Direct Torque Control of a Permanent Magnet Synchronous Motor with Pulse Width Modulation using Fuzzy Logic

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Abstract: - During a long time, permanent magnet synchronous motor (PMSM) were only reserved for some specific applications, however, recently, these machines are becoming more used due to the powerful magnetic characteristic of the rare earth, being used in different areas. Recently several researchers have proposed implementations combining the use of permanent magnet synchronous motor with the direct torque control (DTC) technique offering a quick and precise control. The present work combines these techniques and it proposes the use of pulse width modulation by means of diverse fuzzy logic strategies to reduce the ripple and to improve flux and torque response. Simulations are carried comparing the results obtained with the different fuzzy scheme proposed to solve the problem.

Key-Words: - Permanent magnet synchronous motor, Direct torque control, Pulse width modulation, Fuzzy control.

1 Introduction

During the last decade, permanent magnet synchronous motors have been used widely in the industry to replace classic DC motors and induction machines (IM), like in paper mills, where power ranges are common. The main characteristics of these motors are the low inertia, the high efficiency, power density and reliability. Being this power density higher than one of induction motor with the same ratings due to the no stator power dedicated to the magnetic field production. Also it is designed not only to be more powerful but also with lower mass and lower moment inertia. Due to these advantages, the permanent magnet synchronous motors are ideal for the applications where a quick accurate torque control, low resolution position sensors is required, considering its performance and cost minimization.

For the induction machines, there have been developed methods to control the electromechanical torque in an indirect way using spatial vectors and transformations to the system of oriented field [1]. By means of these techniques it is possible to reproduce the behavior of the classical DC machines. The main limitations of this method are that it depends on the parameters of the machine to carry out the transformations, as well as of a wide capacity of control calculation and the necessity of position sensors for the rotor, increasing the costs of the total system.

The strategy proposed of Direct Torque Control for the induction machines [2], it reduces the dependence of the parameters of the machine and improves considerably the system dynamics and has become an accepted control method beside the field oriented control. The DTC was first applied to asynchronous machines and later to synchronous machine. This technique compares by means of a hysteresis band the flow and the torque with its respective references and it selects form a vectors tables the commutation state of the inverter bridge that will correct the error.

The three-phase inverter bridge has only six active states, which gives to the control system a "bang-bang" behavior with a marked ripple. To solve this problem it has been proved techniques that try to modulate the vector size selected from commutation table by pulse width modulation, being able this to reduce the ripple.

The idea of combining the advantages of DTC in PMSM were presented in the ‘90 [3], [4], and from then many authors have proposed diverse applications to improve this technique.

In this work it is proposed to combine the DTC advantages for the control of PMSM by using pulse width modulation by means of fuzzy logic [5][6], this will produce an inclusion additional states in the inverter bridge the a significant reduction of stator flux and electric torque ripple. The proposed strategies are also compared with a control DTC without pulse width modulation, "bang-bang", as well as with a DTC control using a classical PI controller for the pulse width modulation.

2 The Direct Torque Control

Takahashi and Noguchi [2] suggested a new technique of AC motor control in 1986. They proposed to control the stator flux linkage and the torque directly, not via controlling the stator current. This was possible by controlling the power switches directly using the outputs of hysteresis comparators for the torque and the module of the stator flux linkage and selecting an appropriate voltage vector from a preset switching table.

The direct torque control (DTC) has become an accepted vector control method beside the current vector control. The DTC was applied at the beginning to asynchronous machines and then to synchronous machine. This is based on the direct calculus of the instantaneous torque from the measurement of the voltages and currents at the machine terminals. Figure 1 shows a classic scheme of DTC control.

The stator flux links are obtained integrating the electromotive forces of the stator winding, forming a vector that is rotating around the rotor of the machine, that it can be modified in magnitude and phase depending on the applied voltage vector:

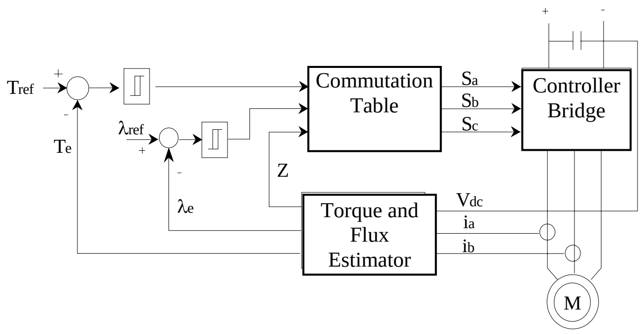


Fig. 1. DTC basic diagram

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

where:

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

The electric torque is obtained from the flux an current as:

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

A three-phase bridge inverter produces eight different states, each one of which it defines a voltage vector applied to the stator winding that are able to modify the flux vector in magnitude and in phase, modifying this way the magnitude of the generated electric torque. The voltage vector plane is divided into six sectors so that each voltage vector divides each region into two equal parts. In figure 2 these vectors are shown, where six active vectors of same magnitude are presented and two remaining vectors are zero.

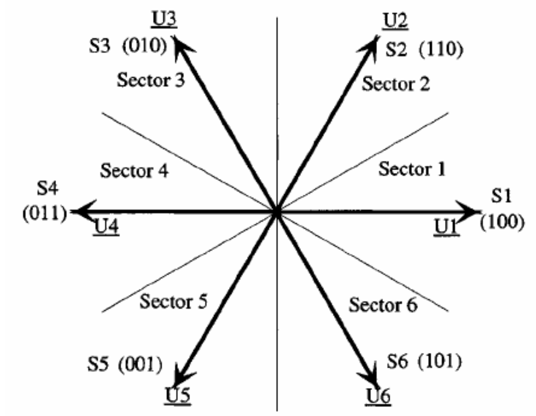


Fig. 2. Spatial voltage vectors as function of the state inverter

The DTC technique 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 1 is presented the DTC selection algorithm.

Table 1. DTC commutation table

e Te	e λe	S1	S2	S3	S4	S5	S6
> 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

Based on this, several techniques can be developed to control the torque, induction motors speed [7] or PMSM [3], [4].

Some of the advantages that the DTC are the simple control structure, the exact machine model is not required, it reduces the influence of parameter variation, transformation frame is not needed, high dynamic response, less complex algorithm and rotor position sensor is not required, as it can be noticed, fuzzy logic fits perfectly to be used due the possibilities of uncertainties on the model or rotor position. Also can be mentioned the disadvantages like high start-up current, bang-bang behavior and prominent ripple torque.

3 Permanent Magnet Synchronous Motor Model

The permanent magnet synchronous motor is a rotating electric machine where the stator is a classic three phase stator, it is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. The most common applications are servo drives in power ranges from a few watts to some kilowatts.

The generated stator flux, which is approximately sinusoidal, together with the rotor flux, which is generated by a rotor magnet, defines the torque, and thus speed, of the motor. Figure 3 shows the variables of a PMSM

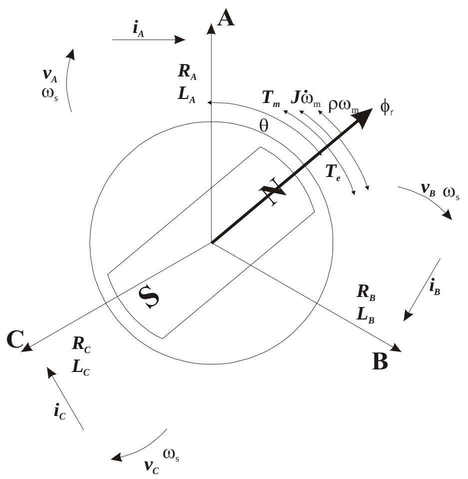


Fig. 3. Basic diagram of PMSM

Where the variables are defined as::

v_A, v_B, v_C:: stator voltage.

i_A, i_B, i_C:: stator current.

ω_e: stator currents and voltages angular frequency.

R_A, R_B, R_C: stator resistances.

L_A, L_B, L_C: stator winding inductances.

θ: angular distance between rotor and stator,

Φ_{IP}: flux of the rotor permanent magnet.

T_e: electric torque produced by the field interaction.

T_m: mechanical torque.

J: rotor inertia.

ρ.: friction coefficient.

ω_m: motor angular speed.

