Modified Direct Torque Control for Permanent Magnet Synchronous Motor Drive Based on Fuzzy Logic Torque Ripple Reduction and Stator Resistance Estimator

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Abstract: The two important disadvantages of Direct Torque and Flux Control (DTC), are torque and flux ripples and stator resistance variation (which affects seriously the estimation stator flux and electromagnetic torque). This paper proposes a fuzzy-logic based DTC (FLC) using modified switching table for permanent magnet synchronous motor (PMSM) and Fuzzy-logic Resistance Estimator. The high-performance of the proposed FLC applied to PMSM drive, are investigated and compared with traditional DTC. The proposed system has proven successful in controlling the instantaneous torque so as not to depend only on the estimation flux**,** torque and position, but also on variable amplitude torque hysteresis bands and stator resistance (r_s) delivered by fuzzy-logic.

Keywords: DTC, PMSM, FLC, Switching table, Torque and flux ripples, Stator resistance estimator.

1. INTRODUCTION

Recently, the areas of industrial application of high performance AC drives are considerably expanded with the development of power electronics, Microelectronics and computer Engineering. Indeed, technological developments have permitted alternative machines, especially the synchronous machine; to acquire the control suppleness and high dynamic performance naturally obtained, (Boussak, 2005). In addition, depth research has led to the development of the new materials, such as permanent magnets based on rare earths, (Kadjoudj *et al.*, 2007). These allow obtaining synchronous machines which are compared to other types of DC machines, synchronous with electrical excitation and asynchronous many advantages, among others, low inertia and high power density and efficiency, (Zhong *et al.*, 1999). They are currently the best placed to meet the requirements of applications such as robotics, machine tools, space technology (actuators aviation, satellites) and general embedded systems.

DTC offer high advantages performances in terms of simplicity control scheme and 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, except stator resistor, DTC is not sensitive to parameters variations, (Takahashi and Ohmori, 1989).

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, (Wang *et al.*, 2008).

The variation of r_s due to changes in temperature or frequency degrade the performance of DTC controller by introducing errors in the estimated flux linkage magnitude, position and the electromagnetic torque, (Haque and Rahman, 2001). So the compensation for the effect of r_s variation then becomes necessary, (Ameur *et al.*, 2010).

In this paper, two fuzzy-logic (FL) are proposed to overcome the problem of torque and flux hysteresis bands with variable amplitude based on switched table, in over hand the effect of r_s variation is discussed and the r_s is estimated by FL estimator using the error between the reference and actual stator flux linkage. The performance of the controller is examined by extensive simulation studies, which shows that the drive system becomes unstable if the r_s value used in the controller differs at real resistance.

2. PMSM MODEL

The stator and rotor flux equation of PMSM can be written in the reference frame of *Park,* in the following form:

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

In this same reference, the stator voltages equations are written in the following form:

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

In addition the electromagnetic torque can be expressed by:

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

The motor mechanical equation can be expressed as flows:

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

3.   CONVENTIONAL DTC

The methods of 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, (Mokhtari *et al.*, 2009). The reference frame related to the stator makes it possible to estimate the stator flux (magnitude and argument) and torque. 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):

$$\overline{\varphi}_s(k+1) \approx \overline{\varphi}_s(k) + \overline{V}_s T_E \quad \rightarrow \quad \Delta \overline{\varphi}_s \approx \overline{V}_s T_E \tag{6}$$

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

More over:

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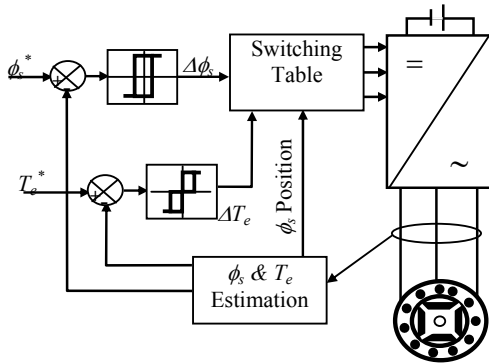

Fig. 1. Diagram of DTC control applied for PMSM supplied with a three-phase inverter with PWM.

