DIRECT TORQUE CONTROL OF PMSM USING FUZZY LOGIC WITH PWM

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ABSTRACT

Since its development, Permanent Magnet Synchronous Machines (PMSM) has been used in a number of specific applications. However, in recent years PMSMs have become more attractive due to developments in new materials for permanent magnets and in semiconductor technology for converter design. Recent investigations have proposed some implementations applying the Direct Torque Control (DTC) technique to PMSM motor drives, offering a fast and accurate control. This paper presents a modified DTC scheme, using fuzzy logic with Pulse Wide Modulation (PWM) to improve stator flux and the electric torque by significantly reducing their ripple. The proposed method effectiveness has been verified by computer simulations and experimental tests on a laboratory prototype. These results are compared with the ones obtained with a modified DTC using a PI controlled PWM with current limit.

Keywords: PMSM, DTC, PWM, fuzzy logic.

1 INTRODUCTION

During the last decade, the use of PMSMs has been steadily growing in industrial applications, replacing DC and induction machines. The principal advantages of these machines are their low inertia and high efficiency, power density and reliability. Additionally, PMSMs are ideal for applications where fast and accurate torque control is required.

The use of space vectors and field oriented transformations has been thoroughly developed for applications requiring fast dynamical response [1]. The main limitations of these techniques are due to the transformation dependence upon machine model parameters and the need for a rotor position sensor, increasing the system cost. The use of DTC in PMSMs was proposed in the late nineties [3], [4]; since then there have not been major contributions for improving this control technique. DTC [2] improves the machine controller performance and reduces the influence of parameter variation during its operation, and uses an inverter bridge switching table that sets the converter output depending on the flux/torque errors and flux angle. The bang-bang behaviour produced by the limited number of states available in the inverter bridge (only seven different states) produces a prominent electrical ripple torque. To solve this problem, in this paper a space vector PWM-DTC with fuzzy control is proposed to produce an effect equivalent to the inclusion of additional states in the inverter bridge. This is achieved by altering the resulting amplitude of the stator voltage. The results of the proposed fuzzy-DTC method are compared with the ones obtained using a standard DTC with on-off current limitation, and with a modified DTC using a PI controlled PWM with current limit.

1 DIRECT TORQUE CONTROL

The classical DTC scheme is shown in figure 1. The torque and flux estimator uses the DC converter's voltage and currents, measured directly on the machine terminals.

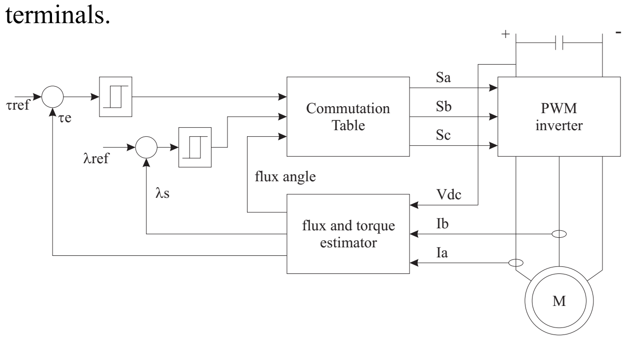


Figure 1 Classical DTC scheme

The flux space vector can be adjusted with the proper selection of one of the seven stator voltage vectors produced by the inverter bridge. The stator flux can be adjusted by increasing or decreasing its magnitude, and rotated clockwise or anticlockwise to obtain the required torque. The seven different voltage space vectors are function of the bridge connectivity, as described in figure 2. Stator flux is obtained integrating the electromotive force in the stator windings using the following relation,

$$\vec{\lambda}_s = \int_0^t \vec{e}_s dt = \int_0^t \left(\vec{v}_s - R_s \vec{i}_s\right) dt \quad (1)$$

