Intelligent DTC of PMSM, fed by a three-phase NPC three-level Inverter

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Abstract *- Direct Control of Flux and Torque control (DTC) has its disadvantages including torque ripples and stator resistance variation, which affects seriously the estimation stator flux and electromagnetic torque used for the implementation of this control. In this present paper, we propose to reduce the electromagnetic torque ripples of the permanent magnet synchronous motor (PMSM) controlled by DTC, by using a three-level NPC inverter associated with PI Fuzzy logic estimator to cure the problem of PMSM parametric variation. In the other hand, we propose to replace conventional selector states of switches inverter by a neural selector able to generate the same signals to control this inverter. Simulation results are presented and show the effectiveness of the proposed estimator.*

Keywords*: EKF, PMSM, DTC, three-level NPC inverter Neuronal selector, Fuzzy, stator resistance variation.*

1. INTRODUCTION

High dynamic performance of servo motor drives is indispensable in many applications of today's automatically controlled machines [1]. AC motor control has attracted much attention recently in the power electronics field.

The development of the magnetic material in the last two decades and advantages of high power factor, faster response, rugged construction, less maintenance, low dependency on the motor parameters ,high torque/inertia ratio, ease of control and high efficiency, enables the permanent magnet synchronous motor (PMSM) to be widely used in high performance drives[2].

Direct Torque Control (DTC) was introduced in 1985 by Takahashi and Depenbrock especially for the asynchronous and synchronous machines [3], [4]. The main advantages of DTC are the simple control scheme, a very good torque dynamic response, as well as the fact that it does not need the rotor speed or position to realize the torque and flux control, moreover DTC is not sensitive to parameters variations (except stator resistor),[3].

In the classic DTC the employment of the hysteresis controllers to regulate the stator magnetic flux and torque is natural to have high torque ripples and variable switching frequency, which is varying with speed, load torque, selected hysteresis bands and difficulty to control torque and flux at very low speed. It also results in higher acoustical noise and in harmonic losses [5]-[11].

To overcome the above drawbacks, some researchers have been trying to propose solution to solve these problems by substitute hysteresis control by fuzzy control [5].

An effective modality for reducing the torque ripple to use space vector modulation (SVM) [8]. Other researchers use

multilevel inverter, the resolution of the voltage vectors can be improved and hence, more smooth torque and flux responses[7], [8].

The stator resistance variation due to the changes of the temperature can destroy the performance of the DTC, by introducing errors into estimated flux and torque and the position between the components of flux [9]-[11]. The stator variation of this resistance can also reduce the robustness of the drive and can in the same way cause instability of the system.

Several control schemes have been proposed to overcome the problem of stator resistance variation [9]-[11].

A recent study [6] proposed the use of stator current error with a proportional plus integral (PI) estimator, reporting good performance for tuning the stator resistance of a permanent magnet synchronous motor.

The fuzzy logic controller (FLC) is one of the useful control schemes used for plants having difficulties in deriving mathematical models [11]. In addition FLC has the ability to deal with nonlinearities and uncertainness in motor control system. The FLC contains a set of parameters that can be altered on-line in order to improve its performance and robustness.

Several studies have suggested the application of artificial intelligence techniques to select states of the

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switches of inverter used to feed the PMSM controlled by DTC.

In this paper, the technique of neural networks to select the states of the switches of an inverter type three-level NPC used to minimize torque fluctuations manifested in the case of a two-level inverter. In addition, the effect of stator resistance variation on stator flux and torque of PMSM is presented first, followed by an investigation of the proposed Fuzzy Logic estimator for the stator resistance. The performance intelligent DTC associated with FL estimator is examined by extensive modeling and simulation studies.