A two levels classical voltage inverter can achieve seven separate positions in the phase corresponding to the eight sequences of the voltage inverter, (Takahashi and Ohmori, 1989).
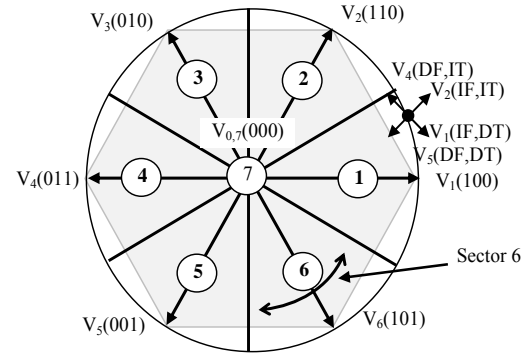

Fig. 2. Different vectors of stator voltages provided by a two levels inverter.

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

Table 1. Vectors voltage localization.

$\Delta\phi_s$	ΔT_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

4.   DTC MODIFIED

The same principle of basic DTC control of the PMSM, which is supplied by a two-level inverter, is applied for the other *ST*.

All sectors are shifted by an angle of 30° leading to an angle of the first sector between 0° and 60° as shown in figure 3.
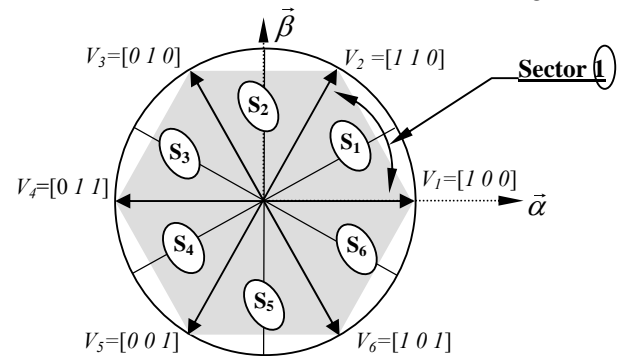

Fig. 3. Different vectors of stator voltages, in case of table with sectors shifted by 30°.

The difference between a DTC with a simple switching table and that with sectors shifted is summarized in table 2.

Table 2. Comparison between the simple table and the table with sectors shifted by 30°.

	Traditional DTC	Modified DTC
V_1	-30° → 30° Torque undetermined	-60° → 0° DT , IF
V_2	30° → 90° IT , IF	0° → 60° IT , IF
V_3	90° → 150° IT , DF	60° → 120° Flux undetermined
V_4	150° → 210° Torque undetermined	120° → 180° IT , DF
V_5	210° → 270° DT , DF	180° → 240° DT , DF
V_6	270° → 330° DT , IF	240° → 300° Flux undetermined

Table 3 presents the switching table when the sectors are shifted by 30°. We can see the difference from the conventional DTC in the third and the fourth lines for conventional switching table, (Mokhtari *et al.*, 2012).

Table 3. Switching table of DTC with shifting 30°.

$\Delta\phi_s$	ΔT_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	100	110	010	011	001	101
0	1	011	001	101	100	110	010
	0	000	000	000	000	000	000
	-1	001	101	100	110	010	011

5. REDUCTION OF ELECTROMAGNETIC PMSM TORQUE RIPPLES USING CONTROLLERS BASED ON FUZZY LOGIC

The basic idea is to replace bands flux and torque controllers hysteresis desired by bands issued by FLC. The value of the change in the speed error can be used for measuring or estimating the torque smoothing, (Zidani and Nait Said, 2005).

The equation of mechanical motor neglecting viscous friction is:

$$J\frac{d\Omega_r}{dt} = T_e - T_l \qquad (9)$$

Replacing the error speed $e = \Omega_r - \Omega_{ref}$ in equation (9), we find:

$$J\frac{d(\Omega_{ref}+e)}{dt} = J\frac{d\Omega_{ref}}{dt} + J\frac{de}{dt} = T_e - T_l \qquad (10)$$

For a constant reference speed and a constant load, the change of the error speed is related to motor torque by:

$$\frac{de}{dt} = \frac{T_e - T_l}{J} \qquad (11)$$

From (11), we can conclude that the change of speed error signal can indeed be a good measure and a good indicator of motor torque ripple.