A mathematical model of PMSM is given in (4)

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

Then the vectors for the voltage and current are given by:

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

Also the matrixes for inductance and resistance can be written as:

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

$$[R] = \begin{bmatrix}R_A & 0 & 0\\ 0 & R_B & 0\\ 0 & 0 & R_C\end{bmatrix} = \begin{bmatrix}R & 0 & 0\\ 0 & R & 0\\ 0 & 0 & R\end{bmatrix} \quad (7)$$

Becoming (4) as a spatial vectors equation located in the stationary reference, it is obtained:

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

with

$$L_0 = \frac{L_d + L_q}{2}$$

$$L_1 = \frac{L_d - L_q}{2}$$

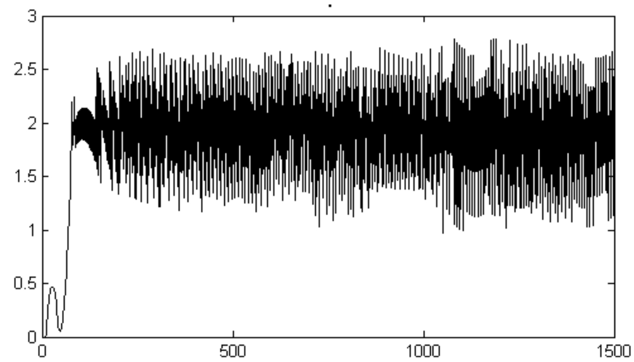
Where Lq and Ld are the stator inductances measured in the direct and quadrature directions. For non-salient rotor Ld is equal to Lq because the magnetic path does not change with the angular position. For salient rotor machines Ld is not equal to Lq, and the magnetic path for the flux depends on the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

$$\frac{d}{dt}\omega_R = \frac{1}{J}(T_e - T_L) \quad (9)$$

Equations (1), (3), (5) and (6) describe the synchronous machine model used for the control system simulations here outlined. The experimental tests were carried out in a machine of 5 HP, 1750 RPM, 640 Vdc BUS, 8.4 Amps RMS and Ke = 169 V / KRPM.

In Figure 4 can be observed the results of a simulation of DTC applied to the Permanent Magnet Synchronous Machine, without any kind of modulation.

To improve the control dynamic response to reduce the ripple, several fuzzy strategies are presented in this work.



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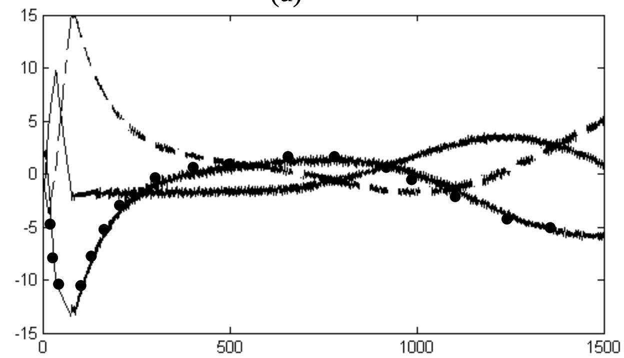

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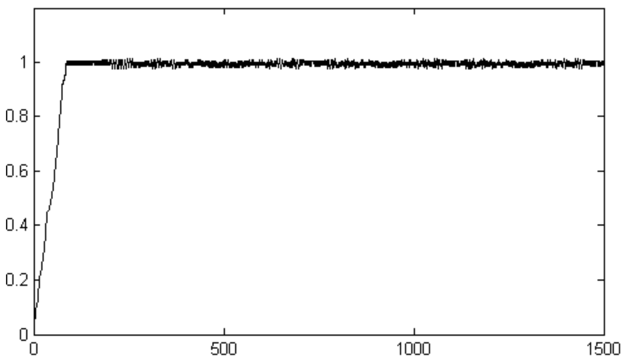


(c)

Fig 4. Simulation of DTC applied to a SMPM without modulation (a) Torque. (b) Currents. (c) Flux.

4 PD Fuzzy Controller

There will be applied four different schemes using fuzzy logic to the permanent magnet synchronous motor.

The first strategy to be implemented is PD fuzzy controller as is shown in Figure 5.

The system fulfills the equations (10) and (11).

$$u(k) = f\left(e(k), \Delta e(k)\right) \quad (10)$$

$$u(k) = K_P e(k) + K_D \Delta e(k) \quad (11)$$

The variable to be controlled is the torque (*T*), therefore the fuzzy variables considered for the inference system are the torque error (*eT*) and its variation (*ΔeT*) , Figure 6 shows the membership function of the variables. Table 2 shows rules-base for the controller.