2. PMSM MODEL

The stator and rotor flux equation of PMSM can be written in the reference frame of Park in the following form [3]:

$$\begin{bmatrix} \phi_d \\ \phi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \begin{bmatrix} \phi_e \\ 0 \end{bmatrix} \tag{1}$$

While the equations of the stator voltages are written in this same reference frame in the following form:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = r_s \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + p\Omega_r \begin{bmatrix} 0 & -L_q \\ L_d & 0 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + p\Omega_r \begin{bmatrix} 0 \\ \phi_e \end{bmatrix} \tag{2}$$

In addition the electromagnetic torque can be expressed:

$$T_e = \frac{3}{2}\, p\left(\left(L_d - L_q\right) I_{sd}\ I_{sq} + \varphi_e\ I_{sq}\right) \tag{3}$$

The mechanical equation of the motor can be expressed as flows:

$$J\,\dot{\Omega} = T_e - T_l - f_r\Omega \tag{4}$$

3. CONVENTIONAL DTC

The methods of direct torque control (*DTC*) as shown in figure 1 consist of directly controlling the turn off or turn on of the inverter switches on calculated values of stator flux and torque from relation (6). The changes of state of the switches are linked to the changes in electromagnetic state motor. They are no longer controlled based on voltage and frequency references given to the commutation control of a pulse width voltage modulation inverter [3],[4]. The reference frame related to the stator makes it possible to estimate flux and the torque, and the position of flux stator. The aim of the switches control is to give the vector representing the stator flux the direction determined by the reference value

$$\begin{cases} \phi_{s\alpha} = \int_0^t (v_{s\alpha} - r_s I_{s\alpha})\,dt \\ \phi_{s\beta} = \int_0^t (v_{s\beta} - r_s I_{s\beta})\,dt \end{cases} \tag{5}$$

The *DTC* is deduced based on the two approximations described by the formulas (6) and (7) [1]:

$$\bar{\phi}_s(k+1) \approx \bar{\phi}_s(k) + \bar{V}_s T_E \ \rightarrow \Delta\bar{\phi}_s \approx \bar{V}_s T_E \tag{6}$$

$$T_e = k(\bar{\varphi}_s \times \bar{\varphi}_r^{'}) = k\left|\bar{\varphi}_s\right|\ \left|\bar{\varphi}_r^{'}\right|\ \sin\left(\delta\right) \tag{7}$$

More over:

$$\begin{cases} \hat{\phi}_s = \sqrt{\hat{\phi}_{s\alpha}^2 + \hat{\phi}_{s\beta}^2} \\ \angle\hat{\phi}_s = arctg\,\dfrac{\hat{\phi}_{s\beta}}{\hat{\phi}_{s\alpha}} \end{cases} \tag{8}$$

A two levels classical voltage inverter can achieve seven separate positions in the phase corresponding to the eight sequences of the voltage inverter.

These positions are illustrated in Fig .2. In addition, Table 2 shows the sequences for each position, such as: S_i = 1,.,6, S_i are the areas of localization of stator flux vector.

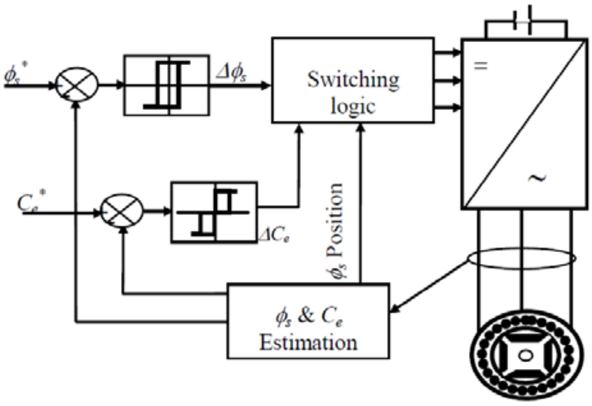

Fig. 1. Diagram of DTC control applied for PMSM supplied with a three-phase inverter with PMW.

Three levels NPC inverter release 19 vector voltages and 16 different sequences switches. These positions are illustrated in Figures 4. Furthermore, Tables I and II have the sequences corresponding to the position of the stator flux vector in different sectors (see

Figures 1 and 2). The flux and torque are controlled by two comparators with hysteresis illustrated in Figure 3. The dynamics torque are generally faster than the flux then using a comparator hysteresis of several levels, is then justified to adjust the torque and minimize the switching frequency average [3].

