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Fuzzy logic based vector control of multi-phase permanent magnet synchronous motors

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Abstract - *This paper presents a fuzzy-logic-based vector control for a five-phase permanent-magnet synchronous motor (PMSM). The high-performance of the proposed fuzzy logic control (FLC)-based PMSM drive are investigated and compared with the conventional proportional-integral (PI) controller at different conditions, such as step change in command speed and load, and robustness against machine parameter variations. Finally, Simulation results shows that FLC presents better performances and high robustness compared to the conventional PI controller.*

Résumé - *Cet article présente une commande vectorielle basée sur la logique floue pour un moteur synchrone à aimants permanents à cinq phases (PMSM). Les performances de la PMSM basé sur la commande de la logique floue (FLC) proposée sont examinées et comparées au contrôleur PI (proportionnel intégral) classique dans différentes conditions, telles que le changement de la vitesse et de la charge et la robustesse par rapport aux variations paramètres de la machine. Enfin, les résultats de simulation montrent que le FLC présente de meilleures performances et une grande robustesse par rapport au contrôleur PI conventionnel.*

Keywords: Five-phase permanent-magnet synchronous motor (PMSM) - Vector control - Fuzzy logic control (FLC) - Robustness - PI controller.

1. INTRODUCTION

In electrical drive applications, three-phase drives are widely used in the industry. Numerous features made them the most studied and used for long time [1, 2].

The interest in multi-phase motor drives has increased in recent years as they offer several advantages when compared to three-phase machines such as [3]:

1) Improved reliability and increased fault tolerance;

2) Greater efficiency;

3) Higher torque density and reduced torque pulsations;

Many different multiphase machine control schemes such as multiphase direct torque control (DTC) and field orientation control (FOC) have been introduced [4, 5].

Control system design is a multi-stage process including more than designing the controller itself. Before a controller is designed, a control engineer must have sufficient knowledge of the system to be controlled. Traditional vector control structures which include proportional-integral (PI) regulator for application to an multiphase machine driven have some disadvantages such as parameter tuning complications, mediocre dynamic performances and reduced robustness [6, 7].

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To overcome the poor robustness and static and dynamic performances of PI controller, the fuzzy logic controller (FLC) approach suitable for five-phase PMSM has been presented.

Among the various intelligent controllers, fuzzy logic controller (FLC) is the simplest, robust and better than others in terms of quick response time, also insensitivity to parameter and load variations etc, [8].

The concept of 'Fuzzy Logic' was first introduced by L.A. Zadeh in 1965 with a novel proposal of fuzzy set theory [9, 10]. Fuzzy logics had been studied since the 1920s as infinite-valued logics notably by Łukasiewicz and Tarski.

Fuzzy logic control (FLC) technique can be considered as an alternative to conventional feedback approaches to control complex nonlinear plants where mathematical modelling is uncertain [9]. This technique has been successfully applied to electrical motor drives [11-13]. The main advantage of FLC resides in the fact that no mathematical modelling is a priori required to design the control law.

Seen from this major drawback, contribution of this paper is to change conventional controllers “PI” with fuzzy logic controllers and test its robustness.

This paper is devised in six sections as follows: in section 2 we briefly review the system modelling. In Section 3 the field oriented strategy by employing the PI controller of the five-phase PMSM is presented. Section 4 provides the application of the fuzzy logic control. The simulation results and its discussion are presented in Section 5. Finally, in section 6 the main conclusions of the work are drawn.

2. MATHEMATICAL MODEL OF FIVE-PHASE PMSM

The electric equation of a five-phase PM synchronous machine in the natural base is given by the following expression for each phase (here the k^{th} phase) [14, 15].

$$v_s = R_s . i_k + \frac{d\varphi_{sk}}{dt} + e_k \tag{1}$$

The model of the five-phase PMSM is presented in a rotating d, q frame as [15]:

$$\begin{cases} v_{ds} = R_s . i_{ds} + L_d \frac{d}{dt} i_{ds} - w_r L_q i_{qs} \\ v_{qs} = R_s . i_{qs} + L_q \frac{d}{dt} i_{qs} + w_r L_d i_{ds} + \sqrt{5/2}\, w_r \phi_f \end{cases} \tag{2}$$

