Adaptive Field-Oriented Control for the Permanent Magnet Synchronous Machine

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Abstract: Applications of Permanent magnet synchronous machine(PMSM) are increasing widely because of its inherent advantages. The mathematical model of the machine is highly nonlinear. Designing controllers for nonlinear systems is challenging. In this paper our contribution lies in the development vector control, we eliminate all two PI self ajustages controllers used a MRAC. Results are verified using MATLAB/SIMULINK simulations.

Key–Words: Permanent magnet synchronous machine(PMSM); Field-Oriented Control (FOC); PI Adaptive regulator; Model Reference Adaptative Control (MRAC).

1 Introduction

Nowadays, the machines with alternating currents replace the machines more and more with D.C. current in many fields. However, constraints of productivity associated robotics forced the originators criteria in order to obtain high dynamic performances.

The synchronous machines must have raised dynamic performances. For that of thorough research are carried out in various laboratories in order to develop new materials, such as for example the permanent magnets. The latter make it possible the magnet synchronous machines to compete with the other types of machines with D.C. current, synchronous with electric and asynchronous excitation.

Indeed, the permanent magnet synchronous machines make it possible to have a significant instinctual couple, a raised output, a weak mechanical time-constant an increased specific power, reduced maintenance costs.

More and more the synchronous permanent magnet machine is used like actuator in the mechanisms and the systems of positioning [1]. Because it is one robust machine, one can use it in explosive, corrective and dusty environments contrary to the machine with D.C. current.

The establishment of new techniques of control (vectorial control, adaptive control, sliding mode and fuzzy logic) improved the dynamic performances of the electric drive. This improvement was made possible thanks to the use of the microprocessors, micro-controllers and microcomputers which allowed the numerical establishment of these sophisticated but complex controls.

One of the adaptive control techniques is the model reference adaptative control. This one consists in proposing a model of reference such as the divergence between the system response and that model tends towards zero.

To satisfy the needs for this study, we organized our work as follows:

- Nonlinear model of the PMSM
- Vectorial Control of the PMSM
- Simulations and results

2 Nonlinear model of the PMSM

With the simplifying assumptions relating to the PMSM, the model of the machine expressed in the reference of PARK, in the form of state is written [2, 3, 4]:

$$\begin{aligned} \frac{di_d}{dt} &= -\frac{R}{L_d} i_d + \frac{L_q}{L_d} p\Omega i_q + \frac{1}{L_d} V_d \\ \frac{di_q}{dt} &= -\frac{L_d}{L_q} p\Omega i_d - \frac{R}{L_q} i_q - \frac{\Psi}{L_q} p\Omega + \frac{1}{L_q} V_q \\ \frac{d\Omega}{dt} &= \frac{3}{2}\frac{p}{J}\left(\Psi i_q + (L_d - L_q) i_d i_q\right) - \frac{f_v}{J}\Omega - \frac{1}{J} T_l \end{aligned} \quad (1)$$

Where V_d, V_q are quadrature axis and direct axis voltages, i_d, i_q are quadrature axis and direct axis currents. Ω rotating speed, T_l applied external load torque.

If the machine is with constant air-gap (without polar parts).

In these equations:

R	: stator resistance,
Ψ	: flux linkages of permanent magnet rotor,
L_d	: direct stator inductance,
L_q	: quadrature stator inductance,
f_v	: frictional coefficient,
p	: number of poles.

3 Vectorial Control of the PMSM

The synchronous machine model in the reference frame of PARK led to a system of differential equations where the currents are not independent one of the other, they are connected by nonlinear terms or coefficients. This coupling is eliminated by a method of compensation [6]. The principle of this decoupling amounts defining two new variables of control such as [6]:

$$\begin{cases} V_d &= v_d - e_d \\ V_q &= v_q + e_q \end{cases} \tag{2}$$

Where e_d and e_q are the terms of coupling given by :

$$\begin{cases} e_d &= L_q p \Omega i_q \\ e_q &= L_d p \Omega i_d + \Psi p \Omega \end{cases} \tag{3}$$

and orders it uncoupling

$$\begin{cases} v_d &= L_d \dot{i}_d + R i_d \\ v_q &= L_q \dot{i}_q + R i_q \end{cases} \tag{4}$$