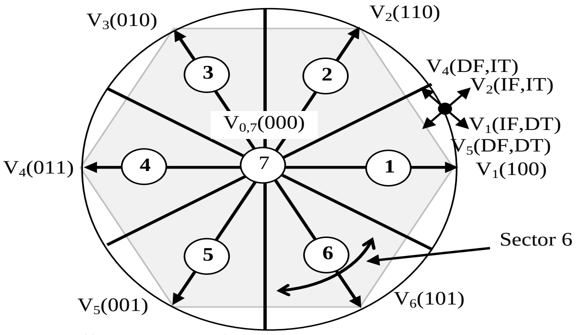

Fig. 2. Different vectors of stator voltages provided by a two levels inverter.

Where:
I(D)F : Increase (Decrease) of Flux amplitude.
I(D)T : Increase (Decrease) of Torque amplitude.

Table 1 Vectors Voltage Localization Table (Two Levels Inverter)

$\Delta\phi_s$	ΔC_e	S_1	S_2	S_3	S_4	S_5	S_6
1	1	110	010	011	001	101	100
	0	000	000	000	000	000	000
	-1	101	100	110	010	011	001
0	1	010	011	001	101	100	110
	0	000	000	000	000	000	000
	-1	001	101	100	110	010	011

Where, Si=1...,6 are localization sectors of the stator vector flux.

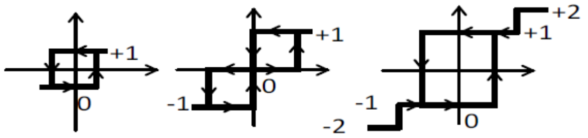

Fig. 3. Comparators with hysteresis used to regulate flux and torque.

The same principle of *DTC* command of *PMSM* supplied by an inverter two levels applied for three *NPC* inverter unless the comparators hysteresis are 3 and 5 levels, which increases the number of sequences to apply. In the case of 3-level inverter (see Figure 4), sequence voltage 211 is similar to the sequence 100 so 221 is like 110, etc.... So we have 19 combinations of vectors achievable voltages including zero sequence [8].

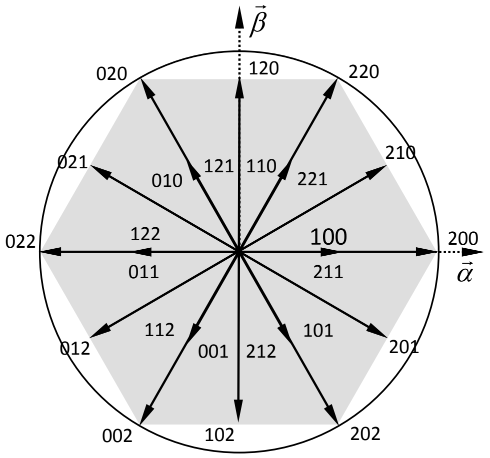

Fig. 4. Different vectors of stator voltages provided by a three levels inverter.

Table 2 Vectors Voltage Localization Table (Tree Levels Inverter)

$\Delta\phi_s$	ΔC_e	S_1	S_2	S_3	S_4	S_5	S_6
1	2	220	020	022	002	202	200
	1	210	120	021	012	102	201
	0	200	220	020	022	002	202
	-1	201	210	120	021	012	102
	-2	202	200	220	020	022	002
0	2	120	021	012	102	201	210
	1	120	021	012	102	201	210
	0	000	000	000	000	000	000
	-1	102	201	210	120	021	012
	-2	102	201	210	120	021	012
-1	2	020	022	002	202	200	220
	1	121	122	112	212	211	221
	0	211	221	121	122	112	212
	-1	112	212	211	221	121	122
	-2	002	202	200	220	020	022

4. DTC EQUIPPED WITH A THREE-LEVEL INVERTER NEURAL SELECTOR.

The application of neural networks currently occupies an important place among the different types of control electrical machines drivers. And as the DTC uses algorithms to select a large number of combinations of states of the switches in the case of multilevel inverters, neural networks can perform this task after a learning phase [12].

A neural network may have one or more inputs, one or more hidden layers and one or more outputs. The inputs of the neural selector used, are the position of the stator flux vector represented by the number of the corresponding sector, the gap between the estimated and the reference value of flux (more precisely the output of the comparator with hysteresis flux) and the difference between the electromagnetic torque and the estimated reference torque (more precisely the output of comparator hysteresis torque), are three neurons in the input layer. The output layer is composed of a neuron that represents the state of Ei one of the three pairs of switches of the inverter Ti connected to the positive terminal of the DC source. While for the hidden layers, the simulation led us to choose an eight-layer neurons (see figure 5). The adopted encoding of the neural selector is summarized in the table (3).