The electromagnetic torque expression is given by,

$$T_e = p\left((L_d - L_q)\, i_{ds} . i_{qs} + \sqrt{5/2}\, \phi_f\, i_{qs} \right) \tag{3}$$

On the other hand, the mechanical equation of the machine is,

$$J_m \frac{dw_r}{dt} = p\, T_e - p\, T_r - f_m\, w_r \tag{4}$$

This set of equations allows characterizing the electromechanical behavior of a five-phase PMSM machine.

3. VECTOR CONTROL MODEL OF THE FIVE-PHASE PMSM

The vector control technique was firstly proposed for induction motors, while it was applied to PM machine later.

Its basic principle is to decouple the stator current to get direct axis (d-axis) and quadrature axis (q-axis) components. The vector control strategy is formulated in the synchronously rotating reference frame. An efficient control strategy of the vector control technique is to make the d-axis current i_d zero so that the torque becomes dependent only on q-axis current [16, 17].

If the current i_d is maintained null, physically the flux of reaction is in squaring with the rotor flux produced by the permanent magnets and $\phi_f = \phi_d$. The equations (2) become,

$$\begin{aligned} v^*_{ds} &= v'_{ds} + w_r L_{qs} i_{qs} \\ v^*_{qs} &= v'_{qs} + w_r (L_{ds} i_{ds} + \sqrt{5/2}\, \phi_f) \end{aligned} \tag{5}$$

where v'_{ds} et v'_{qs} are the d-q current controllers outputs.

The expression of the torque given by (3) becomes,

$$T_e = p \sqrt{5/2}\, \phi_f\, i_{qs} \tag{6}$$

A system illustration of the vector control of five-phase motor is given in figure 1.

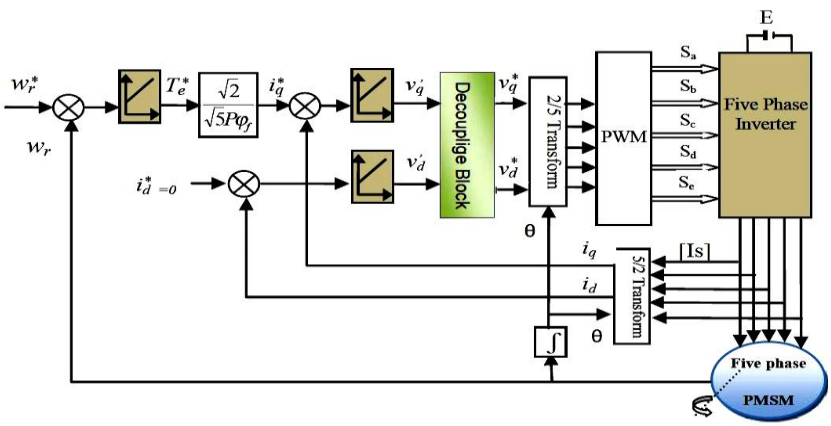

Fig.1: Vector control for the five-phase PMSM

4. FUZZY LOGIC CONTROL OF THE FIVE-PHASE PMSM

Fuzzy logic is one of the most powerful control methods. It is known by multi-rules-based resolution and multivariable consideration. Fuzzy logic theory is an artificial intelligence method which has been as been employed to many fields like control theory to artificial intelligence [18].

Fuzzy logic controllers (FLC) have the advantages of working with imprecise inputs, no need to have accurate mathematical model, and it can handle the nonlinearity [19]. Thus, here a FLC is implemented as another speed and current controller for proposed vector control of the five-phase PMSM and also to study the performance comparison of the proposed five-phase PMSM drive with conventional PI controller based drive in Matlab/Simulink environment. The proposed FLC is shown in figure 4.

The membership function (MF) of the associated input and output variables is generally predefined on a common universe of discourse. The fuzzy logic control is based on these four elements: a bases rule, an inference mechanism, a fuzzification interface and a defuzzification interface. The interface used in this work is Mamdani's procedure based on max-min decision. For the defuzzification, the Center of Area (COA) method is employed [20].