We will present in the following a fuzzy approach dedicated to reducing torque ripples.

A fuzzy controller seems to be a reasonable choice to evaluate the hysteresis bands of the torque and flux amplitude, (Adam *et al.*, 2007).

In this approach, the hysteresis bands of torque and flux are not prefixes, but they are determined by two fuzzy controllers. Figure (4) shows the two adapted controllers torque and flux hysteresis bands.
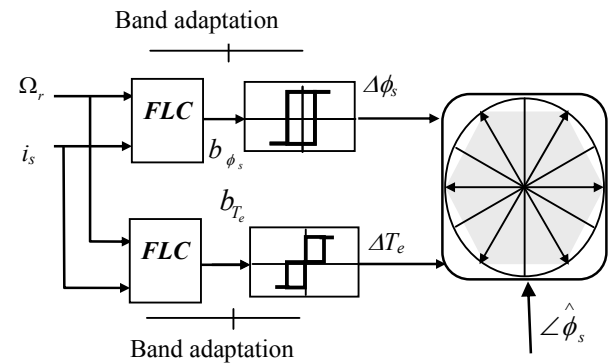

Fig. 4. Adapted fuzzy bands torque and flux hysteresis controller.

Based on the proposed analysis and the diagram above, two inputs are chosen, error rate speed and stator current, variations:

$$e_1(k) = \Omega_r(k) - \Omega_r(k-1) \qquad (12)$$

$$e_2(k) = i_s(k) - i_s(k-1) \qquad (13)$$

The magnitude of the stator current is deduced from the following relation: $i_s = \sqrt{i_{s\alpha}^2 + i_{s\beta}^2}$.

The net output (with a hysteresis band appropriate) is integrated in such a way that the amplitude of the hysteresis band of the torque and flux is obtained from the following two equations:

$$b_{T_e}(k) = b_{T_e}(k-1) + \Delta b_{T_e}(k) \qquad (14)$$

$$b_{\phi_s}(k) = b_{\phi_s}(k-1) + \Delta b_{\phi_s}(k) \qquad (15)$$

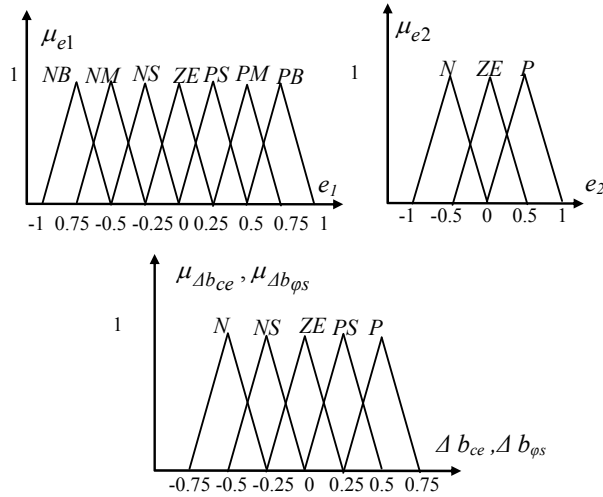The fuzzification of input variables and outputs of the two fuzzy controllers is shown in figure (5).

Fig. 5. Fuzzy controller inputs and outputs membership functions.

Table 4. Linguistic rules base for two PI-Type fuzzy-logic controllers.