Transfer functions of this system uncoupled while taking as in-puts $v_d,\ v_q$ and as out-puts $i_d,\ i_q$ and :

$$\begin{cases} \dfrac{i_d}{v_d} &= \dfrac{1}{L_d\left(s + \frac{R}{L_d}\right)} \\ \\ \dfrac{i_q}{v_q} &= \dfrac{1}{L_q\left(s + \frac{R}{L_q}\right)} \end{cases} \tag{5}$$

We will present the synthesis of each regulator separately closely connected to clarify the methodology of synthesis of each one of them.

i_d-***current regulator*** :
We wish to obtain in closed loop a response of the type 1^{st} order. To achieve this objective, one takes an adaptive proportional-integral regulator with MRAC of the type:

$$PI_i(s) = k_p + \frac{k_i}{s} = \frac{\theta_1\left(s + \theta_2\right)}{s} \text{ with } \theta_2 = \frac{k_i}{k_p} \tag{6}$$

We can represent the system in closed loop by the figure (FIG.1)

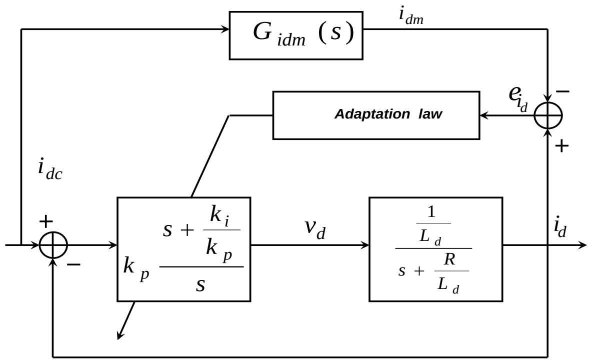

Figure 1: Diagram block in closed loop of PI adaptive regulator with model reference of direct axis current.

The reference model of the system in closed loop is selected with a first-order transfer function:

$$G_{idm}(s) = \frac{a_{idm}}{s + a_{idm}}$$

That is to say the optimality criterion $J(e)$ of the adjustment loop is expressed by the quadratic integral [5]:

$$J(e) = \frac{1}{2}\int_0^T e^2(\tau)d\tau \tag{7}$$

Its derivative is :

$$\begin{aligned} \frac{\partial J(e)}{\partial e} &= \frac{\partial}{\partial e}\left(\frac{1}{2}\int_0^T e^2(\tau)d\tau\right) \\ &= \frac{1}{2}\int_0^T \frac{\partial}{\partial e}e^2(\tau)d\tau = \int_0^T e(\tau)d\tau \end{aligned} \tag{8}$$

Let us compensate for the slowest pole by the numerator of the transfer function of our regulator, which is translated by the condition:

$$\frac{R}{L_d} = \theta_2 \tag{9}$$

In open loop, the transfer function is written:

$$G_{BOi}(s) = \frac{\theta_1 K_i}{s} \text{ with } K_i = \frac{1}{L_d} \tag{10}$$

And in closed loop:

$$G_{BFi}(s) = \frac{\theta_1 K_i}{s + \theta_1 K_i} \tag{11}$$

If the condition (9) is not considered, therefore one will have

$$G_{BFi}(s) = \frac{K_i\theta_1\left(s + \theta_2\right)}{s^2 + K_i\left(\theta_1 + R\right)s + K_i\theta_1\theta_2} \tag{12}$$

