HYBRID FUZZY LOGIC AND VECTOR CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE FOR ELECTRIC VEHICLE

H. GHODBANE[1], O. KRAA[2], A. ABOUBOU[2] AND A.A. TALEB[3]

[1] Department of Electrical engineering from the Mohamed Kheider University, Biskra, Algeria,
[2] Laboratory of Energy Systems Modeling, Mohamed Kheider University
[3]AMIH Laboratory from Valenciennes University, France,
o.kraa@mselab.org

ABSTRACT

This paper presents the modelling and the control of a Permanent Magnet Synchronous Motor (PMSM) speed used in an electric vehicle. The classical vector control technique is enhanced using a specific Fuzzy Logic Controller FLC instead of a simple PI, IP or PID control. These classical controllers need the adjustment of controller gains. The determination the gains is not easy and needs to be adjusted if the operating conditions change. The optimization problem of regulators IP parameters used in the vector control method, has been solved by using a Fuzzy Logic. The FLC can be dedicated entirely to vector control of PMSM and it offers a robust and a realizable controller acting as a non linear (and optimized) PID. Than, the combination of fuzzy control strategy with vector controlled can give a good combination. In order to validate the simulation results, a comparison between the results obtained by classical vector control and the presented hybrid controller using FLC obtained by Matlab/Simulink software tool is included.

INDEX TERMS: Hybrid Control, Fuzzy Logic, Vector Control, Synchronous Motor, Modelling, traction control, Electric Vehicle

1 INTRODUCTION

Recently the development of the new generation vehicle which is more efficient and less air polluting is accomplished actively. This vehicle generation development can be divided in two axes, one is the Electric Vehicle (EV) and the other is the Hybrid Electric Vehicle (HEV). EVs may be particularly well suited to fleet applications and commuter/town cars. To use EVs in fleets as a practical solution, it is necessary to have technical feasibility and commercial viability that meets the user's needs and affordability. The EV must first be safe, reliable and cost effective, with consistency of the battery system being the key to determine the usefulness as a fleet vehicle [1]. There are several types of motorization for electric traction. At present time, the Direct Current (DC) machines, and more particularly the separated excitation and the permanent magnet (PM) synchronous machines are the most widely used. PM synchronous motor adjustable speed drives offer significant advantages over induction motor drives in a wide variety of industrial applications (high power density, high efficiency, improved dynamic performance and reliability) [1,2]. Since vector control in PM synchronous motors provides fast dynamic response with a less complex and non-parameter dependent controller, PM motor drives can be an attractive alternative choice [3]. Improvement of PM motor efficiency is a most important priority, especially in cases where drives are powered by a battery source as in EV traction. Therefore, significant efforts are taken to improve their efficiency. Since there are a great variety of PM motor configurations, the efforts are mainly focused on the search for the optimum rotor

structure [4,5]. However, efficiency can also be improved by intervening in the motor operation principle with automatic control techniques. In this paper, a methodology of Fuzzy Logic Control (FLC) is adopted in the vector controlled of an PM synchronous motor speed. Fuzzy logic systems (FLSs) have been credited in control system and applications as powerful tools capable of providing robust controllers for mathematically ill-defined systems that may be subjected to structured and unstructured uncertainties [6]. This paper is started by a description of Permanent Magnet Synchronous Motor. In section III, the vector controlled of the studied system is detailed. Indeed, the proposed FLC is deduced in section IV. The section VI of this work presents some results obtained with the proposed control traction. The simulation results of classical and proposed vector control are compared in order to validate the developped controller. Finally, conclusions are drawn in Section VI.

2 MODELLING OF PM SYNCHRONOUS MOTOR THE STUDIED ARCHITECTURE

The usual simplifying assumptions adopted in the modelling of the machine, given in the majority of the references [3,5], are :

The magnetic circuits are not saturated, which makes it possible to express flux like a linear function of currents.

The losses by Foucault currents and hysteresis are neglected.

The capacitive couplings between rolling up as well as the effect of skin are neglected.

The distribution of the magneto-motive force created by rolling up with the stator is sinusoidal.

Do not exist rolling up shock absorber with the rotor.