$e_1 \downarrow$ $\;\;\;e_2 \rightarrow$	PB	PM	PS	ZE	NS	NM	NB
P	P	P	PS	ZE	NS	NS	N
ZE	P	P	PS	ZE	NS	N	N
N	P	NS	PS	ZE	NS	N	N

For example, for e_1 Positive Big (*PB*), and a variation e_2 Positive (*P*), then Δb_{Te} must be Positive (*P*) as well. In this case, the overshoot in the torque error can touch the upper band which will lead us to select a reverse voltage vector. This will cause a rapid reduction in torque but slow response torque below the hysteresis band, (Zidani and Nait Said, 2005). Thus, Δb_{Te} should not be Positive Small (*PS*) but positive (*P*), to avoid this situation.

6. EFFECT OF STATOR RESISTANCE VARIATION

The unknown of r_s may have several origins. They may be due to an incorrect identification of the parameters of the machine, change in the load or the temperature of the surroundings. Because an incorrect value of the r_s certainly causes an error estimation of the stator flux module its position. It can cause serious problems in the choice of voltage vector to apply, (Tang *et al.*, 2002). Several studies have been proposed for this estimate to address the problem of variation of r_s, (Mir *et al.*, 1998), . In this section we will propose to illustrate the influence of this variation, and then we present a block estimate that compensates each variation of r_s, using a fuzzy-logic controller.

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

$$\phi_s = \phi_{sa} = \hat{\phi}_s = \int_0^t (v_s - r_s I_s)\,dt \tag{16}$$

The estimated and actual electromagnetic torque are given by

$$T_e = T_{ea} = \hat{T}_e = \frac{3}{2}p(\phi_{s\alpha}I_{s\beta} - \phi_{s\beta}I_{s\alpha}) \tag{17}$$

Any variation of r_s can cause an imbalance in the equations of the stator flux PMSM components, expressed in steady state.

$$\phi_{sa} = \hat{\phi}_s + \Delta\phi_s = \int_0^t (v_s - (r_s + \Delta r_s)(I_s + \Delta I_s)\,dt \tag{18}$$

$$T_{ea} = \hat{T}_e + \Delta T_e = \frac{3}{2}p[(\phi_{s\alpha} + \Delta\phi_{s\alpha})(I_{s\beta} + \Delta I_{s\beta}) \\ -(\phi_{s\beta} + \Delta\phi_{s\beta})(I_{s\alpha} + \Delta I_{s\alpha})] \tag{19}$$

The quantities estimated by the controller are given by:

$$\hat{\phi}_s = \int_0^t (v_s - (r_s)(I_s + \Delta I_s)\,dt \tag{20}$$

$$\hat{T}_e = \frac{3}{2}p[(\phi_{s\alpha} + \Delta\hat{\phi}_{s\alpha})(I_{s\beta} + \Delta I_{s\beta}) \\ -(\phi_{s\beta} + \Delta\hat{\phi}_{s\beta})(I_{s\alpha} + \Delta I_{s\alpha})] \tag{21}$$

Errors in the estimation of flux and torque are given by:

$$\Delta\phi_s = \phi_{sa} - \hat{\phi}_s = -\int_0^t (\Delta r_s)(I_s + \Delta I_s)\,dt \tag{22}$$

$$\Delta T_e = T_{ea} - \hat{T}_e = \frac{3}{2}p[(\Delta\phi_{s\alpha} - \Delta\hat{\phi}_{s\alpha})(I_{s\beta} + \phi_{s\alpha}\Delta I_{s\beta}) \\ -(\Delta\phi_{s\beta} + \Delta\hat{\phi}_{s\beta})(I_{s\alpha} + \Delta I_{s\alpha})] \tag{23}$$

$$\Delta T_e = T_{ea} - \hat{T}_e = \frac{3}{2}p[((I_{s\beta} + \Delta I_{s\beta})\int_0^t \Delta r_s \Delta I_{s\alpha}\,dt) \\ -((I_{s\alpha} + \Delta I_{s\alpha})\int_0^t \Delta r_s \Delta I_{s\beta}\,dt)] \tag{24}$$

Equations (22) and (24) gives the errors of the stator flux and torque are taking into account the variation of the r_s during operation. Estimated quantities differ sensibly from actual magnitudes of the machine, so the resistive term can be comparable to the supply voltage V_s and the error in the stator flux becomes more important, leading to a dysfunction in the choice of voltage vector applied to the machine, so the DTC will lose performance and may become unstable.