In general, using a conservative transformation for the active power, space vectors are defined as:

$$\vec{x}_s=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & e^{j\frac{2\pi}{3}} & e^{j\frac{4\pi}{3}}\end{bmatrix}\cdot\begin{bmatrix}x_{as}(t) & x_{bs}(t) & x_{cs}(t)\end{bmatrix}^t \quad (2)$$

The electric torque is calculated using the estimated flux space vector $\vec{\lambda}$ and the stator current space vector $\vec{i}$, obtained from measurements:

$$T_e=\vec{\lambda}_s\times\vec{i}_s \quad (3)$$

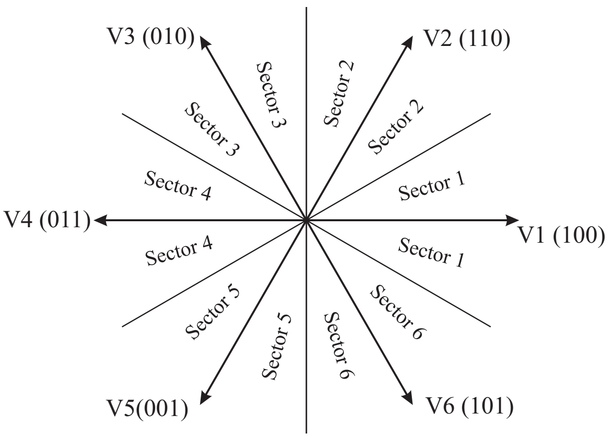


Figure 2 Voltage space vectors as function of the inverter connectivity

The classic DTC technique [2] selects as the new voltage vector the one that maximizes the flux and torque error correction, and minimizes the number of commutations required to change from the old to the new inverter output. Each vector will produce a different change depending on the angular region where stator flux is located. Table 1 shows the DTC switch selection algorithm.

Table 1: DTC commutation table

e Te	e λe	Sector					
		1	2	3	4	5	6
> 0	> 0	V2	V3	V4	V5	V6	V1
> 0	< 0	V3	V4	V5	V6	V1	V2
< 0	> 0	V6	V1	V2	V3	V4	V5
< 0	< 0	V5	V6	V1	V2	V3	V4

3 PERMANENT MAGNET SYNCHRONOUS MACHINE MODEL

A mathematical model of the PMSM on the primitive frame is written in (4), where the symbols used in the model are:

v_A, v_B, v_C : stator voltages,
i_A, i_B, i_C : stator currents,
ω_e : stator frequency,
R_A, R_B, R_C : stator resistance,
L_A, L_B, L_C : stator winding inductance
θ : angle between stator and rotor,
Φ_{IP} : rotor permanent magnet flux,
T_e : electric torque,
T_m : load torque,
J : moment of inertia,
ρ : viscous friction coefficient,
ω_m : mechanical speed,
K_e: back EMF constant.

$$[v(t)]=[R]\cdot[i(t)]+[L]\frac{d}{dt}[i(t)]-\phi_{IP}N_e\begin{bmatrix}\sin(\theta)\\ \sin(\theta-2\pi/3)\\ \sin(\theta-4\pi/3)\end{bmatrix}\omega_m(t) \quad (4)$$

The voltage and current vectors are represented by:

$$[v(t)]=\begin{bmatrix}v_A(t)\\ v_B(t)\\ v_C(t)\end{bmatrix}\ [i(t)]=\begin{bmatrix}i_A(t)\\ i_B(t)\\ i_C(t)\end{bmatrix} \quad (5)$$