The system of tension is balanced (component homo-polar null).

2.1 Equations of PM machine

2.1.1 Machine model in the abc reference frame: The Fig. 1 illustrates the PM motor in abc reference frame, The machine can be modelled by the electromechanical equations.

2.1.1.1 The stator model

The equations of tension model of the selected synchronous machine are [7]:

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \begin{pmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{pmatrix} \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} + \frac{d}{dt} \begin{pmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{pmatrix} \quad (1)$$

Where The three-phase machine being balanced symmetrical, the resistance of the stator phases is given by :

Rs =Ra = Rb =Rc.

2.1.1.2 The rotor model

For the rotor, the equations of tension are:

$$v_f = R_f i_f \quad (2)$$

Where v_f , R_f and i_f are the tension, resistance and the rotor current respectively. The relation flux current is given by :

$$[\varphi] = [L][I] + [\varphi_f] \quad (3)$$

Where [L] : matrix of Inductances and mutual company stator, it is independent of the angle between the rotor and the stator Θ, since some is the position of the rotor, the machine is geometrically symmetrical. The following equation presents excite flux of the permanent magnets.

$$\varphi_f = M_f i_f \quad (4)$$

Where M_f and i_f are fictitious constants.

$$[\varphi] = [L][I] + [M_f I_f] \quad (5)$$

The permanent magnet is represented by a fictitious rolling up, of this fact the inductance is constant. The expression of the electromagnetic Torque is :

$$\Gamma_{em} = \frac{1}{2}[i]^T + \left(\frac{d}{d\theta}[L]\right)[i] \quad (6)$$

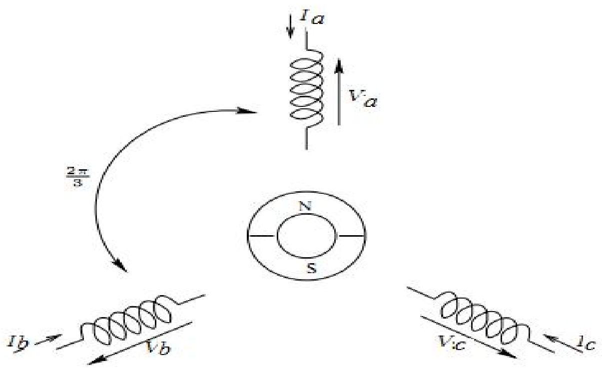

Figure 1: Symbolic representation of the studied three-phase machine

The electric energy transformation into mechanical energy is governed by the following mechanical equation :

$$J_m \frac{dw_r}{dt} = \Gamma_{em} - \Gamma_{res} - f w_r \quad (7)$$

Where

ωr : rotor velocity ;

Jm : Inertia of machine turning part ;

Γem : the resistive torque ;

fr : the coefficient of strongly.

2.1.2 Machine Equation on Park reference frame (d, q)

The equations obtained in the a b c reference frame are non-linear and coupled. They are dependent of the rotor position Θ. This makes the system resolution more difficult. To simplify this problem, the majority of works in the Literature call upon the use of the transformation of Park [8]. This transformation, applied to the real variables (tensions, currents and flux), makes it possible to obtain fictitious variables called the components d-q of Park. This can be interpreted as being a substitution of rollings up of phases of the real system (a b c) orthogonal rollings up of axes (d q) turning at a speed compared to the stator as illustrated in Fig. 2. This change of reference frame makes the dynamic equations of the machine simpler what facilitates their study, their analysis and the control of machine [9].

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\Pi}{3}) & \cos(\theta + \frac{2\Pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\Pi}{3}) & (\theta + \frac{2\Pi}{3}) \end{pmatrix} \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \quad (3)$$

