

FUZZY DIRECT TORQUE CONTROL OF PMSM

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Abstract: *The direct torque control (DTC) suffers in the low speeds due to the effect of changes in stator resistance on the flux measurements. To improve the system performance (PMSM) at low speeds a fuzzy resistance estimator is proposed to eliminate the error due to change in stator resistance. The stator current error caused by the change in stator resistance of the induction at constant flux and torque commands is used by the fuzzy estimator for correcting the stator resistance used by the controller to match machine resistance. The fuzzy controller computation speed is a key factor to obtain fast torque control. To enable DTC to be applied at low speed while the stator flux estimation compensation has been developed. The simulation results show the effectiveness of the new control strategy.*

Key words: *Permanent Magnet Synchronous Machine, direct Torque Control, fuzzy controllers and fuzzy estimators.*

1. Introduction

For a long time, permanent magnet synchronous motors (PMSM) were only applied in some particular application fields, e.g. for servo drives. However, in the recent years PMSMs gained increasing importance in novel domains like in automotive hybrid drive trains or wind power plants as a result of powerful rare earth magnets. Characteristic of these new applications is the borderline design to aim for highest utilization of torque and power. The behaviour of these motors may differ considerably from the well known servo motor. Particularly, the often favoured interior magnet motor exhibits an asymmetrical and strongly nonlinear behaviour, which is not covered by the standard control theory of three-phase drives. Furthermore, modern applications often require a wide constant power range which results in extreme flux weakening ratios up to 1:5 or even more, which was unheard of with former PMSM. These items have carefully to be considered during control design, but they touch also such matters as converter protection schemes and the risk of irreversible demagnetization.

Due to its high torque to inertia ration, superior power density, high efficiency and many other advantages, the PMSM is the most widely used electrical motor in industrial applications.

The most commonly used method of control for PMSM is field oriented control (FOC) [1]. The FOC represents the attempt to reproduce, for a PMSM, a dynamical behaviour similar to that of the dc machine, characterized by the fact that developed torque is proportional to the modulus of the stator current: to reach this objective, it is necessary to keep the rotor flux value constantly equal to the nominal value, so that, contemporarily, the optimal magnetic circuits exploitation guarantees the maximum power efficiency [2]. Regulation of currents i_d and i_q in closed loops leads indirectly to control of the motor developed torque.

After FOC, the Direct Torque Control (DTC), proposed by Depenbrock and Takahashi [3:11], has been drawing increasing interest. The name DTC is derived from the fact that, on the basis of the errors between the reference and the estimated values of the torque and flux it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits [3]. Current regulators followed by pulse width modulation (PWM) or hysteresis comparators and coordinate transformations to and from one of the rotating reference frames are not used in DTC systems figure (fig.1). DTC controller is less sensible to the parameter detuning in comparison with FOC and it allows good torque control in steady state and transient operating conditions. Nevertheless DTC presents some drawbacks such as difficulty to control torque and flux at very low speed, high noise level at low speed, high current and torque ripple, and variable switching frequency behaviour [2].

The DTC has the advantage of being independent of the parameters of the machine except for stator

The diagram illustrates the control architecture for a Permanent Magnet Synchronous Motor (PMSM). It starts with a 'Continue voltage' source connected to a 'Voltage inverter'. The inverter's output is split: one path goes to the PMSM, and another path provides U_{dc} to the 'Concordia Transformation With Filtering' block. The PMSM also provides current signals I_c, I_b, I_a to the Concordia block. The Concordia block performs transformation and filtering, outputting $V_\alpha, V_\beta, I_\alpha, I_\beta$ to the 'Flux Estimator'. The Flux Estimator calculates the flux components $\varphi_\alpha, \varphi_\beta$ and provides them to the 'Electromagnetic Torque Estimator'. The torque estimator outputs Γ_{elm} , which is summed with a reference torque Γ_{ref} at a summing junction. The resulting reference torque Γ_{ref} is fed into the 'Commutation Table'. The commutation table also receives $ccpl$ and N as inputs and outputs $cflx$ to the voltage inverter. The voltage inverter also receives S_a, S_b, S_c as feedback signals from the Concordia block. A feedback loop for flux is shown where φ_{ref} and φ_s are compared at a multiplier to produce φ_s , which is then fed into the Flux Estimator.

Fuzzy logic constitutes an interesting alternative approach today. Several advantages are recognized to him: reasoning close to the natural reasoning of the human operator, controls systems to be controlled with a nonlinear behaviour, obtaining better dynamic services and its intrinsic qualities of robustness [9]. This article is devoted the establishment of the direct torque control of the PMSM using a fuzzy controller with a minimal number of rules, and a fuzzy estimator of the stator resistance of the machine in order to correct the value used in the estimator of stator flux. The results of digital simulations obtained make it possible to evaluate the very satisfactory performances of this approach.