The resistance and inductance matrix are:

$$[R]=\begin{bmatrix}R_A & 0 & 0\\ 0 & R_B & 0\\ 0 & 0 & R_C\end{bmatrix}=\begin{bmatrix}R & 0 & 0\\ 0 & R & 0\\ 0 & 0 & R\end{bmatrix} \quad (6)$$

$$[L]=\begin{bmatrix}L_E+L'_E\cos(2\theta) & \frac{1}{2}\left(L_E+L'_E\cos2(\theta+\frac{\pi}{6})\right) & \frac{1}{2}\left(L_E+L'_E\cos2(\theta-\frac{\pi}{6})\right)\\ \frac{1}{2}\left(L_E+L'_E\cos2(\theta+\frac{\pi}{6})\right) & L_E+L'_E\cos2(\theta-\frac{2\pi}{3}) & \frac{1}{2}\left(L_E+L'_E\cos2(\theta-\frac{\pi}{2})\right)\\ \frac{1}{2}\left(L_E+L'_E\cos2(\theta-\frac{\pi}{6})\right) & -\frac{1}{2}\left(L_E+L'_E\cos2(\theta-\frac{\pi}{2})\right) & L_E+L'_E\cos2(\theta-\frac{4\pi}{3})\end{bmatrix} \quad (7)$$

The presence of trigonometric terms in these equations is due to the use of two different coordinate systems, one for the stator and another for the rotor. The angle θ is the relative position between these reference frames. By transforming (4) to the stationary reference frame, a simpler relation can be obtained:

$$\begin{bmatrix}v_\alpha\\ v_\beta\end{bmatrix}=\left\{\begin{bmatrix}R & 0\\ 0 & R\end{bmatrix}+\frac{d}{dt}\left(\begin{bmatrix}L_0 & 0\\ 0 & L_0\end{bmatrix}+L_1\begin{bmatrix}\cos(2\theta) & \sin(2\theta)\\ \sin(2\theta) & -\cos(2\theta)\end{bmatrix}\right)\right\}\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}+K_e\begin{bmatrix}-\sin(2\theta)\\ \cos(2\theta)\end{bmatrix}\omega_m(t) \quad (8)$$

$$v_e=v_\alpha+jv_\beta$$

$$v_e=\left\{Ri_\alpha+\frac{d}{dt}i_\alpha\left(L_0+L_1\cos(2\theta)\right)+\frac{d}{dt}i_\beta L_1\sin(2\theta)-K\sin(2\theta)\omega_m(t)\right\}$$
$$+j\left\{Ri_\beta+\frac{d}{dt}i_\beta\left(L_0-L_1\cos(2\theta)\right)+\frac{d}{dt}i_\alpha L_1\sin(2\theta)+K_e\cos(2\theta)\omega_m(t)\right\} \quad (9)$$

With

$$L_0=\frac{L_d+L_q}{2}$$
$$L_1=\frac{L_d-L_q}{2} \quad (10)$$

Where L_q and L_d are the stator inductances measured in the direct and quadrature directions. For non-salient rotor L_d is equal to L_q because the magnetic path does not change with the angular position. For salient rotor machines L_d is not equal to L_q, and the magnetic path for the flux depends on the rotor's relative position, hence:

$$L_d = L_E + L'_E \cos(2 \cdot 0^\circ) = L_E + L'_E \qquad (11)$$

$$L_q = L_E + L'_E \cos(2 \cdot 90^\circ) = L_E - L'_E \qquad (12)$$

Using (3), the electric torque equation is obtained as:

$$T_e = \lambda_{ed} i_{eq} - \lambda_{eq} i_{ed} \qquad (13)$$

Dynamic equation (14) completes the space vector model of the PMSM:

$$T_e = J \frac{d}{dt} \omega_m(t) + \rho \omega_m(t) + T_m \qquad (14)$$

3 FUZZY INFERENCE SYSTEM

Fuzzy logic has been applied to the standard DTC algorithm to improve the drive performance, reduce ripple in the electromagnetic torque and in the stator currents. The voltage vector to be used is selected from the switching Table 1, and its magnitude is determined with a three dimensional fuzzy inference system, using torque, torque error and stator current magnitude as input variables. Figures 3 and 4 show the membership function for each variable.

The inference systems used with the electric torque and the torque error have a uniform distribution that gives a variable value. The membership function for the fuzzy region labelled "small" (S) is an L shaped membership function, for the fuzzy region labelled "medium" is a triangular membership function, and for the fuzzy region labelled "big" (B) is a gamma shaped membership function. For the current inference system used to limit the stator current there are only two fuzzy regions labelled "small" and "big", and using an L shaped and gamma shaped membership functions respectively.