2.1.3 Park's inverse transformation : The following equations present the inverse Park transformation for currents

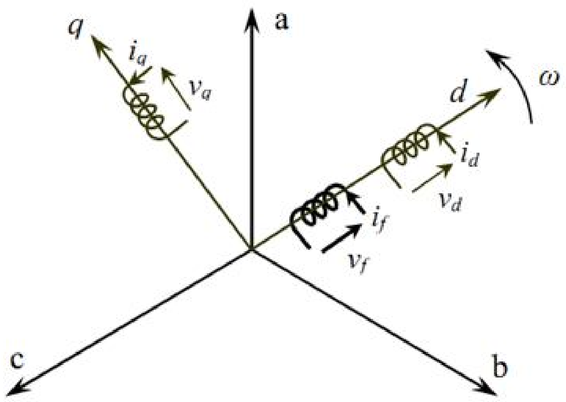

Figure. 2: Park Symbolic representation of the studied machine

$$\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - \frac{2\Pi}{3}) & -\sin(\theta - \frac{2\Pi}{3}) \\ \cos(\theta + \frac{2\Pi}{3}) & -\cos(\theta + \frac{2\Pi}{3}) \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} \quad (9)$$

After the Park transformation to the system (1) and (3), all the vectors are expressed on a (d q) reference frame related to the rotor. If Θ are the electrical angle between the rotor and the stator then [7] :

$$\begin{cases} v_d = R_s i_d + \dfrac{d\varphi_d}{dt} - p w_r \varphi_q \\ v_q = R_s i_q + \dfrac{d\varphi_q}{dt} + p w_r \varphi_d \end{cases} \quad (10)$$

The relations flux-current become :

$$\begin{cases} \varphi_d = L_d i_d + \varphi_f \\ \varphi_q = L_q i_q \end{cases} \quad (11)$$

From (10) and(11), the state variables model of PMSM is presented by (12) [10-13] :

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} -\dfrac{R_s}{L_d} & -\dfrac{P L_q w_r}{L_d} \\ \dfrac{P L_q w_r}{L_d} & -\dfrac{R_s}{L_d} \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} + \begin{pmatrix} \dfrac{1}{L_d} \\ \dfrac{1}{L_q} \end{pmatrix} \begin{pmatrix} v_d \\ v_q - P w_r \varphi_f \end{pmatrix} \quad (12)$$

Where $\omega s = P\omega r$ is angular speed, P is the number of pairs of poles.

$$\begin{cases} \Gamma_{em} = P[L_d - L_q] i_d i_q + \varphi_f i_q \\ \dfrac{dw_r}{dt} = \dfrac{1}{j}[\Gamma_{em} - \Gamma_{res} - f_r w_r] \end{cases} \quad (13)$$

3 VECTOR CONTROL

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 id zero so that the torque becomes dependent only on q-axis current.[11,12]

3.1 Vector Control Model of the PMSM

If the current id is maintained null, physically the flux of reaction is in squaring with the rotor flux produced by the permanent magnets and $\varphi f = \varphi d$. The equations (10) become :

$$\begin{cases} v_d = -p w_r \varphi_q \\ v_q = R_s i_q + L_q \dfrac{di_q}{dt} + p w_r \varphi_f \end{cases} \quad (14)$$

The expression of the torque given by (13), becomes :

$$\Gamma_{em} = P \varphi_f i_q \quad (15)$$

The variation of the Torque is proportional to that of the current, therefore the model of the machine is reduced to that of a Direct Current (DC) machine with separate excitation as is illustrated in Fig.3 [12]. The control of angular speed, requires a simultaneous control of two variables *id* and *iq*. So the system comprises a loop of speed control, imposing the reference of current *iq* and the current *id* are imposed equal to 0 by PI regulators in order to have a null static error. In classical vector control, a PI control has been used to estimate reference current

i^* of i_q In this paper, a Fuzzy Logic Control(FLC) based vector control structure is designed to control angular speed and estimate the reference current of i^*_q PM machine as illustrated in Fig. 5 .