Table 3 Coding adopted for the neural selector

	Inputs			*Outputs*
Code	*Position*	$\Delta\phi_s$	ΔC_e	E_i
1,.,6	*Sector*			
1		>0		
0		=0		
-1		<0		
2			>0.01. C_e^*	
1			0.01. C_e^*>…>*0*	
0			=0	
-1			0>…>-0.01. C_e^*	
-2			<-0.01. C_e^*	
2				T_i locked
1				Down Switch T_i locked
0				T_i open

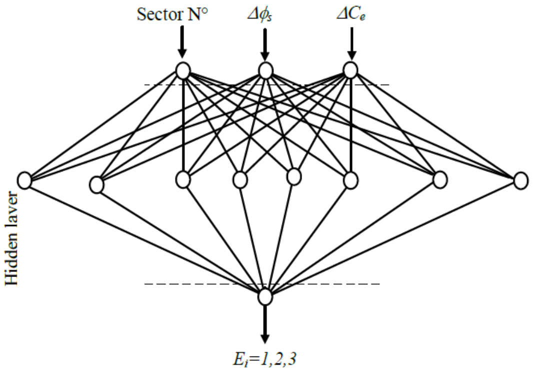

Fig. 5. a) Neuronal structure proposed for the implementation of the DTC switching, in the case of an NPC three level inverter

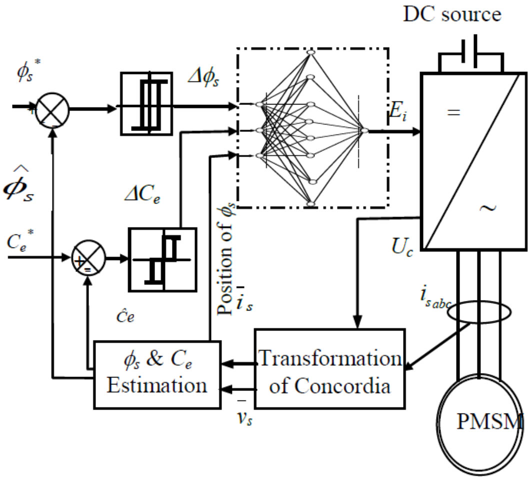

Fig. 5 b). Diagram of DTC Applied for PMSM fed By a Three-Phase NPC Three-Level with Neural Selector.

5. PROBLEMS RELATED TO THE STATOR RESISTANCE VARIATION

In DTC drive, the stator flux is estimated by integrating the difference between the input voltage and the voltage drop across the stator resistance as given by equation (5).

Operating at low speed, a variation of r_s implies that the obtained information by the preceding expressions of flux and torque would be false, and consequently the DTC control loses its performances and it may become unstable [6], [11]. The motor back-emf is small, and the resistive voltage drop $i_{s*}r_s$ can be comparable with the supply voltage vector v_s.

Any variation of stator resistance can cause an imbalance in the equations of the stator flux PMSM components, expressed in steady state. The estimate of the stator flux on the basis of an changing model which does not take in account the evolution of stator resistance during its operation, is undoubtedly sullied with error compared to the real flux of the machine [6]. This error influences the stator flux as well as the electromagnetic torque, which means significant error on the position which causes a bad selection of state of the switches and generates instability of the machine operation.

6. FUZZY ESTIMATOR OF STATOR RESISTANCE

A Fuzzy Logic corrector is developed to establish the DTC. Thus, we seek an estimator who detects the stator resistance variation during the operation of the PMSM that can be used to correct the value of r_s and to obtain good estimation of flux and electromagnetic torque. In PMSM with smooth poles, $(L_d - L_q) \approx 0$ [13]. The equation (3) can be simplified and then, we can deduce the reference stator current I^*_{sq} according to the relation (11) :

$$\phi_s^* = \sqrt{(L_d I_{sd} + \phi_e)^2 + L_q^2 I_{sq}^2} \tag{9}$$

$$C^*_e = \frac{3}{2} p(\phi_{sd} I_{sq} - \phi_{sq} I_{sd}) \tag{10}$$

$$I^*_{sq} = \frac{2.C_e^*}{3.p.\phi_e} \tag{11}$$

After having solved the system of the two equations (9). (11), we find the reference stator current I_s^*:

$$I_s^* = \sqrt{(I^*_{sd})^2 + (I^*_{sq})^2} \tag{12}$$

The difference between the reference stator current of and the real current, $e(k) = I_s^*(k) - I_s(k)$, and the variation of this variation $\Delta e(k) = e(k) - e(k-1)$, are used input fuzzy variables of the fuzzy estimator of rs, whose block diagram are illustrated by the figure (6). The fuzzification of the input and output linguistic variables of the fuzzy estimator is illustrated by the figure (5), and the defuzzification was carried out by the method of the centre of gravity [11]. In addition, the inference rules are summered in table (4).

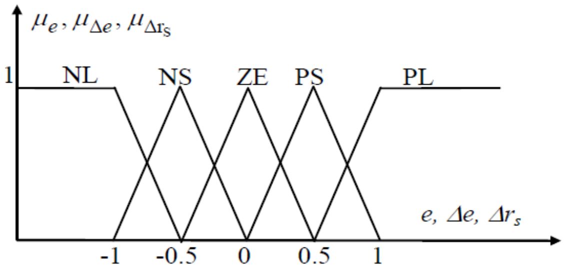

Fig. 6. Memberships of the input /output functions

Table 4. Rules base of FLC stator resistance estimator.

e ↓ Δe →	PL	PS	ZE	NL	NS
PL	PL	PL	PL	PS	ZE
PS	PL	PL	PS	ZE	NS
ZE	PL	PS	ZE	NS	NL
NL	PS	ZE	NS	NL	NL
NS	ZE	NS	NL	NL	NL

According to the relation (5), if stator resistance undergoes an increase with for a given voltage and, the stator current of the machine decreases. Consequently, we have to decrease the estimated current in order to follow the real variation of the stator current, to do so; we have to increase the estimated resistance. Therefore one must increase r_s for a reduction in I_s compared to I_s^*, and vice versa.

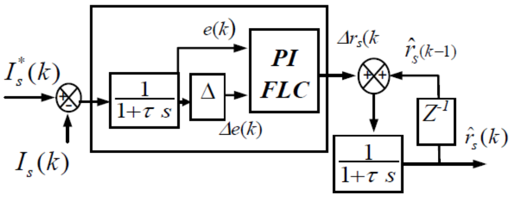

Fig.7. a) Block diagram of fuzzy logic stator resistance estimator.

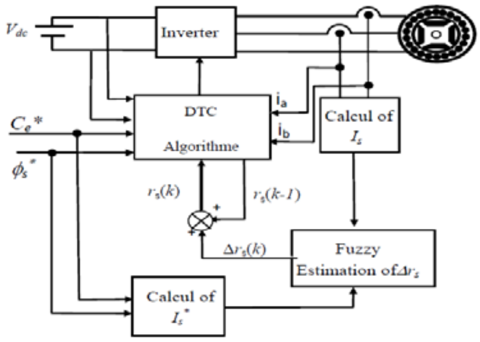

Fig. 7. b) Diagram of DTC control applied for PMSM with a fuzzy stator resistance estimator.

7. RESULTS OF SIMULATION

Table (5), summarizes the *PMSM* parameters used in this simulation [14].

Table 5 PMSM parameters

Pole pairs	3
Rated power KW (at 50 Hz)	1.5
Rated voltage (V)	220/380
Rated Flux (Wb)	0.30
Rated torque (Nm)	5
R_s (Ω)	1.4
L_d ; L_q (H)	0.0066; 0.0058
Flux magnet (Wb)	0.15
J(Kg.m²)	0.00176
f_r (Nm/(rad/s))	0.0038

In this simulation study, we will carry two cases of the PMSM Control:

Control without compensation.

We simulated the system drive for a reference speed of 100 (rd / s) load at startup. At t = 0.1(s), the *PMSM* is tracking load equal to 5 (Nm), then from t = 0.02 (s), we assumed a variation of the stator resistance (see Fig. 8).