The structure of FLC is shown in figure 2. For our study, the input of the fuzzy controller is the error of speed E_w, as well as its variation dE_w, the output of the regulator will be the Torque increment dC_w. It is enough to integrate to have the value of the electromagnetic couple of command T_e. The if-then rules for fuzzy scalar control for speed control will be twenty five rules.

Figures 2**a**, 2**b** and 2**c** shows membership functions of input variables E_w and dE_w respectively and output variable, which are with conventional triangular shapes. Each membership is divided into five fuzzy. The fuzzy rule algorithm includes 25 fuzzy control rules listed in **Table 1**.

The fuzzy labels used in this study are negative big (NB), negative small (NS), equal zero (ZE), positive small (PS) and positive big (PB).

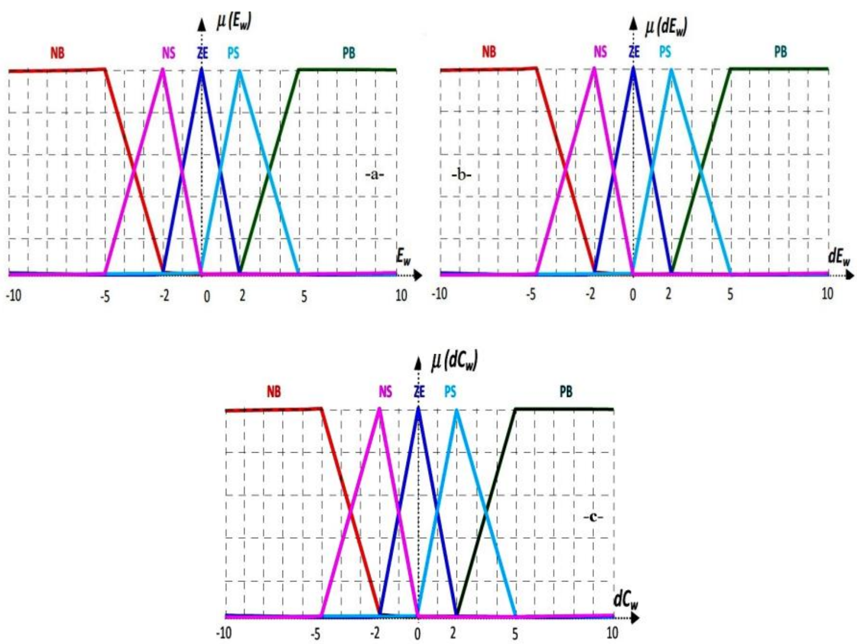

Fig. 2: Membership functions of input/output variables:
a- input speed error; **b-** input change speed error; **c-** output

Table 1. The rule base for controlling the speed

		E_w				
		NB	**NS**	**ZE**	**PS**	**PB**
dE_w	**NB**	**ZE**	**ZE**	**PB**	**PB**	**PB**
	NS	**ZE**	**ZE**	**PS**	**PS**	**PS**
	ZE	**PS**	**ZE**	**ZE**	**ZE**	**NS**
	PS	**NS**	**NS**	**NS**	**ZE**	**ZE**
	PB	**NB**	**NB**	**NB**	**ZE**	**ZE**

The same steps used for the conception of the speed controller (FLC) will be repeated for the currents controller as shown in figure 3, only we have:

$E_i = i_{ds}^* - i_{ds}$ for the first fuzzy controller of current i_{ds} and for the second fuzzy controller of current $E_i = i_{qs}^* - i_{qs}$ for the first fuzzy controller of current i_{qs}.

The output of the fuzzy controller is v_{ds} or the i_{ds} current controller and v_{qs} or the controller of the current i_{qs} current.

We represent the input/output variables by membership function, as show in figure 3, each one divided into 3 fuzzy. The rule-based table for output variable is presented in **Table 2**, it consist of 9 linguistic rules and gives the change of the output of fuzzy logic controller in terms of two inputs E_i and dE_i for each current's controller (i_{ds} and i_{qs}). Each membership function is also assigned with three fuzzy sets: P (positive), N (negative) and ZE (zero).