The PMSM electrical model, can be written in the rotor reference frame as follows [4:7][10] and [11]:

$$\begin{cases} \varphi_d = L_d \dot{i}_d + \varphi_\gamma \\ \varphi_q = L_q \dot{i}_q \end{cases} \quad (1)$$

$$\begin{cases} v_d = R_s i_d + P\varphi_d - \varpi_\gamma \varphi_q \\ v_q = R_s i_q + P\varphi_q + \varpi_\gamma \varphi_d \end{cases} \quad (2)$$

$$\Gamma = P(\varphi_d \mathbf{i}_q - \varphi_q \mathbf{i}_d) \quad (3)$$

R_s : Stator armature resistance;

The direct torque control (DTC) based on the stator flux orientation, uses the instantaneous values of the voltage vector. A three-phase inverter can provide eight vectors basic voltages instantaneous, among which two are null [3:5]. These vectors are selected starting from a commutation table according to the errors respectively of flux, torque and position of stator vector flux. In this technique, we do not need more the position of the rotor to choose the voltage vector; this characteristic defines the DTC as a method adapted well for control without mechanical sensor of the alternative current machines.

To fix the amplitude of stator flux, the end of the vector flux must have a circular trajectory. For that, the voltage vector applied must always be perpendicular to the vector flux. But like there are only eight vectors, one is obliged to accept a variation of amplitude around the desired fixed value. This is carried out by hysteresis comparators for flux and torque. Thus by selecting an adapted vector, the end of flux can be controlled and moved so as to maintain the amplitude of the vector flux inside a certain fork. The choice of Vs depends on the desired variation for the module of flux but also of the desired evolution for its speed and consequently for the torque.

We generally delimit the referential space in the fixed reference frame (stator) by decomposing it into six symmetrical zones compared to the directions of the non null vectors of voltage. The flux vector position in these zones is given from these components. When the vector flux is in a numbered zone i, the two vectors V_i et V_{i+3} have the most important component of flux. In more their effect on the torque depends on the position of flux vector in that zone (ambiguity on the torque). Thus they are never applied. The control of flux and torque is ensured by selecting one of the four non null vectors or one of the null vectors. The selected voltage vector role is described on the figure (fig.2).

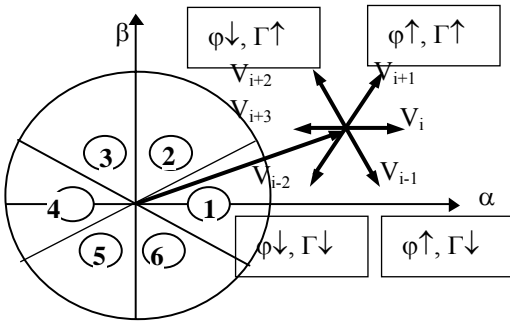


Fig. 2: Voltage space vectors and selection according to the first zone

Several tables of commutation can be used to control the torque. Each table influences the behaviour of the machine in term of torque, of currents undulation (ripples), of commutations frequency and possibilities of operation in two or four quadrants. The following table shows four possible commutations tables.

The electromagnetic torque is controlled by controlling the amplitude and the speed of the stator vector flux also when one applies null vectors voltage to decrease the amplitude of this last; it remains in its position in the case of an asynchronous machine since

stator flux is only determined by the stator voltage. On the other hand in the case of the PMSM, stator flux φ_s continuous to change even when the null vector voltage is applied because the permanent magnets turn with the rotor.

Tab.1: Strategies and possible commutations

	$\Gamma_e \uparrow$ $\varphi_s \uparrow$	$\Gamma_e \uparrow$ $\varphi_s \downarrow$	$\Gamma_e \downarrow$ $\varphi_s \uparrow$	$\Gamma_e \downarrow$ $\varphi_s \downarrow$
Strategy 1	V_{i+1}	V_{i+2}	V_0, V_7	V_0, V_7
Strategy 2	V_{i+1}	V_{i+2}	V_i	V_0, V_7
Strategy 3	V_{i+1}	V_{i+2}	V_i	V_{i+3}
Strategy 4	V_{i+1}	V_{i+2}	V_{i-1}	V_{i-2}

Consequently, the null vectors voltage are not used in the DTC of the PMSM. In other words, stator flux must be always moving compared to rotor flux. We have chosen the 4th strategy and its commutations table as follows:

Tab.2: The 4th strategy and its commutations

Torque	Flux	1	2	3	4	5	6
cpl = 1	Cf=1	V_2	V_3	V_4	V_5	V_6	V_1
	Cf=0	V_3	V_4	V_5	V_6	V_1	V_2
cpl = 0	Cf=1	V_6	V_1	V_2	V_3	V_4	V_5
	Cf=0	V_5	V_6	V_1	V_2	V_3	V_4

4. Fuzzy Direct Torque Control (FDTC)

In the conventional direct torque control, torque and flux errors are directly used to choose the commutation state of the inverter voltage switches without any distinction between a very large or relatively small error. The terms “very large” or “very small” are terms vague and inaccurate which contain a fuzzy concept. It thus seems natural to use a fuzzy controller [8, 9].

The first idea to use a fuzzy controller to establish the DTC resulted in using a complete table of 180 fuzzy rules (with 12 fuzzy sets for the flux stator vector position, 5 fuzzy sets for the torque variation and fuzzy sets for stator flux variation). It can be reduced to an incomplete table of 132 fuzzy rules in the case of the PMSM by eliminating the null vectors but there remains however a difficulty of time real implementation that the DTC of the PMSM requires sampling period very small from 10 to 40 μs . To reduce the computing time, we propose an original approach which makes it possible to reduce the

number fuzzy rules to 22 rules. Thus the proposed approach proves that is the faster one and need less time than the referential approach (fig. 3).

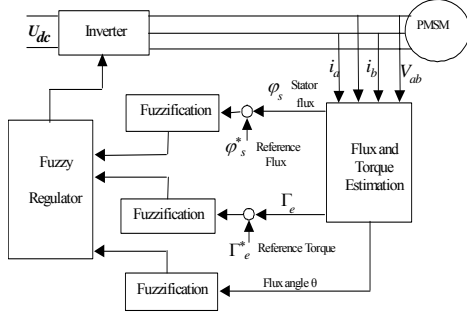


Fig.3: DTC Fuzzy controller for PMSM

Figure (fig. 3) presents the proposed fuzzy controller structure to establish the classical DTC. The studied fuzzy controller has three fuzzy states variables in entry and one control variable out to realise a control with constant torque and flux.

Each variable is represented by fuzzy sets. The fuzzy sets number for each variable is selected to obtain a powerful and consistent control with a minimal fuzzy rules number.

- The first fuzzy variable $E\varphi$, composed of three fuzzy sets, is the difference between the reference flux amplitude and the estimated one:

$$E\varphi = \varphi^* - |\varphi| \quad (9)$$

- The second fuzzy variable E_{Te} , consisted of five fuzzy sets, is the difference between the reference torque and the estimated torque:

$$E_{Te} = T_e^* - T_e \quad (10)$$

- The stator flux angle in our approach covers only the part $[0, \pi/6]$ of the universe and either $[0, 2\pi]$ as in the case of the base of 180 fuzzy rules [8, 9].

While basing itself on the symmetry of the vectors voltage and stator flux angle, we define a transformation which converts angle θ' from $[0, 2\pi]$ domain to θ from $[0, \pi/6]$ domain :

$$\theta = \text{rem}(\theta') \quad (11)$$

Where: θ is the input angle of the fuzzy regulator and the operator rem means remainder of division.

By using two fuzzy subsets for stator flux angle, we obtain an incomplete table of 22 fuzzy rules (tab.3).

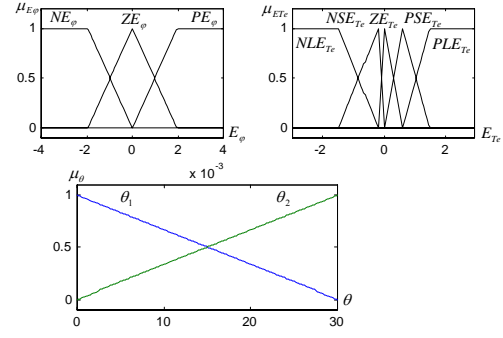


Fig.4: Membership functions distribution of input fuzzy variables

Figure (4), represents the distribution of the fuzzy sets for this base of 22 fuzzy rules. Finally, the vector voltage to be applied is given by the sum of the inferred output of the fuzzy controller and the sector number where the vector stator flux is.