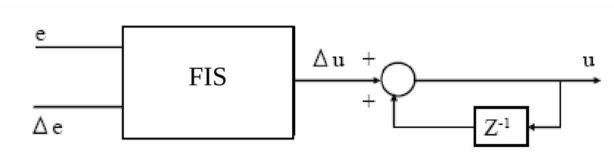
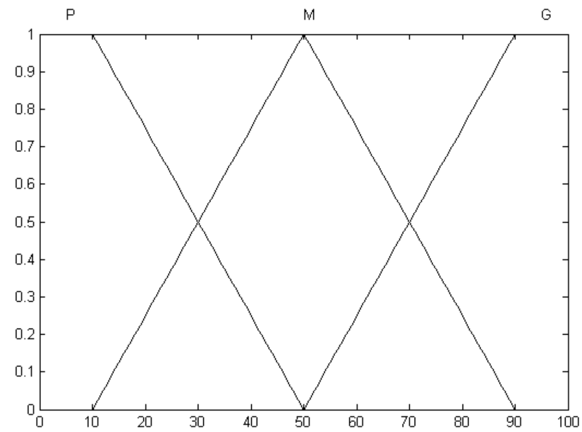


Fig. 5. PD Fuzzy Controller



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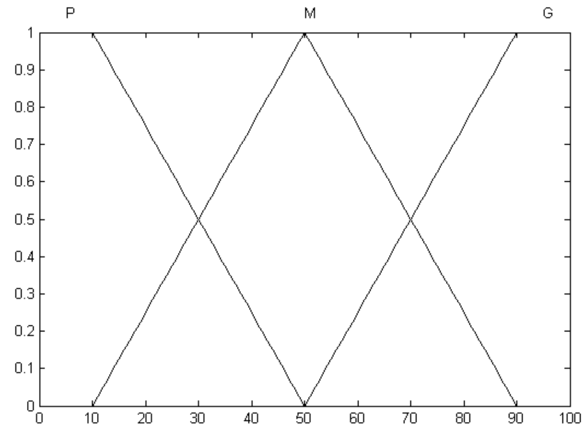


(b)

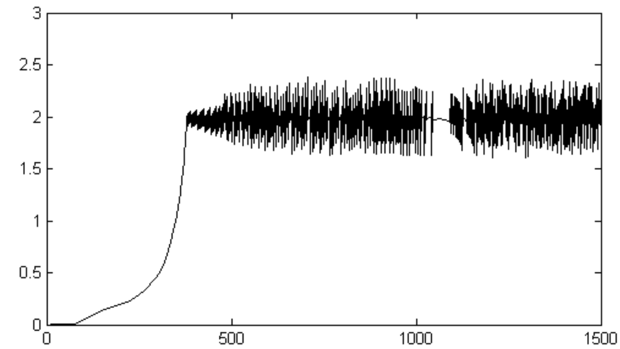
Fig.6. Membership functions (a) Torque error (b) Torque error variation.

It should be remembered that the manipulated variable will be the input voltage vector then depending if the correction needed for the error is positive or negative and on the area in which is it, one of the eight possible vectors will select to correct the error, therefore, the fuzzy inference system can only consider positive corrections, because the negative corrections correspond to another of the commutation vectors of the table.

Table 2. Fuzzy Controller Rule-base.

ΔeT \ eT	**S**	**M**	**B**
S	Z	S	M
M	P	M	B
B	M	B	B

Then, simulating the fuzzy controller using Mandani inference system to DTC of the Permanent magnet Synchronous Machine, the system response can be observed in Figure 7.



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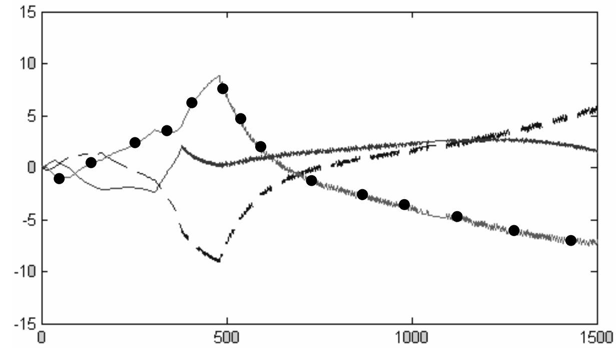