One calculates the adjustable parameters θ_1 and θ_2:

$$\begin{aligned} \frac{\partial G_{BFi}(s)}{\partial \theta_1} &= \frac{a_{idm}}{s+a_{idm}}.\frac{1}{\theta_1}.\frac{s}{s+a_{idm}} \quad (13) \\ \frac{\partial G_{BFi}(s)}{\partial \theta_2} &= \frac{K_i\theta_1 s\left(s+K_iR\right)}{\left(s^2+K_i\left(\theta_1+R\right)s+\theta_1\theta_2K_i\right)^2} \\ &= \frac{K_i\theta_1 s\left(s+\theta_2\right)}{\left(s^2+\left(K_i\theta_1+\theta_2\right)s+\theta_1\theta_2K_i\right)^2} \\ &= \frac{a_{idm}s}{\left(s+a_{idm}\right)^2.\left(s+\theta_2\right)} \\ &= \frac{a_{idm}}{s+a_{idm}}.\frac{s}{s+a_{idm}}.\frac{1}{s+\theta_2} \quad (14) \end{aligned}$$

Taking into account (8), (13) and (14), one can write the equation of gradient θ_1 and θ_2:

$$\begin{aligned} \mathcal{L}\left\{\frac{d\theta_1}{dt}\right\} &= -\kappa_{id1}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \theta_1} \quad (15) \\ \theta_1 &= -\frac{\kappa_{id1}}{s}\left(\int_0^T e(\tau)d\tau\right)\frac{\partial G_{BFi}(s)}{\partial \theta_1}i_{dc}(s) \\ \theta_1 &= -\frac{\kappa_{id1}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{\theta_1} \\ &\quad \frac{a_{idm}}{s+a_{idm}}.\frac{s}{s+a_{idm}}i_{dc}(s) \\ &= -\frac{\kappa_{id1}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{\theta_1}.i_{dm}(s) \\ &\quad \frac{s}{s+a_{idm}} \quad (16) \end{aligned}$$

And

$$\begin{aligned} \mathcal{L}\left\{\frac{d\theta_2}{dt}\right\} &= -\kappa_{id2}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \theta_2} \quad (17) \\ \theta_2 &= -\frac{\kappa_{id2}}{s}\left(\int_0^T e(\tau)d\tau\right)\frac{\partial G_{BFi}(s)}{\partial \theta_2}i_{dc}(s) \\ \theta_2 &= -\frac{\kappa_{id2}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{s}{s+a_{idm}} \\ &\quad \frac{1}{s+\theta_2}.\frac{a_{idm}}{s+a_{idm}}.i_{dc}(s) \\ &= -\frac{\kappa_{id2}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{s}{s+a_{idm}}.i_{dm}(s) \\ &\quad .\frac{1}{s+\theta_2} \quad (18) \end{aligned}$$

Speed regulator :
According to the mechanical equation of the PMSM (1); we have :

$$\Omega = \frac{1}{Js+f_v}\left(T_{em}-T_l\right) \quad (19)$$

From where the expression of the electromechanical torque is given by the formula :

$$T_{em} = \frac{3p}{2}\left(\Psi+(L_d-L_q)i_d\right)i_q \quad (20)$$

While replacing, i_{sq} the system (5) in the torque (20)

$$T_{em} = \frac{3p}{2}\left(\Psi+(L_d-L_q)i_d\right).\frac{1}{L_q\left(s+\frac{R}{L_q}\right)}.v_{sq} \quad (21)$$

Therefore, equation (19) becomes :

$$\Omega = \frac{\frac{3p}{2}\left(\Psi+(L_d-L_q)i_d\right)}{L_q\left(Js+f_v\right)\left(s+\frac{R}{L_q}\right)}.v_{sq} - \frac{1}{Js+f_v}T_l \quad (22)$$

For closed loop speed it was proposed regulator PI with MRAC of the form :

$$PI_{\Omega}(s) = k_{p\Omega}+\frac{k_{i\Omega}}{s} = \frac{\vartheta_1\left(s+\vartheta_2\right)}{s} \text{ with } \vartheta_2 = \frac{k_i}{k_p} \quad (23)$$

The functional diagram is given by the figure (FIG.2)