Table 2: Fuzzy inference system rules

eT \ T	S	M	B
S	S	M	M
M	M	M	B
B	M	B	B

Small Current (S)

eT \ T	S	M	B
S	Z	S	S
M	S	S	M
B	S	S	M

Big Current (B)

The fuzzy inference rules are presented in Table 2. In this table Z stands for Zero, S for Small, M for Medium and B for Big. The rules were heuristically obtained, and had been tested and corrected in simulations.

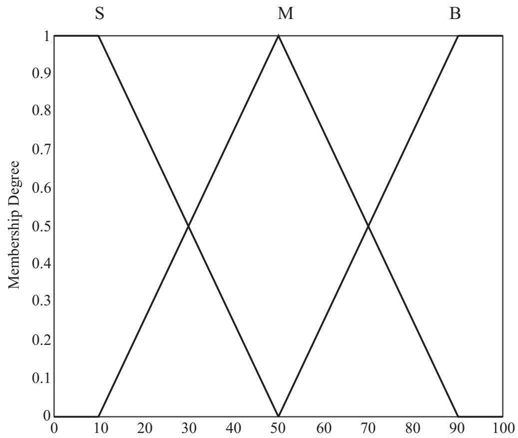


Figure 3 Fuzzy Inference System's discourse universe, torque and torque error

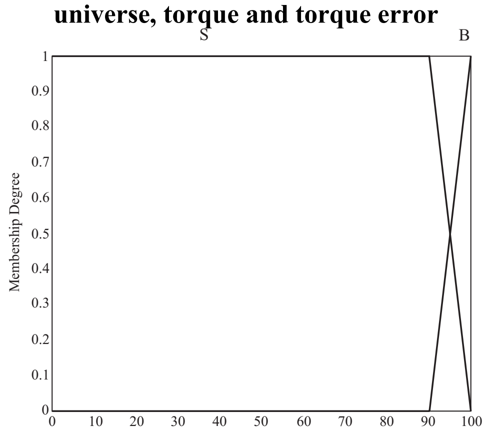


Figure 4 Fuzzy Inference System's discourse universe, stator current magnitude

3 SIMULATIONS

Figure 5 shows the simulation scheme used in this work. The simulations were performed on a digital signal processor ADSP-21061 programmed in C language, using equations (9), (13) and (14). Depending on the magnitude of the torque and flux errors for each stator flux zone, the commutation table selects the next bridge state, and calculates the input voltage applied to the machine model. Torque and flux are obtained directly from the machine model and compared with their corresponding references using two hysteresis comparators. During machine start-up, stator current is limited until the flux gets near its reference value.

A PMSM with the following characteristics was used in the simulations:

Rated power: 5 HP

Rated speed: 1750 RPM
Rated current: 8.4 Amps RMS
Rated Ke: 0,169 V/RPM
A nominal 640 V DC-link was assumed in the simulations.

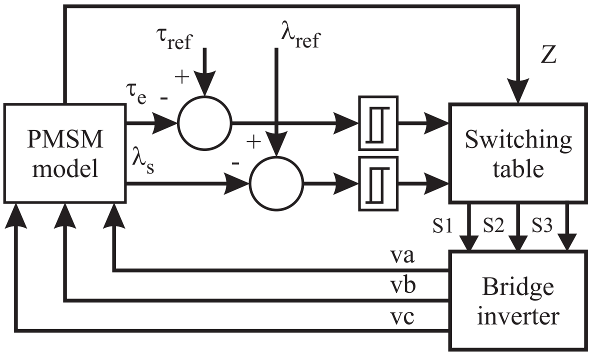


Figure 5. Simulation Scheme

Three different control methods were simulated:

(a) Standard DTC with on-off current limit.
The simulation results obtained with this method are shown in Figure 6. In this case errors in torque or flux are corrected by applying the full amplitude of the selected voltage vector, regardless of the actual error amplitude. This step change in the applied voltage causes prominent torque and flux ripple, and these oscillations are reflected on the stator currents.