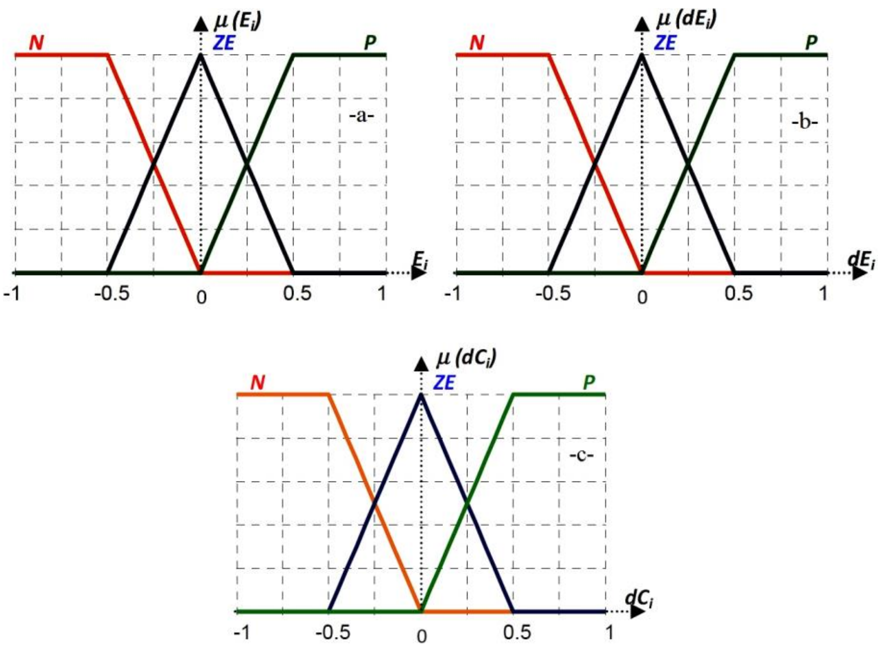

Fig. 3: Membership functions of input/output variables
a- input current error; **b-** input change current error; **c-** output.

Table 2. The rule base for controlling the current

		Ei		
		N	**ZE**	**P**
dEi	**N**	**N**	**N**	**ZE**
	ZE	**N**	**ZE**	**P**
	P	**ZE**	**P**	**P**

The bloc diagram of the fuzzy logic controller for the five-phase PMSM is given by figure 4.

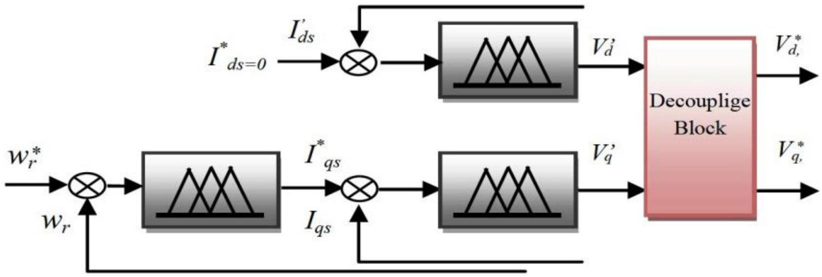

Fig. 4. Block diagram of the five-phase PMSM vector control with the fuzzy controller

5. RESULTS AND DISCUSSIONS

In this study, to figure out the effectiveness of the proposed method, computer simulations have been carried out in Matlab/Simulink environment. The designed five-phase PMSM values and parameters used in simulation are listed as follows: R_s = 1; L_d = 0.0085 H; L_q = 0.0080 H; f = 50 Hz; p = 2; J_m = 0.004 kg/m^2; f_m = 0, € = 0.175 Web.

The goal of this test is to analyze the influence of the load torque variation on five-phase PMSM for the two controllers. For this objective and in the time t = [0.3 s - 0.6 s], the load torque is kept equal to its value T_r = 5 N.m and a step change of the reference speed from 150 rad/s to -150 rad/s at t = 0.9 s.