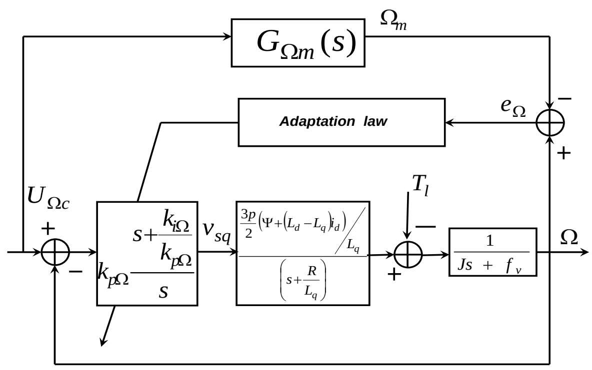

Figure 2: Diagram block in loop closed of PI adaptive regulator to model reference speed .

The reference model of the loop system closed is selected with a second-order transfer function:

$$G_{\Omega m}(s) = \frac{a_{\Omega m}}{s^2+\frac{f_v}{J}s+a_{\Omega m}}$$

Let us compensate for the slowest pole by the numerator of the transfer function of our regulator, which is translated by the condition:

$$\frac{R}{L_q} = \vartheta_2 \quad (24)$$

In open loop, the transfer function is written:

$$G_{BO\Omega}(s) = \frac{\vartheta_1 K_{\Omega}}{s.\left(s+\frac{f_v}{J}\right)} \quad (25)$$

with $K_{\Omega} = \frac{3p}{2L_qJ}\left(\Psi+(L_d-L_q)i_d\right)$
And in closed loop:

$$G_{BF\Omega}(s) = \frac{\vartheta_1 K_{\Omega}}{s^2+\frac{f_v}{J}s+\vartheta_1 K_{\Omega}} \quad (26)$$

If the condition (24) is not considered, therefore one will have

$$G_{BF\Omega}(s) = \frac{\vartheta_1\left(s+\vartheta_2\right)K_\Omega}{s\left(s+\frac{f_v}{J}\right)\left(s+\frac{R}{L_q}\right)+\vartheta_1\left(s+\vartheta_2\right)K_\Omega} \tag{27}$$

The adjustable parameter is calculated ϑ_1 and ϑ_2 :

$$\frac{\partial G_{BF\Omega}(s)}{\partial\vartheta_1} = \frac{a_{\Omega m}}{s^2+\frac{f_v}{J}s+a_{\Omega m}}.\frac{1}{\vartheta_1}.\frac{s\left(s+\frac{f_v}{J}\right)}{s^2+\frac{f_v}{J}s+a_{\Omega m}} \tag{28}$$

$$\frac{\partial G_{BF\Omega}(s)}{\partial\vartheta_2} = \frac{a_{\Omega m}}{s^2+\frac{f_v}{J}s+a_{\Omega m}}.\frac{1}{s+\vartheta_2} \frac{s\left(s+\frac{f_v}{J}\right)}{s^2+\frac{f_v}{J}s+a_{\Omega m}} \tag{29}$$

Taking into account (8), (28) and (29), one can write the gradient equation ϑ_1 and ϑ_2 :

$$\mathcal{L}\left\{\frac{d\vartheta_1}{dt}\right\} = -\kappa_{\Omega 1}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial\vartheta_1} \tag{30}$$

$$\begin{aligned}
\vartheta_1 &= -\frac{\kappa_{\Omega 1}}{s}\left(\int_0^T e(\tau)d\tau\right)\frac{\partial G_{BF\Omega}(s)}{\partial\vartheta_1}U_{\Omega c}(s) \\
\vartheta_1 &= -\frac{\kappa_{\Omega 1}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{\vartheta_1} \\
&\quad \frac{a_{\Omega m}}{s^2+\frac{f_v}{J}s+a_{\Omega m}}.\frac{s\left(s+\frac{f_v}{J}\right)}{s^2+\frac{f_v}{J}s+a_{\Omega m}}U_{\Omega c}(s) \\
&= -\frac{\kappa_{\Omega 1}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{\vartheta_1}.\Omega_m(s) \\
&\quad \frac{s\left(s+\frac{f_v}{J}\right)}{s^2+\frac{f_v}{J}s+a_{\Omega m}} \qquad (31)
\end{aligned}$$