(b) Modified DTC with PI controlled PWM current limit.
The simulation results obtained with this method are shown in Figure 7. The amplitude of the selected voltage vector is modulated by the PI controller as a function of error amplitude, avoiding the big step changes produced in the standard DTC scheme. Ripple in both torque and flux are greatly reduced when compared with the previous method.

(c) Proposed Modified fuzzy DTC with inference based current limit.
The results obtained in this simulation are shown in Figure 8. The selected voltage vector has been modulated by the fuzzy controller. As can be seen, the results here are very similar to the ones produced in case (b), but actual control implementation is much simpler.

4 EXPERIMENTAL RESULTS

Once the proposed modified fuzzy DTC with inference based current limit PMSM control scheme was validated by the simulation results, an experimental set-up using PLATFORM III [6] and a PMSM motor with the same motor parameters used in the simulation was employed to test the three control schemes previously considered in the computer simulations.

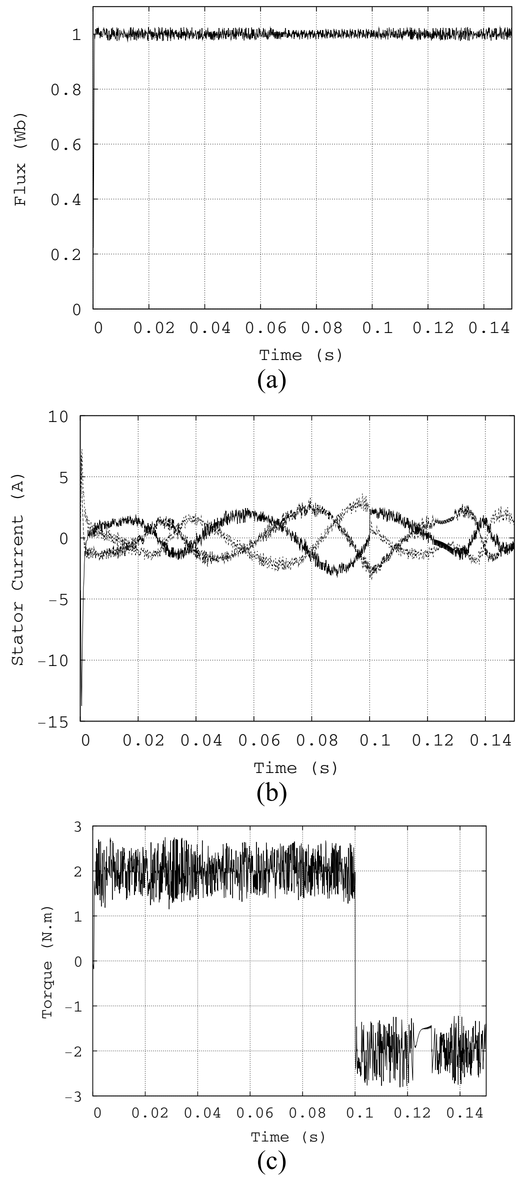
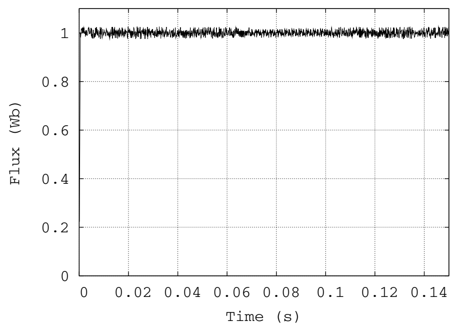


Figure 6 Simulations results for the classical DTC

The experimental tests were performed in conditions equivalent to those considered in the simulations. The experimental results are presented in figures 9 (standard DTC with on-off current limit), 10 (modified DTC with PI controlled PWM current limit) and 11 (modified fuzzy DTC with inference based on current limit).