The simulation results are presented in figure 5 and figure 6. These figures express that the effect produced by the load torque variation is very clear on the speed curve of the system with PI controller, while the effects are almost negligible for the system with the FLC. It can be noticed that these last have a nearly perfect speed disturbance rejection (less than 1%). The current I_q current has the same torque's form which permit to verify last relation in (7) where torque is controlled with I_q current only, I_d is kept zero.

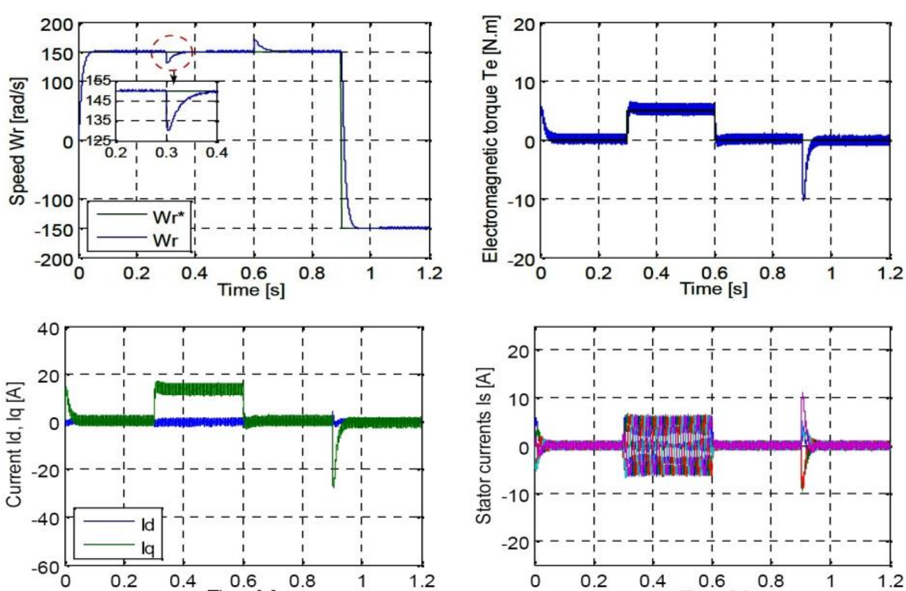

Fig. 5: Performance of vector controlled for five-phase PMSM using PI controllers

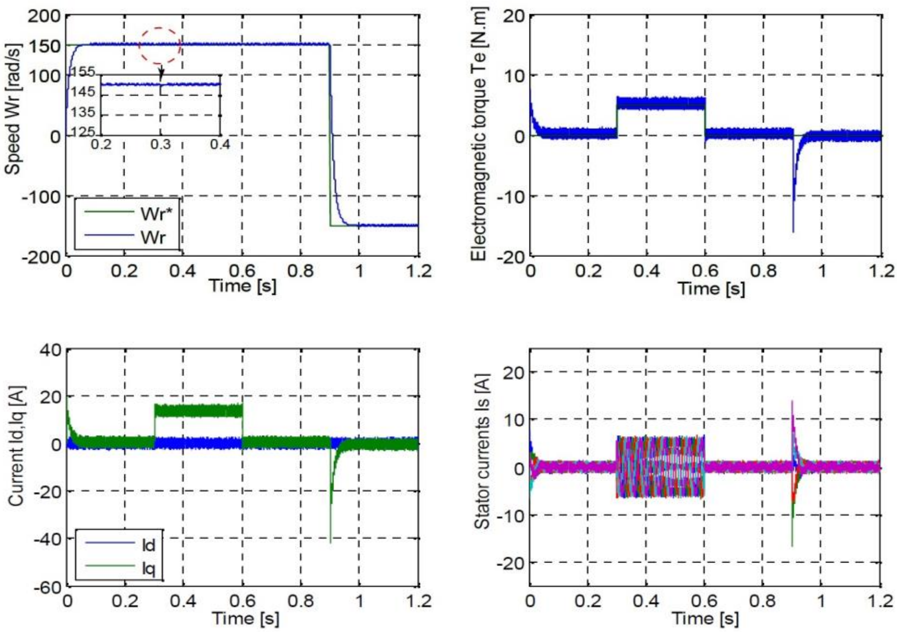

Fig. 6: Performance of vector controlled
for five-phase PMSM using Fuzzy controllers