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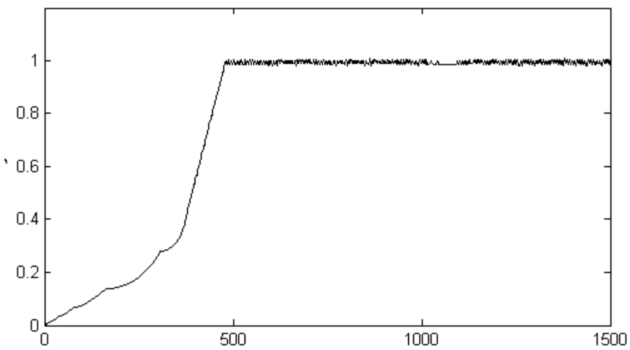

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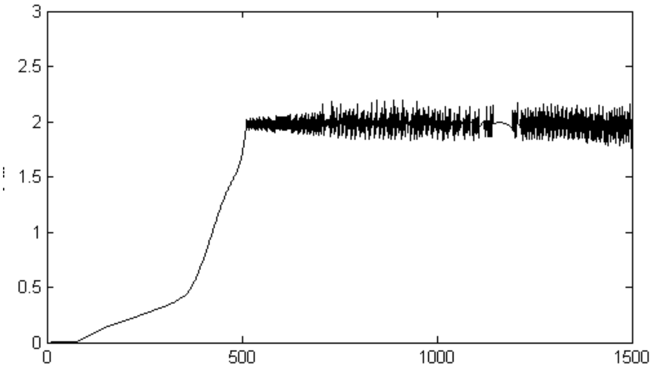
Fig 7. Simulation of DTC with a Mandani inference system to SMPM. (a) Torque. (b) Currents. (c) Flux.

Although the system dynamic response has a small delay, the system has an improvement on the reduction of the electrical torque ripple, it can be also observed an improvement on the three phase current and in the flux links.

After a Takagi-Sugeno inference system is applied to the same system and plant, the simulation results are presented in the Figure 8.

The output variables ripple improve considerably, however, the delay of the dynamic system response becomes bigger. Either this, the response is satisfactory and can be used as a base for other strategies.



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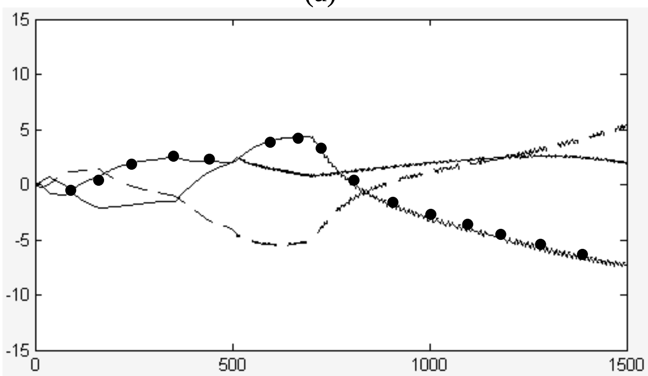

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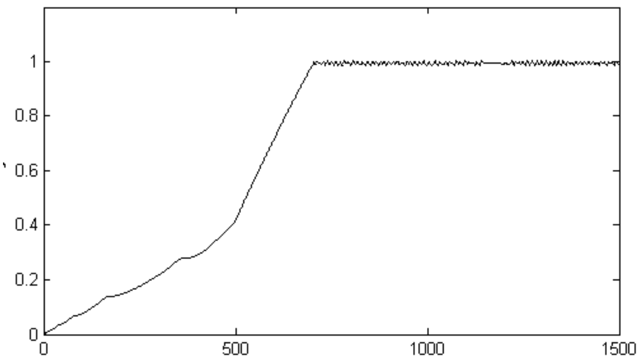


(c)

Fig. 8. Simulation of DTC with a Takagi-Sugeno inference system to SMPM. (a) Torque. (b) Currents. (c) Flux.

5 PI Controller Adjusted by a Fuzzy Inference System

Next, it is proposed and implemented a strategy with a classical PI controller where its proportional gain (Kp) is adjusted by a fuzzy Takagi-Sugeno inference system. The outline scheme is shown Figure 9.