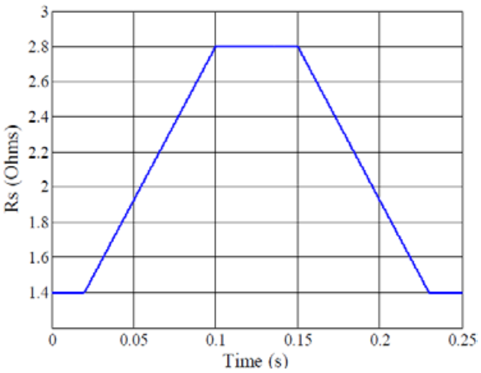

Fig. 8. Real resistance stator of PMSM

Figure (9), presents the influence of such variation on the actual and estimated electromagnetic torque of PMSM. It is noticed that the couple deviated of its reference. In addition, the actual flux of the PMSM machine shown in figure (9), moves away by approx 0.04(Wb) form its reference value.

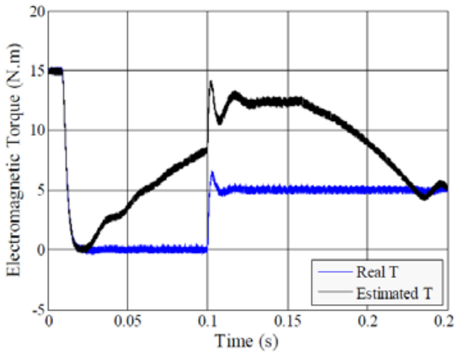

Fig. 9. Evolution of motor's Electromagnetic torque with no compensation of rs.

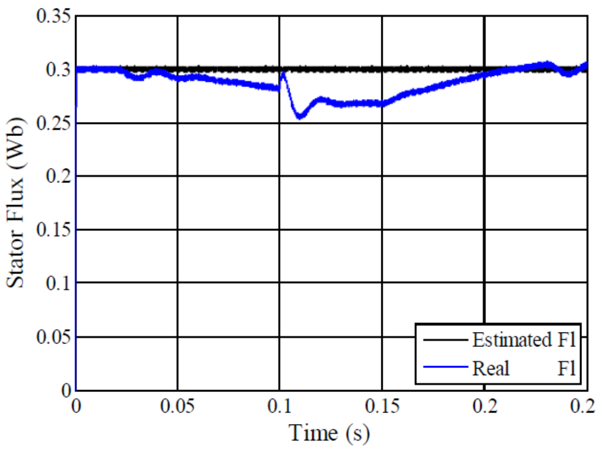

Fig. 10. Evolution of motor's stator Flux with no compensation of rs.

Control with compensation.

In this part of simulation, we introduce a fuzzy logic stator resistance estimator in order to correct the estimate of stator flux and electromagnetic torque, the gains of fuzzy estimator are obtained after several simulations in order to reach the best results, and the following values are then taken:

K_e=150, $K\Delta_e = 800$ and $K\Delta_{rs} = 0.16$

Figure (11) illustrates the evolution of real and estimated resistances, (delivered by the proposed fuzzy compensator). The two values are practically equal in steady state. The actual and estimated electromagnetic torque are illustrated by figure (12). It is noticed that these two curves coincide when estimated resistance reaches its value in steady state.

The figure (13), shows the good compensation of the stator flux response by using the fuzzy regulator. This flux was restored correctly with its reference.

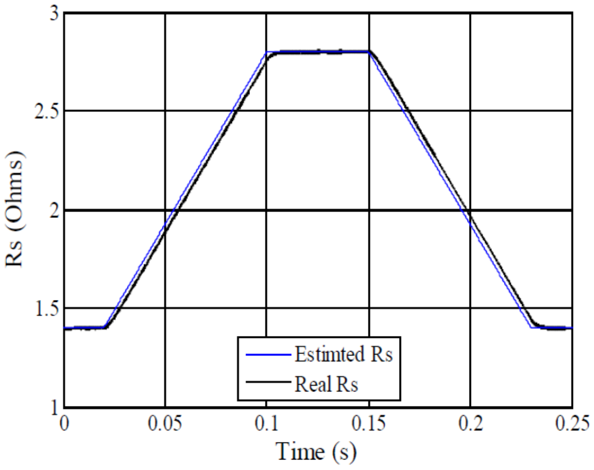

Fig. 11. Estimated and real stator resistance.