7. FUZZY ESTIMATOR OF STATOR RESISTANCE

A Fuzzy-logic corrector is developed to establish the DTC and to obtain a good estimation of flux and electromagnetic torque.   This FL estimator can detects the r_s variation by using the error between the reference and actual stator flux linkage

$$\phi_s^* = \sqrt{(\phi_{s\alpha}^*)^2 + (\phi_{s\beta}^*)^2} \tag{12}$$

The inputs to the r_s fuzzy estimator are the normalized error between the reference and estimated stator Flux, $e(k) = \phi_s*(k) - \phi_s(k)$, and the normalized change in Flux error $\Delta e(k) = e(k) - e(k-1)$, whose block diagram are illustrated by the figure (6). The selected inputs and output memberships for the fuzzy estimator are given in the figure (5), the centroid defuzzification algorithm is used, in which the output fuzzy variable value is calculated as the centre of gravity of the membership function which is always added to the previously estimated $r_s(k-1)$. This updated stator resistance can be used directly in DTC algorithm estimation. In addition, the rule base controlling the defuzzified output according to the fuzzified input values is given in Table (5).
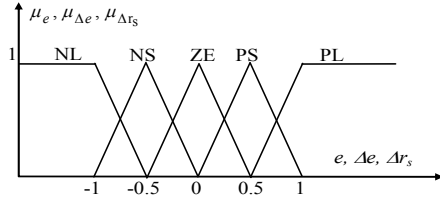

Fig. 6. Memberships of the inputs /outputs functions.

Table 5. Rules base of FLC stator resistance estimator.

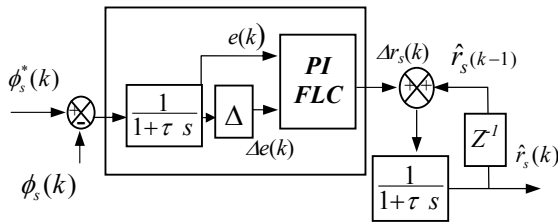| $e\downarrow$ $\quad\Delta e\rightarrow$	PB	PS	ZE	NB	NS
PB	PB	PB	PB	PS	ZE
PS	PB	PB	PS	ZE	NS
ZE	PB	PS	ZE	NS	NB
NB	PS	ZE	NS	NB	NB
NS	ZE	NS	NB	NB	NB

Fig.7. Block diagram of fuzzy-logic r_s estimator.

8. RESULTS OF SIMULATION

Table (6), summarizes the *PMSM* parameters used in this simulation .

Table 6. PMSM parameters.

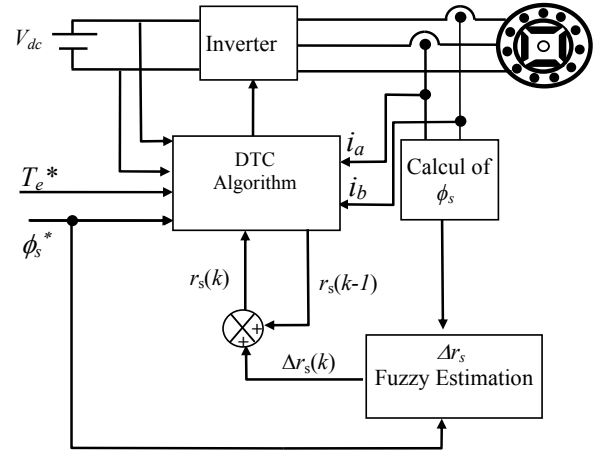| Pole pairs	3
Rated power KW (at 50 Hz)	1.5
Rated voltage (V)	220/380
Rated Flux (Wb)	0.30
Rated torque (Nm)	5
R_s (Ω)	1.4
L_d ; L_q (H)	0.0066; 0.0058
Flux magnet (Wb)	0.15
J(Kg.m²)	0.00176
f_r (Nm/(rad/s))	0.0038

Fig. 8. Diagram of DTC control applied for PMSM with a fuzzy r_s estimator.