Tab.3: Fuzzy rules of PMSM fuzzy controller

$E \varphi$		θ_1		
		P	Z	N
E_{Te}	PL	1	2	2
	PS	1	2	3
	ZE	-	-	-
	NS	0	-	4
	NL	0	5	5

$E \varphi$		θ_2		
		P	Z	N
E_{Te}	PL	1	1	2
	PS	1	2	2
	ZE	-	-	-
	NS	5	-	4
	NL	5	5	4

5. Fuzzy stator resistance Estimator

The proposed estimator here, is designed to determine the variations of the real stator resistance of the machine during operation. This estimator observes the stator current vector and if a change is detected then a corresponding change of stator resistance is produced. This estimator is designed starting from the principles of fuzzy logic. It has for inputs the error of the current and the variation of the error and as an output the variation of stator resistance.

The figure (fig.5) represents the structure of the fuzzy estimator of resistance. The error of the stator current and the variation of the current error are used like inputs of this estimator.

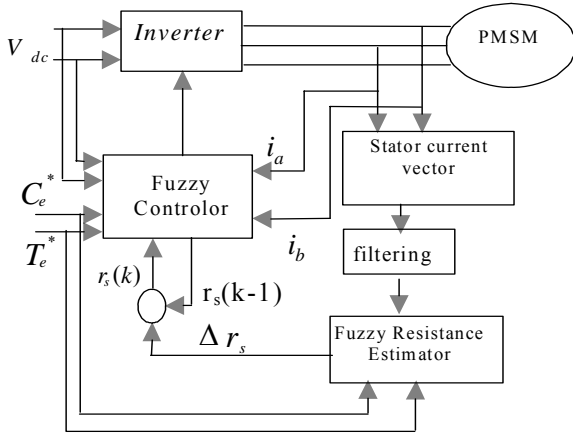


Fig.5: FDCT with Fuzzy stator resistance estimator

The functions of membership of the various variables of the fuzzy rules are represented on the figure (fig.6).

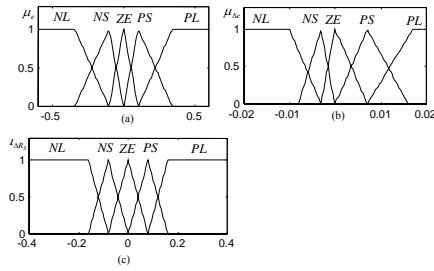


Fig.6: Membership functions of used variables

The fuzzy rules are given by using the current stator response of the synchronous machine for a change of stator resistance. We obtain a table of 25 fuzzy rules with a symmetrical distribution (tab.4).

Tab.4: Fuzzy rules for stator resistance estimator

$e / \Delta e$	PL	PS	ZE	NS	NL
PL	PL	PL	PL	PS	ZE
PS	PL	PL	PS	ZE	NS
ZE	PL	PS	ZE	NS	NL
NS	PS	ZE	NS	NL	NL
NL	ZE	NS	NL	NL	NL

The stator current amplitude is obtained by using the relation:

$$I(k) = \sqrt{i_{\alpha}^2 + i_{\beta}^2} \quad (12)$$

The current error and the variation of the error are defined as follows:

$$\begin{cases} e(k) = I_s(k)^* - I_s(k-1) \\ \Delta e(k) = e(k) - e(k-1) \end{cases} \quad (13)$$

Where I_s^* is the current vector corresponding to flux and torque and I_s is the measured stator current vector. Each one of these two input variables $e(k)$ and $\Delta e(k)$ and output variable ΔR_s are divided into five fuzzy sets designed by NG, NP, ZE, PP and PG. The universes and the functions of membership of these three variables are represented on figure (fig. 6).

6. Simulation and Results

The figures (fig. 7) and (fig. 8) represent the torque and stator flux starting responses for classical DTC and that based on fuzzy logic. The response of the fuzzy controller is faster than that of conventional DTC.

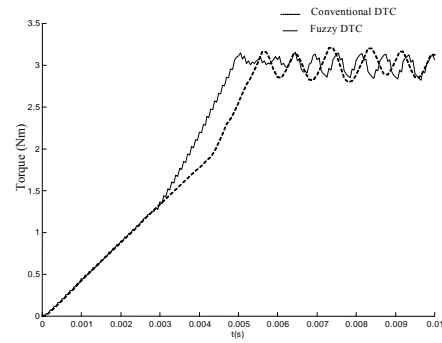


Fig.7: Conventional DTC and Fuzzy controller torque responses

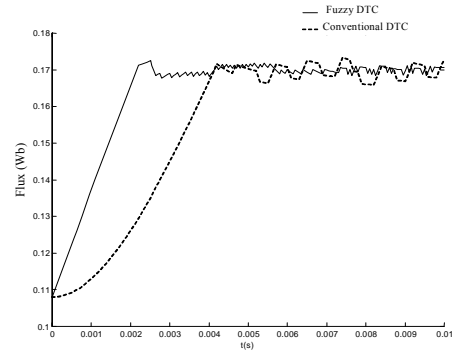


Fig.8: Conventional DTC and Fuzzy controller flux responses

The figure (Fig. 9 shows the response of the system for a variation of the consign torque of 3Nm to 1Nm, for a constant reference flux value. The fuzzy controller response is also faster than the conventional DTC.