As expected from theory and simulations, the Standard DTC with on-off current limit scheme produces in practice a ripple torque equal to almost 50% of the steady-state value. Flux ripple is also present, the stator currents reach an initial peak value more than five times bigger than their steady-state values, and the steady state current ripple is about 20% of the mean current value.



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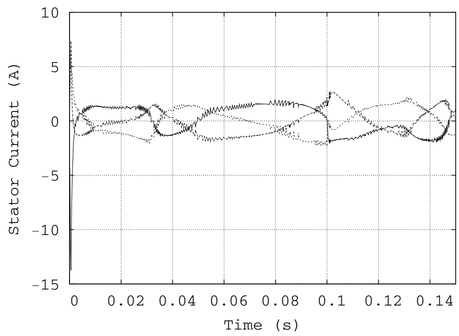

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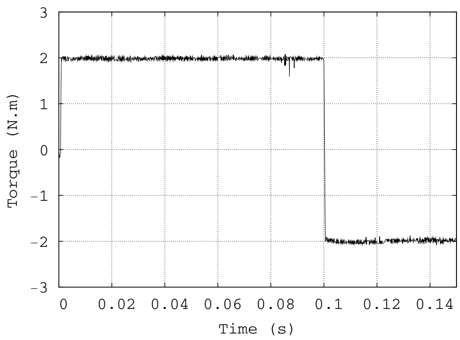
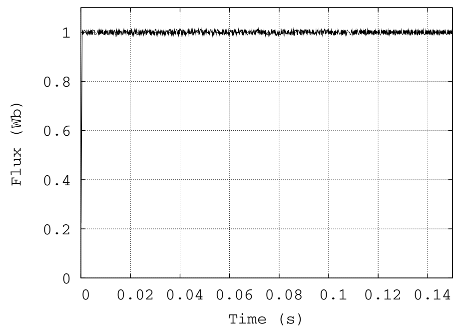


(c)

Figure 7 Simulations results using a DTC-PI controller

As expected, both the modified DTC using PI controlled PWM with current limit and the modified fuzzy DTC with inference based current limit schemes outperform the standard DTC scheme in all accounts: peak initial current is controlled and the torque, flux and stator currents ripples are reduced.

Nevertheless, significant differences between the simulated and the experimental results can be observed in the two modified schemes. In the simulations, the modified DTC with PI controlled PWM current limit scheme produced results that were very similar to those produced by the new modified fuzzy DTC with inference based current limit scheme, hence no clear advantages can be claimed by one over the other. But in the experimental results the new modified fuzzy DTC with inference based current limit scheme clearly out-performs the modified DTC with PI controlled PWM current limit scheme since all the ripple were significantly lower in this case.



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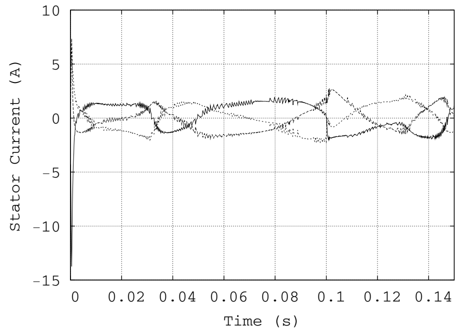

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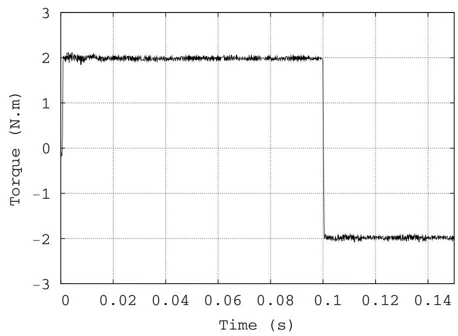