The rule-base used in this case is presented in Table 3 and Figure 10 shows the system response with this strategy.

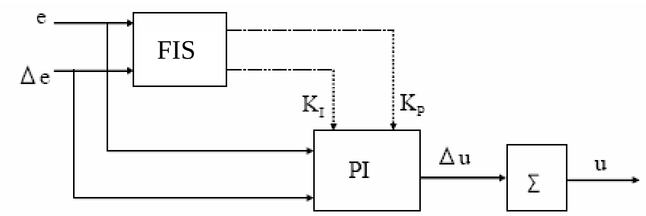


Fig. 9. Outline scheme of the PI Controller adjusted by a FIS.

Table 3. Rule-base tables for the Fuzzy Controller

ΔeT \ eT	S	M	B
S	Z	S	M
M	S	M	B
B	M	B	B

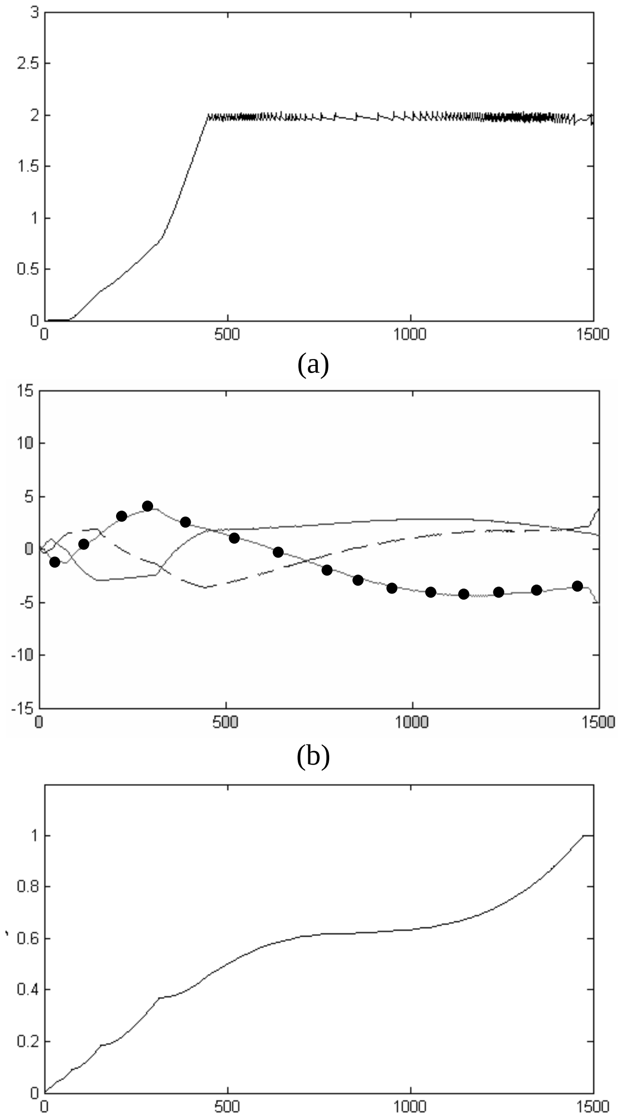
6 Fuzzy Controller Parallel to a Classic PI Controller

The third proposed control strategy can be shown in Figure 11. This type of controller tries to adjust or compensate the output produced by the classical PI controller by using fuzzy controller that corrects the existent error.

Although the flux links have a considerable delay, the electric torque response is improved, the ripples of the three variables (torque, current and flux) that are being considered, have reduced considerably, being made almost imperceptible.

In Figure 12 can be observed the simulation results carried out with this strategy.

With this strategy, there were obtained satisfactory results, the response is faster than the case where only a PI controller was used and also the ripple is smaller than the case where the fuzzy controller was used alone. The torque falls because the system is working without load and then the speed increases without limit.



(a) (b) (c)

Fig 10. Simulation of DTC with a PI Controller adjusted with a FIS to SMPM. (a) Torque (b) Currents (c) Flux.