And

$$\mathcal{L}\left\{\frac{d\vartheta_2}{dt}\right\} = -\kappa_{\Omega 2}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial\vartheta_2} \tag{32}$$

$$\begin{aligned}
\vartheta_2 &= -\frac{\kappa_{\Omega 2}}{s}\left(\int_0^T e(\tau)d\tau\right) \\
&\quad \frac{\partial G_{BF\Omega}(s)}{\partial\vartheta_2}U_{\Omega c}(s) \\
\vartheta_2 &= -\frac{\kappa_{\Omega 2}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{a_{\Omega m}}{s^2+\frac{f_v}{J}s+a_{\Omega m}} \\
&\quad .U_{\Omega c}(s).\frac{s\left(s+\frac{f_v}{J}\right)}{s^2+\frac{f_v}{J}s+a_{\Omega m}}.\frac{1}{s+\vartheta_2} \\
&= -\frac{\kappa_{\Omega 2}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{s+\vartheta_2}.\Omega_m(s)
\end{aligned}$$

$$\frac{s\left(s+\frac{f_v}{J}\right)}{s^2+\frac{f_v}{J}s+a_{\Omega m}} \tag{33}$$

4 Simulation and results

To examine practical usefulness, the proposed regulator has been simulated for a PMSM (see [7]), whose parameters are depicted in Table 1.

Parameters	Notation	Value	Unit
p	Pairs of poles	4	
L_d	d-inductance	$9.\ 10^{-4}$	$Kg.m^2$
L_q	q-Inductance	0.02682	H
Ψ_r	Flux linkage	0.1750	Wb
R	Stator resistance	2.875	Ω
f_v	Friction factor	$2.\ 10^{-2}$	$N.m.s$
J	Inertia	$8.\ 10^{-4}$	$Kg.m^2$

Table 1: PMSM parameters used in simulations.

The vector of machine state is initialized whit $\left[\begin{array}{cccc} i_{sd} & i_{sq} & \psi_{rd} & \Omega \end{array}\right]^T = \left[\begin{array}{cccc} 0 & 0 & 0.2 & 0 \end{array}\right]^T$, and the results are given for the machine of which a direct starting, i.e. a resistive torque null ($T_l = 0$). We conceived simulation by carrying out the diagram general in blocks as the figure shows it (FIG.3). We show a detailed scheme SIMULINK of the control with PI adaptive regulator in Fig.4.

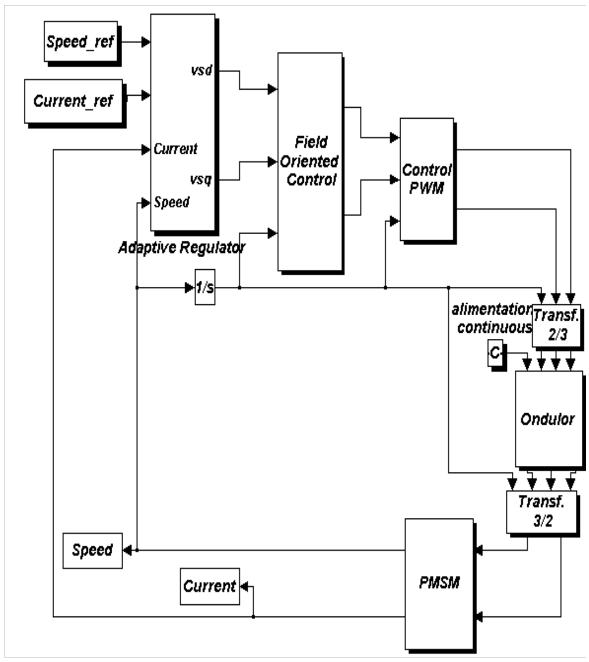

Figure 3: Diagram general of FOC with PI adaptatif regulator with reference model.