4 DEVELOPMENT OF THE CONTROL TRATEGIES BASED ON FUZZY LOGIC

Recently, a lot of researches intend to apply intelligent control theory to the control strategy of EV motor-traction such as adaptive control [17], neural network [14] and fuzzy control [15]. Since fuzzy control is simple, easy to realize, no need for modelling and has strong robustness, it is suitable for non-linear control where parameters and/or model are unknown or variable. It can converses engineers experience to control rules directly. Hence, it is very suitable for EV control. The FLC with a vector control is developped to control a PM synchronous machine used in EV, for estimating the reference

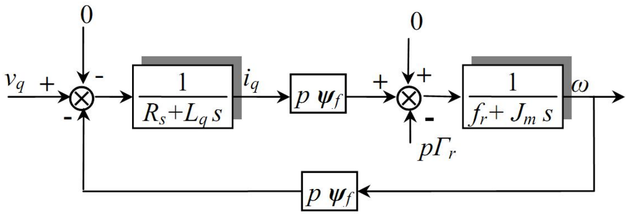

Figure. 3: Uncoupled model of studied machine

Current i_q^* in vector control The input parameters of FLC are the error (ξ) and the change of error $d\xi$ between W^* *and* w_r the FLC *dt* output is the i^*_q which used to control the dynamic behavior of PMSM as shown in Fig. 5.

4.1 Fuzzy Logic System Design

A FLS need to define both input and output membership functions (MFs), fuzzification method, scaling factor values, type of membership, rules, rule processing, inference mechanism, and defuzzification method [16, 17].

4.1.1 Fuzzification Interface

It will transform the input

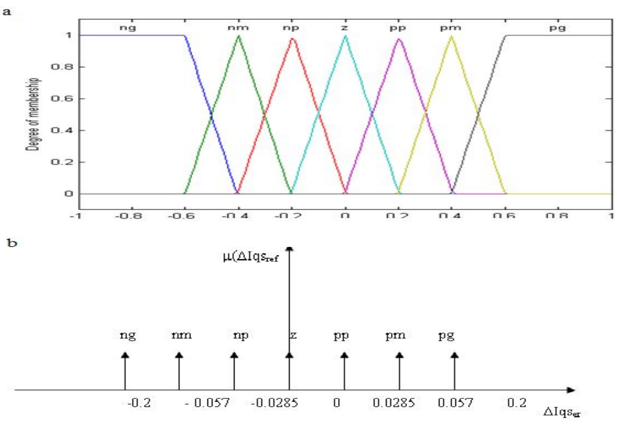

Figure 4: EMR and SMC using FLC for the studied system under Matlab/Simulink [Adapted version of the given in 19]

TABLE 1: The rule base system

ξ \ $\frac{d\xi}{dt}$	NB	NA	NS	ZE	PS	PA	PB
NB	NB	NB	NB	NA	NS	NS	ZE
NA	NB	NB	NA	NS	NS	ZE	PS
NS	NB	NA	NS	NS	ZE	PS	PS
ZE	NA	NS	NS	ZE	PS	PS	PA
PS	NS	NS	ZE	PS	PS	PA	PB
PA	NS	ZE	PS	PS	PA	PB	PB
PB	ZE	PS	PS	PA	PB	PB	PB

TABLE 2: Parameters of the PMSM

Parameter	Value
$P_{util_{nom}}$	$40kw$
L_d	$10mH$
L_q	$12,1mH$
R_s	0.2Ω
f_m	$0.0005N.m/rad/sec$
J_m	$0.12N.m.s^2/rad$

parameters, the error (ξ) and the change of error *dt* between *dt* W^* and w_r of the FLC from distinct quantity to fuzzy quantity. A seven-term sets are negative big (NB), negative average (NA), negative small (NS), zero (ZE), positive big (PB), positive average (PA) and positive small (PS) are used to define FLC output and inputs linguistic variables.

Rule Base System: The fuzzy rule base is a set of linguistic rules are defined with IF-THEN conditions. The rule base which has the M number of rules (j = 1,2,...,M) is shown in (16) [14-17].

$$R^j = If\ x_1\ is\ A_1^j\ and\ x_2\ is\ A_2^j\ and\ ...and\ x_n\ is\ A_n^j \quad Then\ z\ is\ B^j \tag{16}$$

Where xi(i = 1,2,...,n) are the fuzzy system input parameters. The fuzzy output variables are denoted z. The membership functions μ_ξ (xi) and $\mu_{\frac{d\xi^j}{dt_i}}(x_i)$ are represented as the input linguistic term A_i^j. B^j is the linguistic term for the fuzzy output [15]. Equation (17) shows the first rule assigned for the rule base system shown in TABLE I.