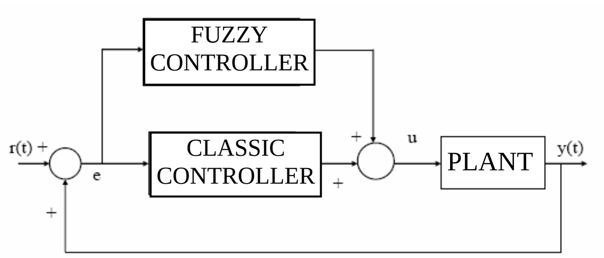
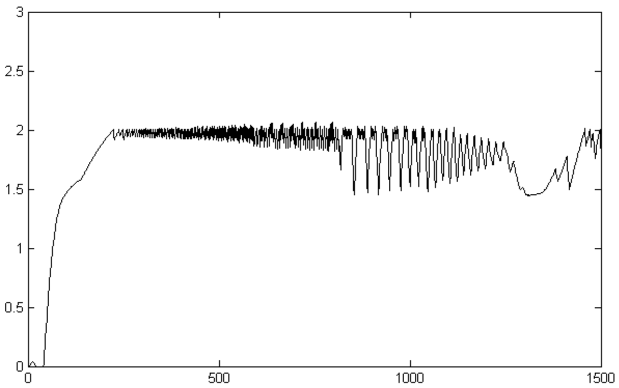


Fig 11. Scheme of the proposed control system.

7 Fuzzy Controller using a Reference Model

The last structure presented here, it is used to force the system output to follow a specific reference, then the closed loop can be modified by adding the output of a fuzzy inference system to the output of a classical PI controller to generate the input control signal to the plant. The overall control system can be observed in Figure 13.

Figure 14 shows the signal generated by the reference model to be followed by the system and in Figure 15 are presented the simulations results when this strategy is applied.



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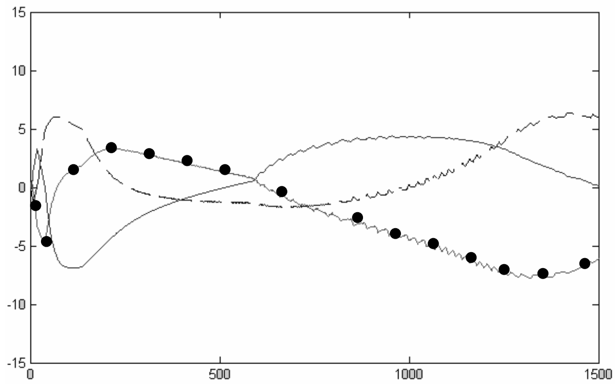

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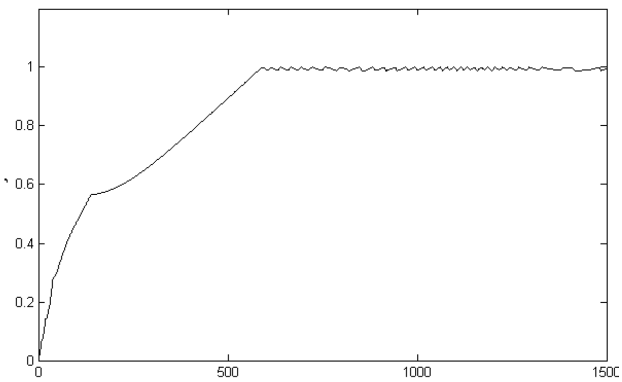

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Fig 12. Simulation of DTC with the proposed control strategy to SMPM. (a) Torque. (b) Currents. (c) Flux.

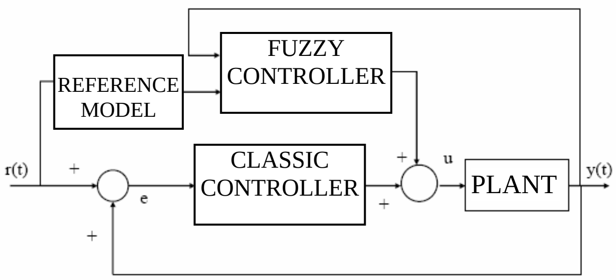


Fig. 13. Block diagram of the reference model using a fuzzy inference system.