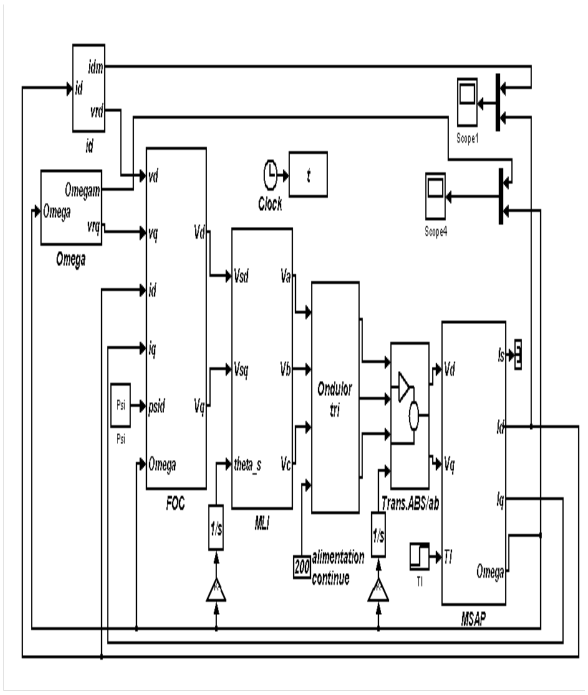

Figure 4: SIMULINK of FOC with PI adaptatif regulator with reference model.

The figure (FIG.5) shows the evolution direct current, this last does not follow the trajectory desired in transient state. Like there are disturbances at the moment $1.2s$ due to the starting speed. Then at the moment $4.5s$ there is another disturbance because of speed shifting. The means direct current error is $-0.1583A$ and the variance is 0.1255 see (FIG.6).

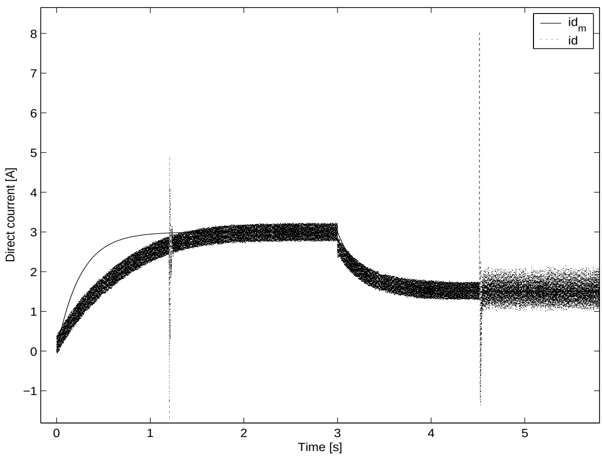

Figure 5: Direct current performance.

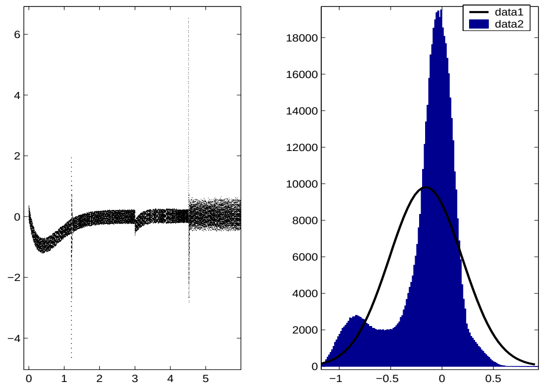

Figure 6: Error direct current performance.

The pace (FIG.7) presents the rotating speed trajectory. It is noted that the curve misses the pace desired in transient state but it follows it in steady operation, in figure (FIG.8) the error speed means is $-2.5395rad/s$ and its variance is 636.1884.