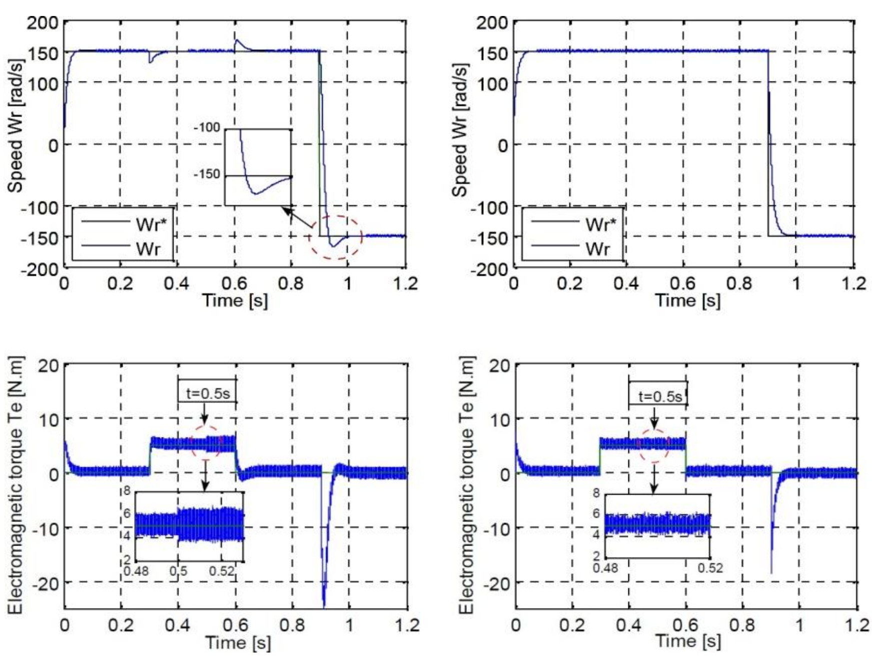

Fig. 7: Sensitivity to the machine parameter variations on the five-phase PMSM
a) PI controllers. **b)** Fuzzy controllers

The second test consists of the robustness test of the system. An example of the robustness of the fuzzy controller compared with the conventional PI controllers. To test the robustness of the controllers used, parameters of the machine has been modified: the values of the stator resistance R_s and the inertia variation J_m are doubled and the values of the inductances L_d and L_q are reduced by 20 % of the nominal value, this variation is made at time t = 0.5 s.

The gotten results are represented in figure 7. These results show that the parameter variation of the five-phase PMSM presents a clear effect on the speed and electromagnetic torque curves and that the effect proves more significant for PI controller than that with the FLC.

This is an example of the robustness of the FLC controller compared with the conventional PI controllers.

6. CONCLUSION

In this paper, a vector control with the fuzzy logic controller (FLC) for the five-phase PMSM has been presented. It combines the capability of fuzzy reasoning in handling uncertain information.

The robustness has been compared with classical PI and fuzzy controllers. Simulation results showed better performance of the proposed FLC of the machine and a very high robustness over the conventional PI controller.

Then, the combination of fuzzy controller strategy with vector control becomes a good combination.

APPENDIX A

A.1 List of symbols

Table 3. List of symbols

Symbol	Significance
$v_{ds}, v_{qs}, i_{ds}, i_{qs}$	*d* and *q* axis stator voltages and currents,
R_s	Stator resistances,
L_d	*d* axis stator inductance,
L_q	*q* axis stator inductance,
ϕ_f	main magnetic flux of the permanent magnet,
p	Number of pole pairs,
J_m	Inertia moment,
f_m	Viscous damping,
w_r	Rotational speed (rd/s),
T_r	Load torque,
T_e	Electromagnetic torque.

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