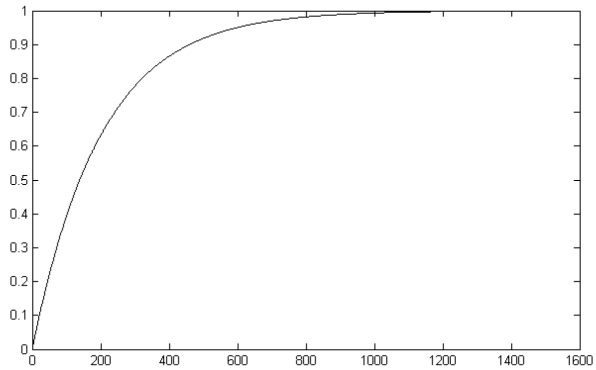


Fig 14. Signal generated by the reference model.

The dynamic response given by the electric torque of the machine has some similarities with the reference signal, however, the difference is notorious, then this method of error correction becomes effectiveness due it is not possible to apply negative voltage vectors in the technique of DTC. Therefore, it is not recommended to use this method to the closed loop system.

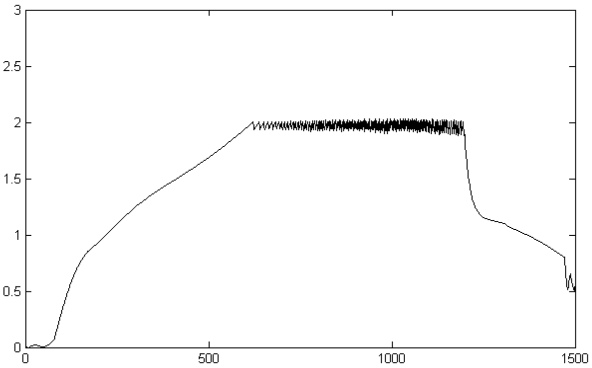
4 Conclusion

It was proposed and implemented an efficiently strategy of control DTC combined with pulse width modulation (PWM) applied to a PMSM. The precision and simplicity of DTC is complemented with fuzzy techniques allowing modulating the voltage vectors applied to SMPM, then improving the system dynamic response, system ripple and therefore reducing the quantity of harmonic presented in the line.

The PD fuzzy controller applied to the system produced considerable improvements in the system response, however, introduces a delay to the system dynamics that should be analyzed to avoid it. Either this, the results assure a better SMPM behavior. The selected fuzzy inference system will depend on the system characteristics and on the wanted response. For this plant, it was proven that either the system dynamics becomes slower, Takagui-Sugeno inference system offers better benefits than Mandani inference system.

The best results were obtained when it was implemented an strategy to adjust the Kp gain of a PI controller by using a fuzzy inference system to prove the behavior of the DTC system applied to SMPM, in this case the ripple was almost imperceptible.

It is not possible to apply a reference model strategy with a fuzzy inference system to control the error of the system due its limitations.



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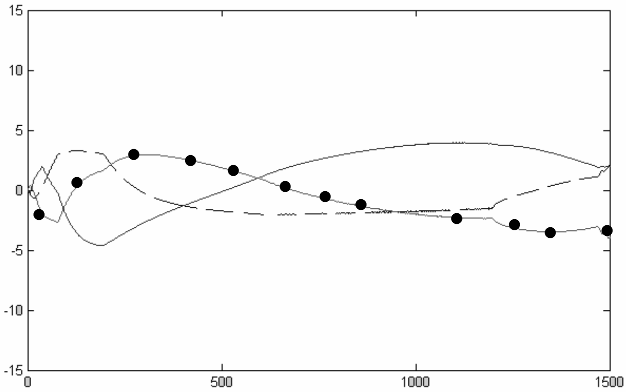

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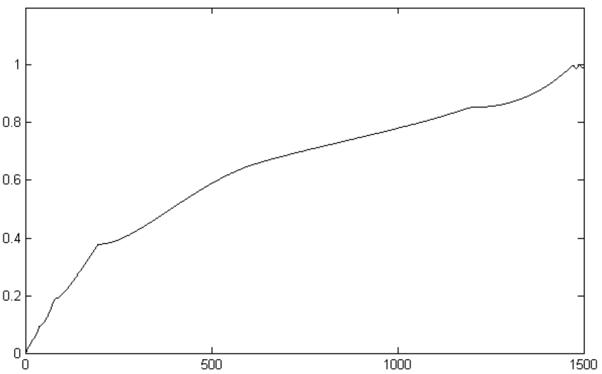

(c)

Fig 15. Simulation of DTC with a FIS using a reference model to SMPM. (a) Torque. (b) Currents. (c) Flux.

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