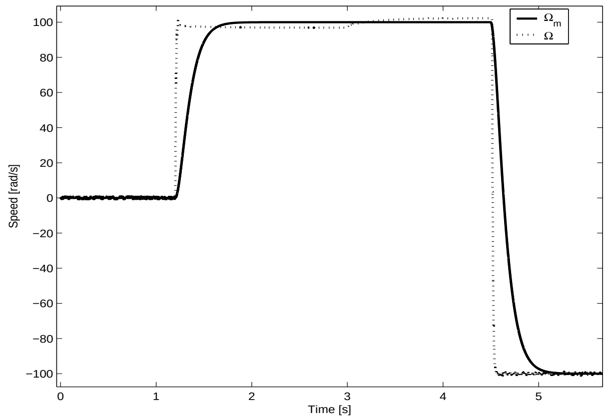

Figure 7: Rotating speed performance.

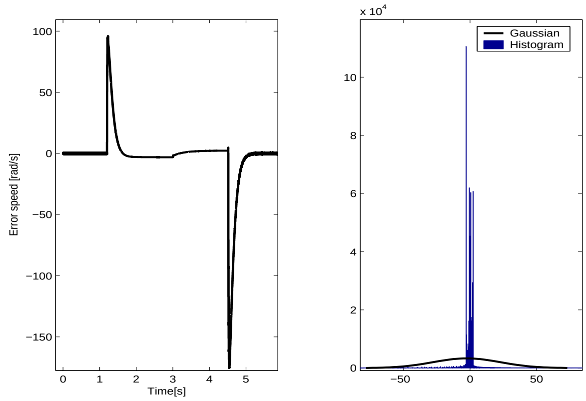

Figure 8: Error rotating speed performance.

Evolution of the adjustable parameters θ_1 and θ_2 is shown by the figure (FIG.9); ϑ_1, ϑ_2 by (FIG.10).

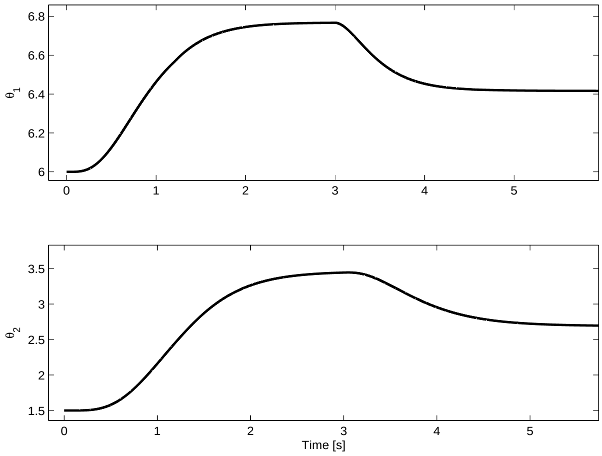

Figure 9: Parameters θ_1 and θ_2.

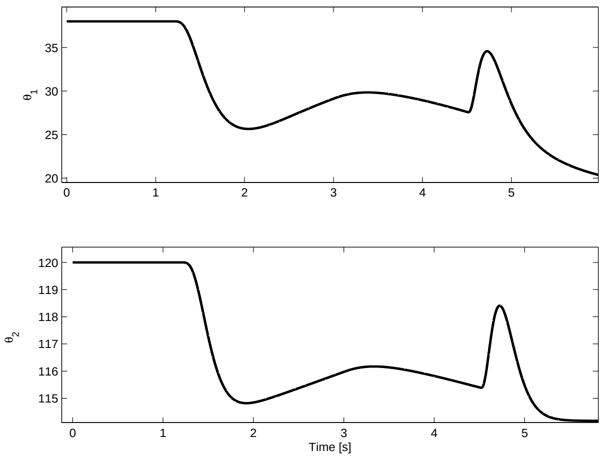

Figure 10: Parameters ϑ_1 and ϑ_2.

5 Conclusion

we clarified FOC control for PMSM. The uncoupling control, us made it possible to use adaptive regulators and to have an effect uncoupled on the regulation from direct current and rotating speed.

The two regulators used are PI adaptive in the control loops of the direct current and of rotating speed. The results are good. Simulations show the effectiveness of adaptation.

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