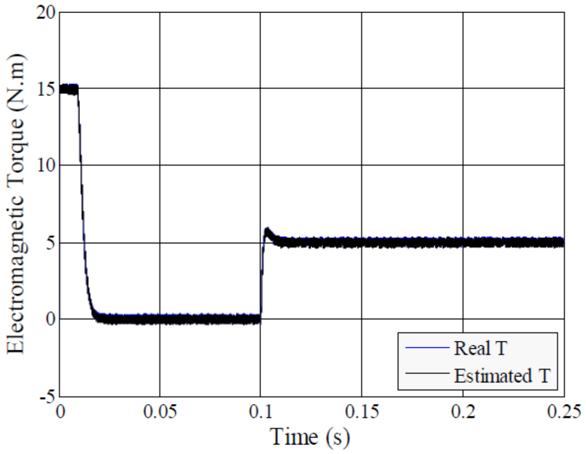

Fig. 12. Evolution of motor's Electromagnetic torque.

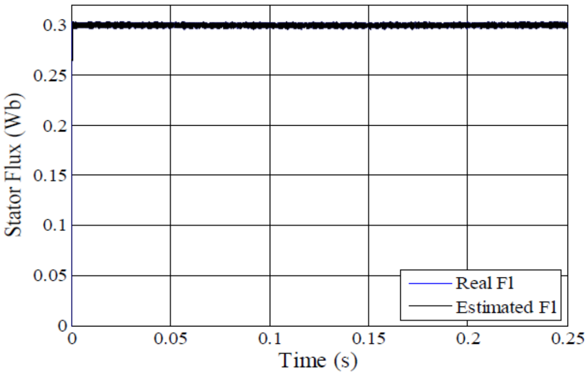

Fig. 13. Evolution of motor's stator Flux.

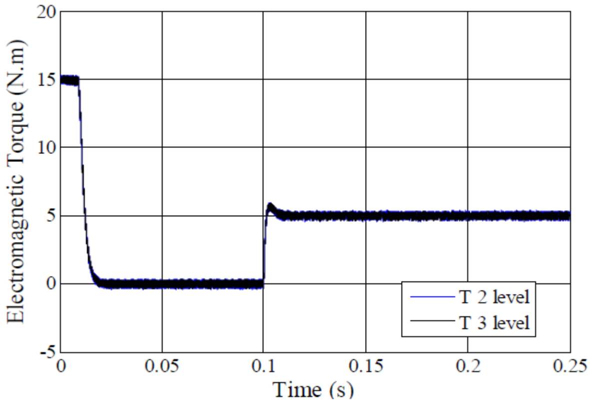

Fig. 14. Evolution of motor's Electromagnetic torque.

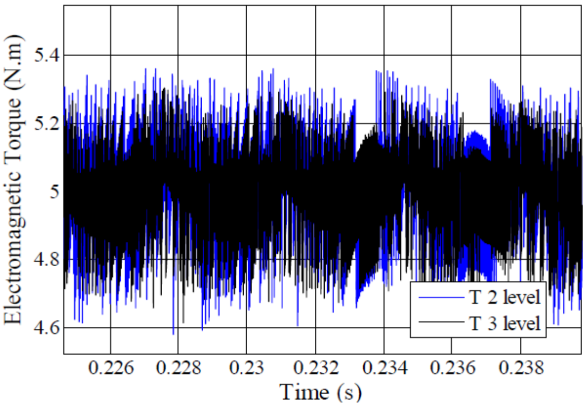

Fig. 15. Scale of the estimated Electromagnetic Torque.

The use of three-level *NPC* inverter has improved the band Electromagnetic Torque are shown in Figure 15. Indeed this reduction is worth approximately 26.43% of the torque value which is an important advantage.

8. CONCLUSION

In this paper, we proposed a Fuzzy logic compensator for estimating the stator resistance of PMSM controlled by *DTC* whit a neuronal selector. The effects of the variations of motor parameters such as torque constant, stator resistance have been studied. Using three-level *NPC* inverter reduces the torque ripple of *PMSM* performance compared to obtain with a two-level inverter.

The simulation results obtained were satisfactory, and system stability has been insured.

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