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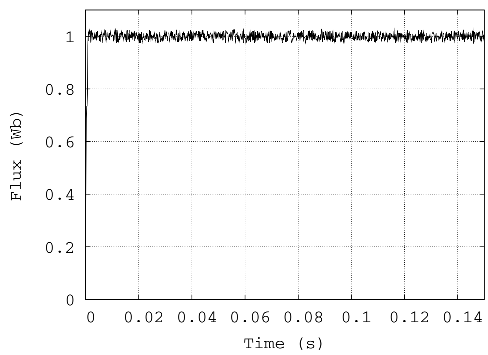
Figure 8 Simulations results with the fuzzy-DTC controller

The biggest reduction was observed in the ripple torque, almost halved in the new method.

The modified fuzzy DTC with inference based current limit scheme improved performance, observed when the experimental results are analysed, is due to the simplifying assumptions in the machine model (constant and precisely know parameter values, linearity, complete symmetry, etc.), hence the precise calculations performed in the PI controller produce precise results in the simulation, where all simplifying hypothesis hold true, but are in practice are affected by errors that degrade the actual system performance. As seen in these experimental tests, a proper selection of the fuzzy parameters can partially compensate for the unavoidable unknowns in any machine model.



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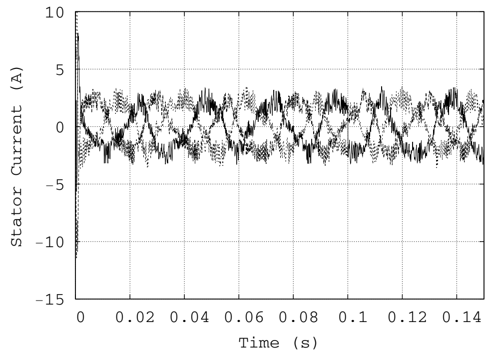

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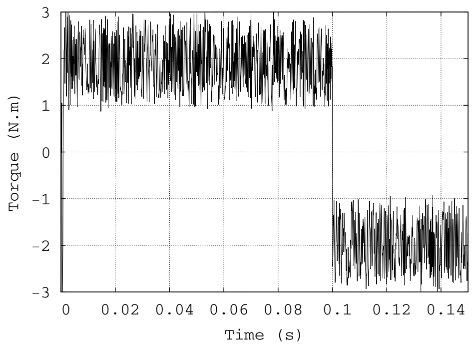

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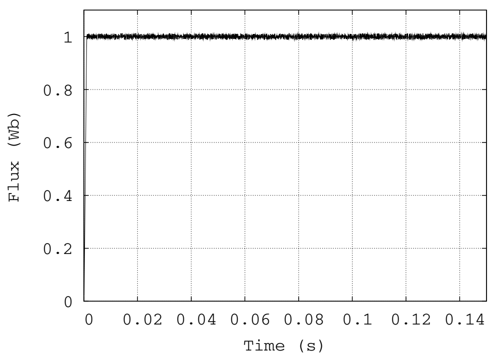
Figure 9 Experimental results using a the classical DTC



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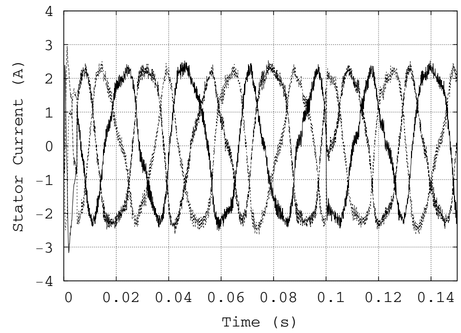

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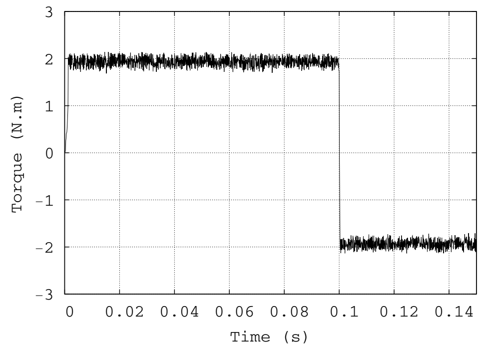