$$R^1 = If\ \xi is\ \mu_\xi\ (NB)\ and\ \frac{d\xi}{dt} is\ \mu_{\frac{d\varsigma}{dt}}\ (NN) \quad Then\ i_q^*\ is\ NB \tag{17}$$

4.1.2 Inference Machine

According to the fuzzy quantity of input parameters, inference machine will find correspon-ding rules in rule base predefined, and use centrobaric method and minimum inference machine to get the output parameter which is the fuzzy quantity of i_q^*. The simplest membership functions are adopted using straight lines. The simplest membership function is the Triangular and Trapezoidal membership for both input and Output membership singletons for fuzzy sets (Fig. 4). These straight line membership functions have the advantage of simplicity.

4.1.3 Defuzzification Interface

In defuzzification interface, the fuzzy output value in the fuzzy inference machine is converted into a non fuzzy output value. The actual value of the i_q^* is obtained by centroid defuzzification method [16].

5 SIMULATION RESULTS

In the following simulations, the battery and MLI shopper are considered ideal and without losses. The parameters of the PMSM are given in Table II. the Simulink model of proposed controller for the angular speed of PMSM is developed into a Matlab/Simulink as shown in the Fig. 5.

5.1 Simulation of the Machine operation without a load

The Fig. 6 shows the behavior of the machine, with continuation of variation of speed reference, it is clear that the response follows its reference in a weak time and without static error. The Fig. 7 shows the stator currents on tow axis (d q) where the decoupling is perfectly carried out. These results prove the effect of proposed controller which is validated by the results of classical vector control. Fig. 8 shows a comparison between the reference and the motor speed controlled using proposed controller (blue results) and classical vector control (red results) for different profile of references signal, where The PMSM works with better performances.

5.2 Simulation of the machine operation with a load

Fig. 9 and 10 show the Simulation of the machine with starting then application of the load at *time* = 1.7*s* with a resistive torque Γres=0.05*N.m*. The speed and torque responses fluctuate clearly and dynamic performances deteriorate markedly with conventional PI speed controller. Using the proposed speed controller based on fuzzy logic, because of These changes, the motor speed changes slightly, but the motor speed approximately tracks the reference speed after that. From these results, the developped controller of PMSM is efficient control strategy of the vector control technique is to make the d-axis current id zero so that the torque becomes dependent only on q-axis current where the decoupling is perfectly carried out for case machine with or without load.

Fig. 11 shows a comparison between the reference and the motor speed controlled using proposed controller (blue results) and classical vector control (red) for different profile of references signal, where The develpped controller works better and PMSM gives better performances too, in presence of load.

