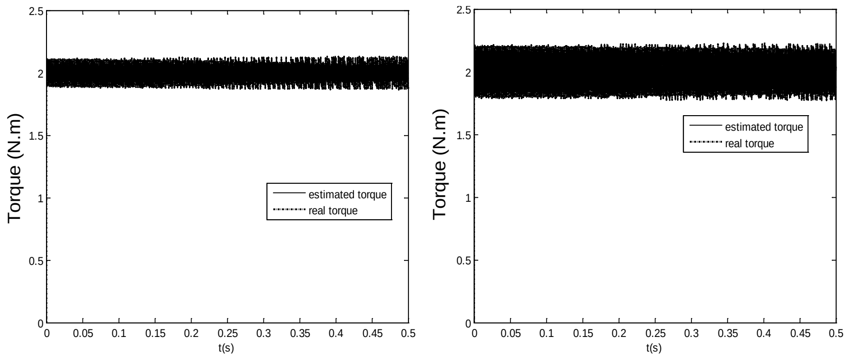

Fig7. Torque response using neural and classical DTC with a load torque applied (2N.m)

Neural DTC　　　　　　　　　　　　　Classical DTC

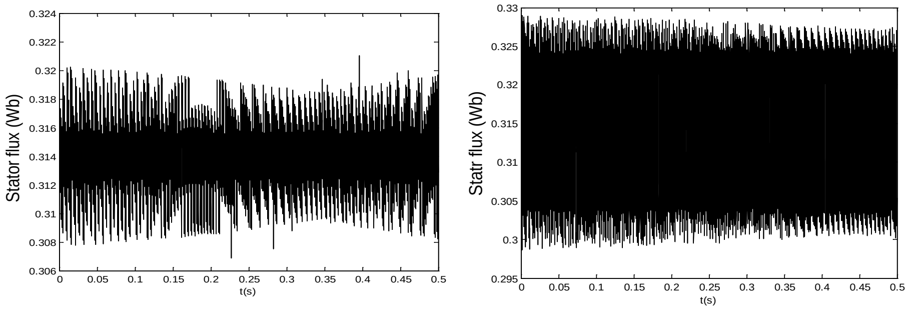

Fig8. Flux response using neural and classical DTC with a load torque applied (2N.m)

Neural DTC　　　　　　　　　　　　　Classical DTC

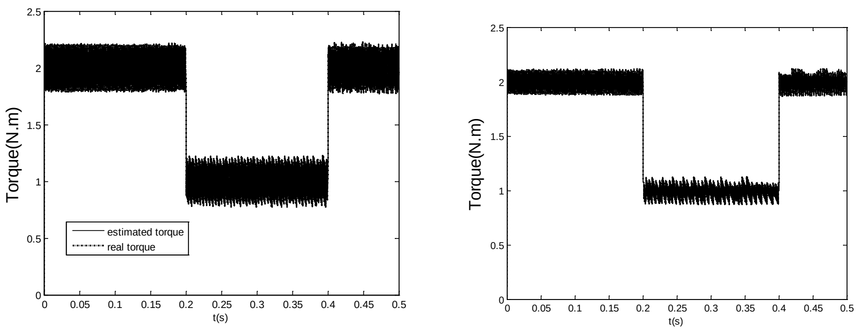

Fig9. Torque response using neural and classical DTC with a load torque applied (2N.m) and changing (1N.m) at (between t=0.2s and t=0.4s)

We can see also in these figures that the estimated values of fluxes, torque converge very well to their simulated values.

IV. CONCLUSION

The classical DTC is simple and gives quick response. But, presents some disadvantages such as difficulties in torque and flux control at very low speed, high current and torque ripple, variable switching frequency behavior. Hence, the acoustical noise is more. To reduce the torque ripple, this paper proposes direct torque control of permanent magnet synchronous motor based on neural network, the application of neural technique gives us considerable reduction in torque ripple and flux ripple compared to the traditional DTC.

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