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

8.1 Control without compensation.

We simulated the system drive for a reference speed of 100 (rd / s) load at startup. At t = 0.08(s), the *PMSM* is tracking load equal to 5 (Nm), then from t = 0.02 (s), we assumed a variation of r_s (see Fig. 8).

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 (10), moves away by approx 0.04(Wb) form its reference value.

8.2 Control without compensation.

In this part of simulation, we introduce a fuzzy-logic r_s estimator in order to correct the estimate of stator flux and electromagnetic torque using modified switching table two FL controllers torque and flux hysteresis adapted band, 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 (14), shows the good compensation of the stator flux response by using the fuzzy regulator. This flux was restored correctly with its reference.

According to the figures (13), we see that the electromagnetic torque is improved by shifting the sectors by 30 ° with adapted fuzzy band torque and flux hysteresis controller. Indeed, the fluctuations are significantly reduced compared to the case of simple table and modified table. It is appreciated that the flux ripples decreases when hybrid modified *DTC* and fuzzy controller are in use but as shown in figure (15).

As in Figure 16, it illustrates rotor speed (rad / s) issued by PMSM, the speed response is achieved without dip and with a shorter recovery time.
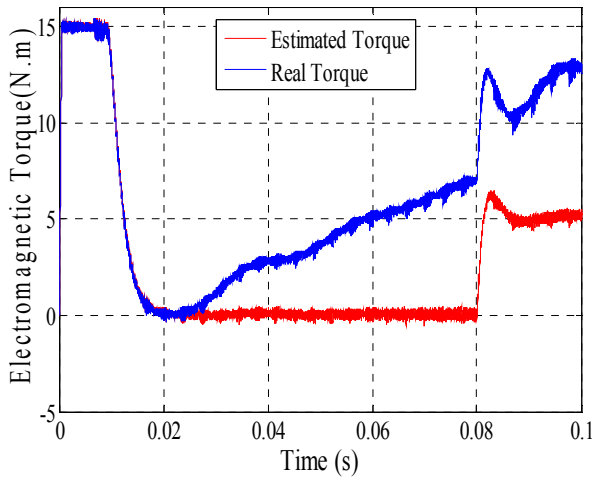
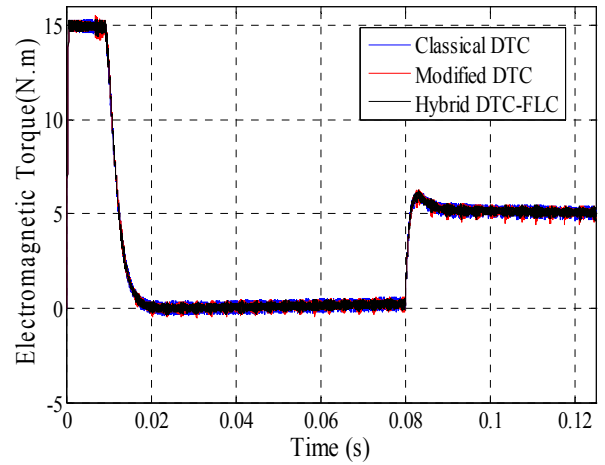Fig. 9. Evolution of motor's electromagnetic torque without compensation of r_s.
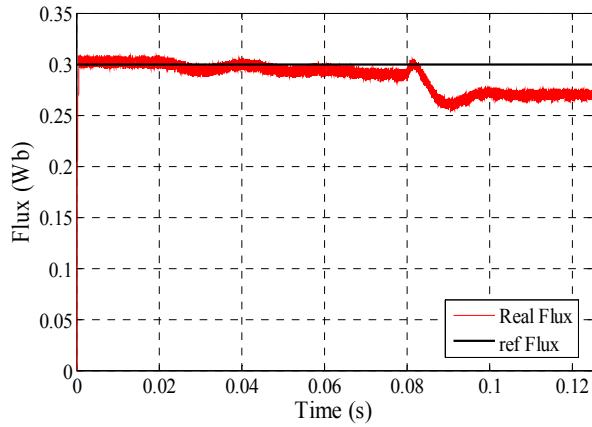

Fig. 10. Evolution of motor's stator flux without compensation of r_s.