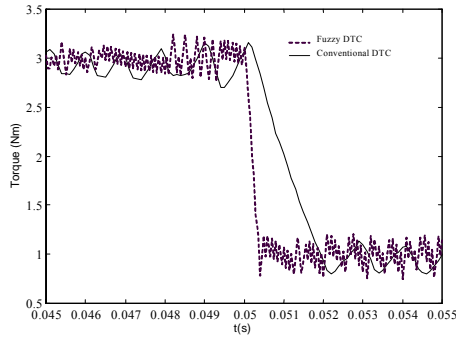


Fig.9: Torque Inversion responses for Conventional DTC and fuzzy controller

The figure (fig. 10) represents the stationary responses of the system. The current takes a sinusoidal form, and we note a reduction in the undulations of the torque and flux in comparisons with the conventional DTC. The trajectory of flux is circular and the average torque is equal to its set point whereas in the conventional DTC. There remains slightly higher than the value of reference.

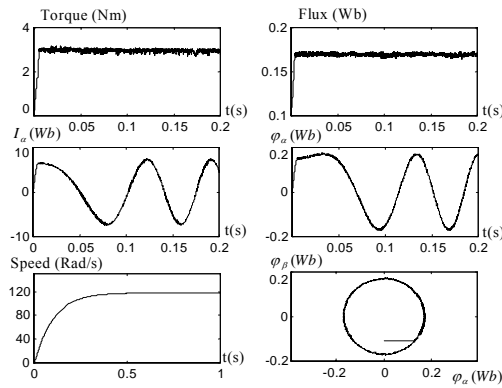


Fig.10: Fuzzy controller Responses

The figure (fig. 11) shows the variation of stator resistance in the case simultaneously of under-estimate and hyper-estimate of stator resistance, with a speed of 4 rad/s and a very weak torque of reference of 0.3 Nm. Stator resistance follows perfectly its reference and the variation of the torque is completely compensated.

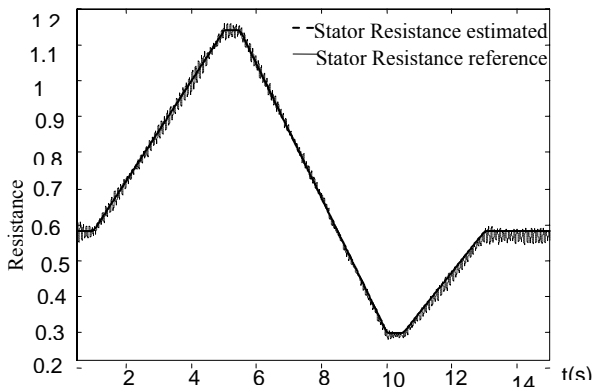


Fig.11: Fuzzy stator resistance estimator

The figure (fig. 12) shows the evolution of the electromagnetic torque without filtering with and without the fuzzy estimator of stator resistance. In this last operation, the torque can fall in relatively important proportions for low speeds.

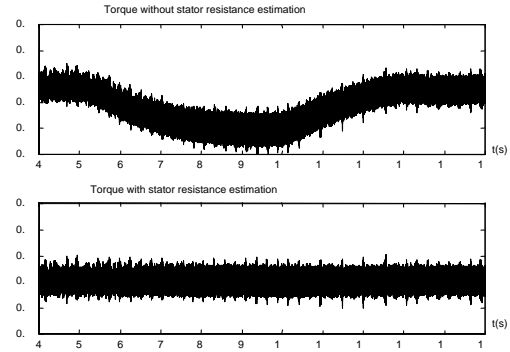


Fig.12: Torque Responses with and without stator resistance compensation

7. Conclusion

The results of simulation show the feasibility of the proposed approach which has the advantage compared to the conventional and fuzzy DTC used previously, of reducing the computing time in the structure of order and to improve the dynamic performances of the machine (reduction in the response time to starting and in transient state and of the undulations (ripples) of the torque and flux.

8. Annexe

Tab.5: PMSM parameters used in the proposed approach

Pole paires number	P	2
Stator Resistance	R_s	0.57Ω
Magnets Flux	ϕ_f	0.108 Wb
Inductance axe d	L_d	8.72 mH
Inductance axe q	L_q	22.8 mH
Phase Voltage	V	50 V
Phase Current	I	8.66 A
Nominal speed	Ω	1200 tr.m

9. References

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