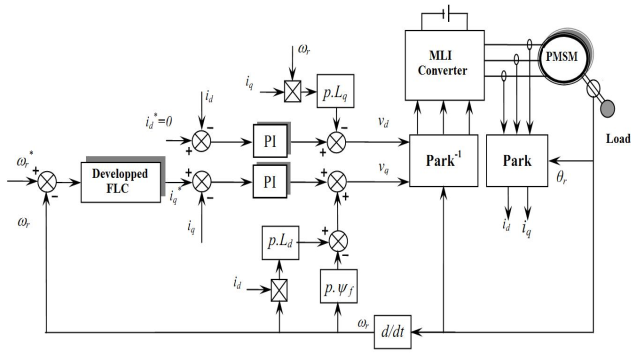

Figure 5: global structure of PM machine Control

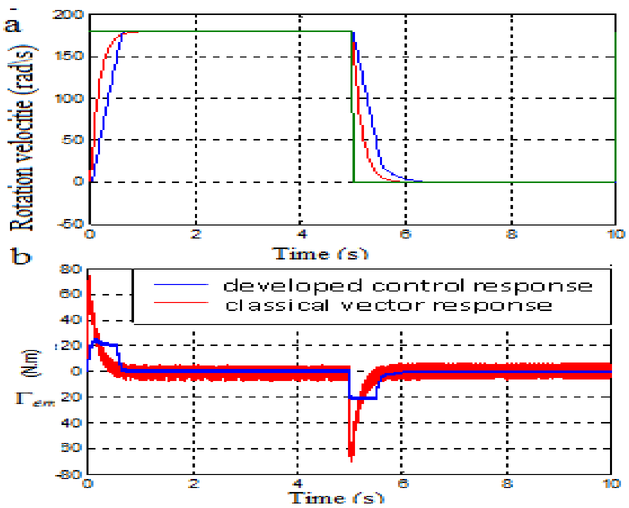

Figure 6: (a) reference and motor angular speed (b) electromagnetic torque

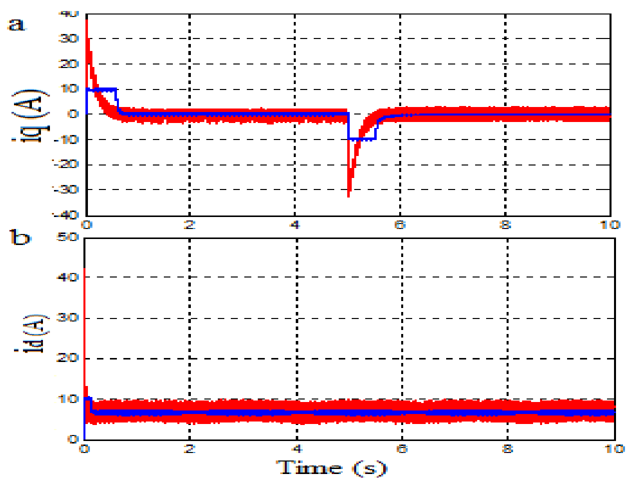

Figure 7: (a) Stator iq ***current (b) Stator*** id

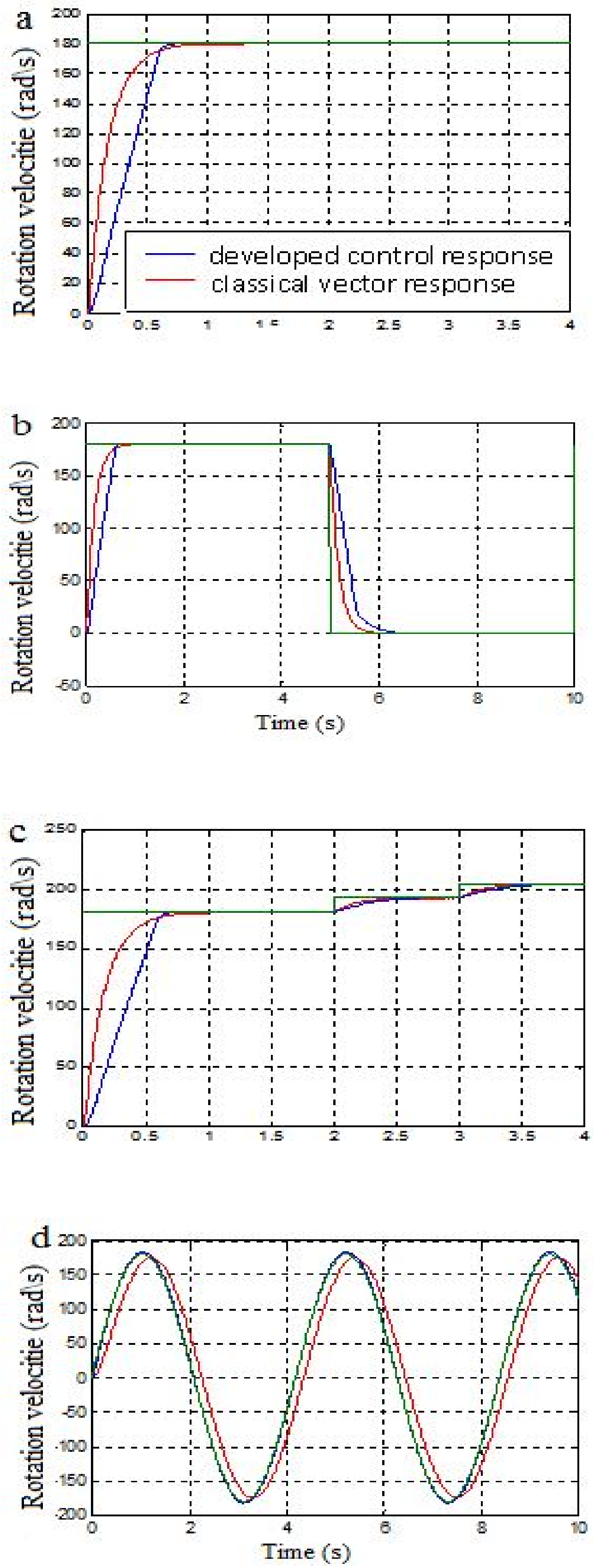

Figure8: Angular speed of machine with out load for difference references speed

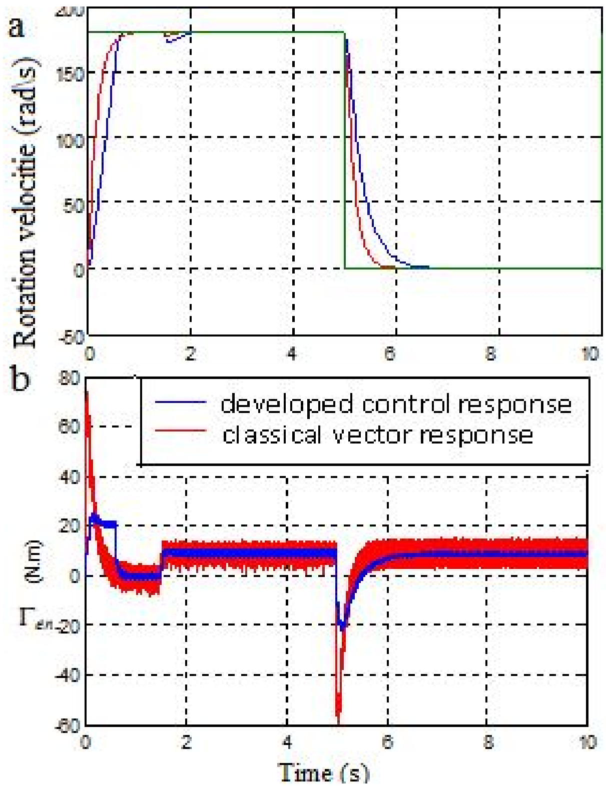

Figure 9: (a) reference and motor angular speed (b) electromagnetic torque

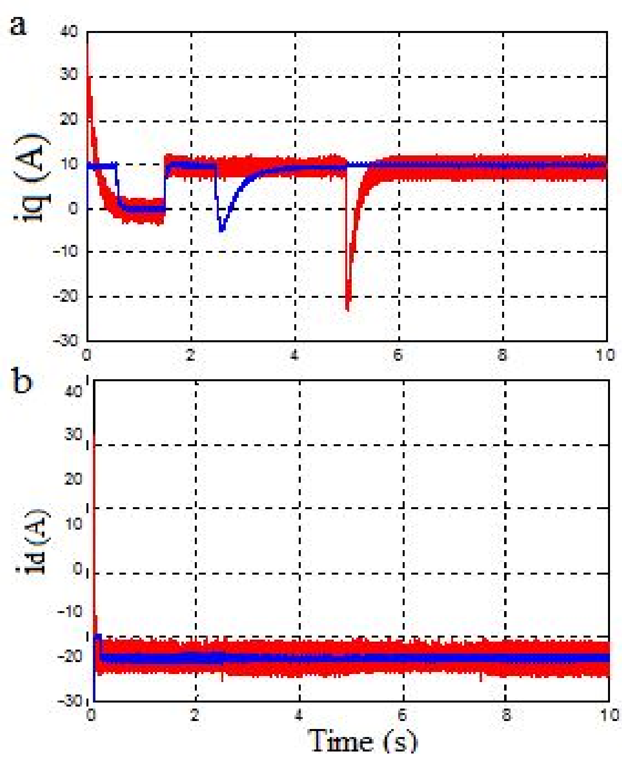

Figure 10: (a) Stator iq *current (b) Stator* id

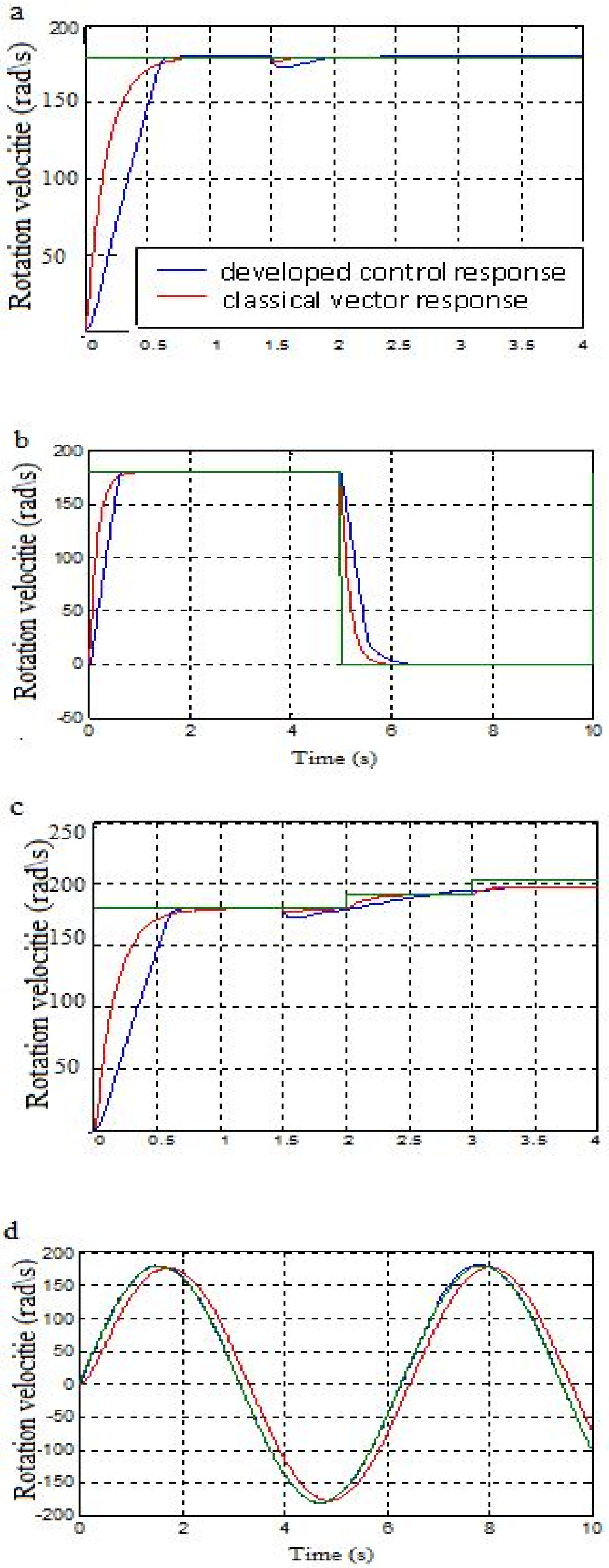

Figure 11: Angular speed of machine with load for difference references speed

6 CONCLUSIONS

In this paper, a vector control with the Fuzzy Logic Controller (FLC) for the PMSM has been presented. It combines the capability of fuzzy reasoning in handling uncertain information. The classical vector control is based on PI, IP or PID, These lasts need the adjustment of controller gains. The determination of gains is not easy and needs to be adjusted if the operating conditions change. This drawback of the vector control can be overcome using the presented FLC in regulation loop of PMSM state variables. The FLC can be viewed as a non linear PI (or PID) controller with an adaptive parameters which are automatically tuned according to the operating point. To improve the dynamic performances of the PMSM drive, an hybrid controller based on fuzzy logic and vector control has been studied and got a good agreement between different types of PMSM profile reference . The FLC can be dedicated entirely to vector control of dynamic system and it offers a robust and a realizable controller acting as a non linear (and optimized) PID. The results of simulation have shown that the PMSM drive with the proposed hybrid controller has the merits of simple structure, robustness and accurate tracking performance. Then, the combination of fuzzy controller strategy with vector control becomes a good combination.

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