Fig. 11. Estimated and real stator resistance.

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

Fig. 13. Scale of the estimated electromagnetic torque.
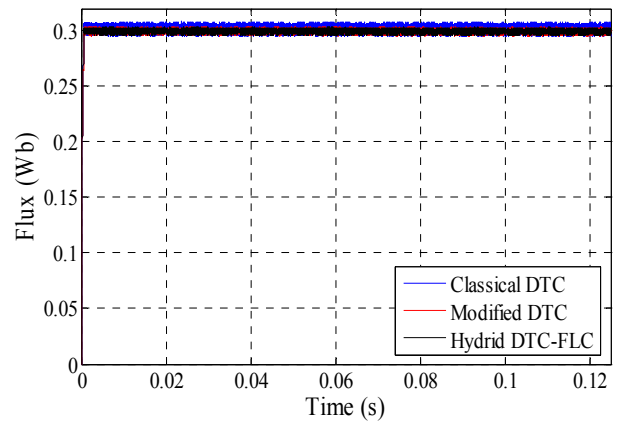

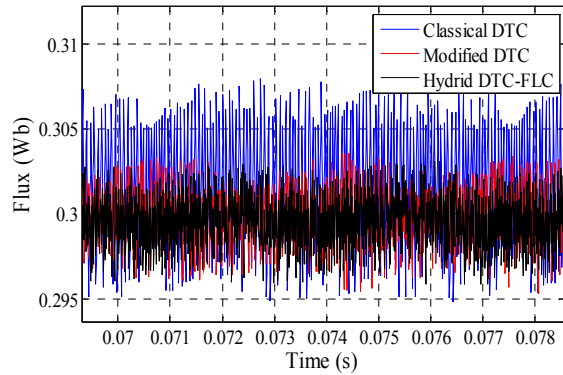Fig. 14. Evolution of motor's stator Flux.
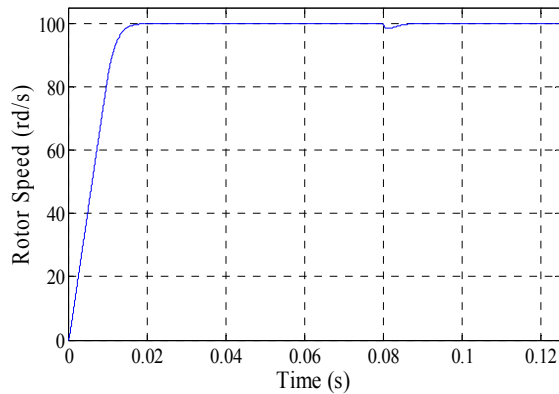
Fig. 15. Scale of motor's stator Flux.

Fig. 16. Evolution of motor's speed.

9. CONCLUSIONS

To reduce the ripples torque and stator flux of the PMSM, controlled by conventional DTC, we proposed in this work, firstly a modified switching table which the sectors are shifted by 30° and secondly, two fuzzy-logic controllers adapted hysteresis bands.

The effects of the stator resistance variations have been studied, and to eliminate them, a Fuzzy-logic compensator has applied.

The simulation results suggests that the proposed modifications via conventional DTC of PMSM can achieve a good reduce of ripples, a precise control of the stator flux and torque and a stability to the study system.

NOMENCLATURE

dq Synchronously rotating frame.

$I_{sd}, I_{sq},$ dq stator current components.

$\phi_{sd}, \phi_{sq},$ dq stator flux components.

ϕ_e Flux magnet.

M Mutual inductance.

$l_d, l_q,$ Stator d and q axis inductances.

R_s Stator resistance.

J, f_r Rotor inertia, friction coefficient.

T_{em} Electromagnetic torque.