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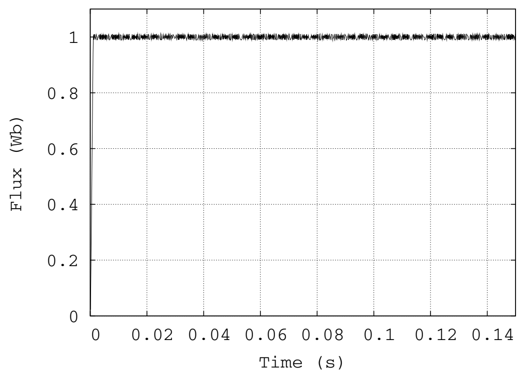
Figure 10 Experimental results using a PI-DTC controller



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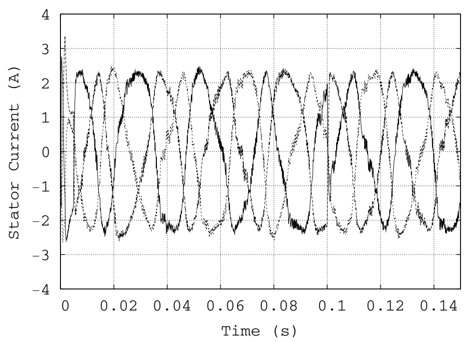

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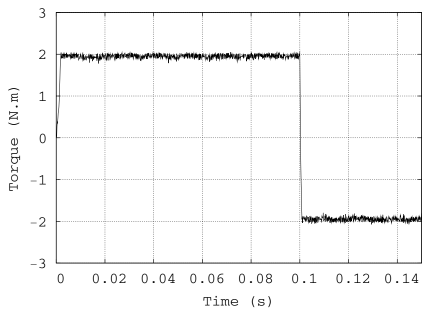

(c)

Figure 11 Experimental results using the proposed fuzzy-DTC controller

5 CONCLUSIONS

The Standard DTC with on-off current limit scheme is a fast and effective way to control electric torque and flux in a PMSM machine. Nevertheless, if no modulation on the vectors selected by the commutation table is used, its behaviour is rather bang-bang like, producing prominent ripple on the generated torque and stator currents, which can cause instability and increase the losses problem in the whole system.

DTC performance can be considerably enhanced if the amplitude of the voltage vector selected is modulated as a function of the error magnitudes. This modulation considerably reduces the ripple produced by DTC, and does not cause big delays on the overall system response but increases the inverter bridge frequency, reducing the efficiency.

Both methods, classical PI and fuzzy logic modulation, show similar capabilities regarding initial peak stator current control, and both are able to reduce torque, flux and stator current ripples.

In the simulations, the modified DTC with PI controlled PWM current limit and the new modified fuzzy DTC with inference based current limit schemes produced almost identical results. Experimental tests showed that the new modified fuzzy DTC with inference based current limit scheme outperformed the modified DTC with PI controlled PWM current limit scheme, producing the best results with the biggest reduction in torque, flux and stator current ripple.

The advantages of the new Modified fuzzy DTC with inference based current limit scheme are due to the fact that fuzzy techniques inherently include the effects of irregularities or non-linearities of the system in their inferences, making this approach more flexible and easier to modify that those based on rigid deterministic models, such as the modified DTC with PI controlled PWM current limit scheme. The implementation of the new Modified fuzzy DTC with inference based current limit scheme is simple, and the increase in computational time are significantly lower that those required to implement the modified DTC with PI controlled PWM current limit scheme.

Overall it can be concluded that the new control technique for PMSM presented in this paper, combining fuzzy logic for PWM and a DTC scheme keeps the robustness, reliability and simplicity of DTC scheme and significantly reduces the torque, flux and current ripples, with a high dynamic response and versatility.

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