T_l Load Torque

p Number of pole pairs.

Ω_r Rotor angular

T_e Sampling Period

k_i, k_p Integral and proportional (IP) speed controller.

I Identity matrix

REFERENCES

Adam, A.A., Gulez, K., and Erdogan, N. (2007). *Minimum Torque Ripple Algorithm with Fuzzy Logic Controller for DTC of PMSM*, in proc of ICIC 2007, pp. 511–521.

Ameur, A., Mokhtari, B., Mokrani, L., Azoui B. (2010). Essounbouli N., and Hamzaoui, A., *An Improved Sliding Mode Observer for Speed Sensorless Direct Torque Control of PMSM Drive with a Three-Level NPC Inverter Based Speed and Stator Resistance Estimator*, In Journal of Electric Engineering, Vol. 10. pp. 1-10, Edition-4.

Boussak, M. (2005)., *Implementation and Experimental Investigation of Sensorless Speed Control With Initial Rotor Position Estimation for Interior Permanent Magnet Synchronous Motor Drive*, IEEE trans. on power electronics, vol. 20, no. 6.

Haque, M. E.,and Rahman, M. F.,(2001). *Influence of Stator Resistance Variation on Direct Torque Controlled Interior Permanent Magnet Synchronous Motor Drive Performance and Its Compensation*, In Proceedings of the Thirty-Sixth IEEE Industry Applications Conference, (IAS-2001), Vol 4, pp. 2563–2569, Chicago.

Kadjoudj, M., Golea,N. and Benbouzid, M.E.H., (2007). *Fuzzy-Rule based Model Reference Adaptive Control of PMSM drives*, Journal SJEE Vol. 4, No 1.

Mir, S., Elbuluk, M. E., and Zinger, D. S., (1998). *PI and Fuzzy Estimators for Tuning the Stator Resistance in Direct Torque Control of InductionnMachines*, IEEE Transaction on Power Electronics, vol. 13, pp. 279-287.

Mokhtari, B., Ameur, A., Mokrani, L., Azoui, B. and Benkhoris, M.F., (2009). *DTC Applied to Optimize Solar Panel Efficiency*, the 35 th annual conference of the IEEE industrial electronics society iecon'09, porto, portugal.

Mokhtari, B., Ameur, A., Mokrani, L., Azoui, B. and Benkhoris, M.F.,(2012), *Comparative Experimental Study of Three Switching Tables of a DTC Applied to an Induction Motor for a Tracking System*, In Journal of Electric Engineering, Vol. 12. pp. 91-98, Edition-3.

Takahashi, I. and Ohmori, Y.,(1989). *High-performance direct torque control of an induction motor*, IEEE Transactions on Industry Applications, Vol.25, pp. 257–264.

Tang, L., Rahman, M. F. and Haque, M. E. (2002). *A Novel PI Stator Resistance Estimator for Direct Torque Controlled Permanent Magnet Synchronous Motor Drive*, In Proceedings of the Australian Universities Power Engineering Conference (AUPEC2002), Monash University, Melbourne, Australia.

Toufouti, R, Meziane, S. and Benalla, H.(2007). *Direct Torque Control Strategy of Induction Motors*, Journal ACTA Electrotechnica et Informatica, Volume 7, Number 1 pp. 22-28.

Wang, J., Wang, H.h., Yuan, X.l. and T.h. L, (2008).,*novel direct torque control for permanent magnet synchronous motor drive*, International Conference on Fuzzy Systems and Knowledge Discovery Volume 3, pp. 226 – 230.

Zhong, L., Rahman, M. F., Hu, W.Y., Lim K. W. and Rahman, (1999). M. A. *A Direct Torque Controller for Permanent Magnet Synchronous Motor Drives*, IEEE Transactions on Energy Conversion, Vol. 14, No. 3, pp. 637-642.

Zidani, F., and Nait Said R., (2005). *Direct Torque Control of Induction Motor with Fuzzy Minimization Torque Ripple*", In Journal of Electric Engineering, Vol. 56, pp. 183-188.