Adaptive Field-Oriented Control with PD Regulator for the Induction Machine

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Abstract: In all the research tasks, the researchers use regulator PI. In this work, one treats the Field-Oriented Control (FOC) where the regulator is PD. Simulation is made by the software MATLAB/SIMULINK.

Key–Words: Field-Oriented Control (FOC); Reference Adaptative Control (MRAC); Proportional-Derive(PD); Induction Machine.

Nomenclature

- L_s : Stator inductance cyclic ,
- L_r : Rotor inductance cyclic ,
- M : Cyclic mutual inductance between stator and rotor
- R_s : Stator resistance,
- R_r : Rotor resistance,
- σ : Scattering coefficient,
- T_r : Time constant of the rotor dynamics,
- J : Rotor inertia,
- T_l : Resistive torque,
- p : Pole pair motor,
- $\mathcal{I}_2$: is the 2-dimensional identity matrix,
- $\mathcal{J}_2$: is a skew - symmetric matrix.

1 Synthesis of Field-Oriented Control

For an asynchronous machine supplied with tension, tensions stator V_{sd} and V_{sq} are the variables of control, and we consider rotor flux, the currents stator and the mechanical speed like variables of state [1].

$$\begin{bmatrix} \dot{i}_{sd} \\ \dot{i}_{sq} \\ \dot{\psi}_{rd} \\ \dot{\psi}_{rq} \end{bmatrix} = \begin{bmatrix} -\gamma & \omega_s & \frac{K}{T_r} & pK\Omega \\ -\omega_s & -\gamma & -pK\Omega & \frac{K}{T_r} \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & \omega_s - p\Omega \\ 0 & \frac{M}{T_r} & -(\omega_s - p\Omega) & -\frac{1}{T_r} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix}$$

$$\dot{\Omega} = \frac{p}{J}\frac{M}{L_r}\left(i_{sq}\psi_{rd} - i_{sd}\psi_{rq}\right) - \frac{f_v}{J}\Omega - \frac{T_l}{J}$$

$$\dot{T}_l = 0 \tag{1}$$

The parameters are defined as follows:

$$T_r = \frac{L_r}{R_r} \quad ; \quad \sigma = 1 - \frac{M^2}{L_s L_r}$$
$$K = \frac{M}{\sigma L_s L_r} \quad ; \quad \gamma = \frac{R_s}{\sigma L_s} + \frac{R_r M^2}{\sigma L_s L_r}$$
$$\mathcal{I}_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad ; \quad \mathcal{J}_2 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$
$$A(\Omega) = \frac{1}{T_r}\mathcal{I}_2 - p\Omega\mathcal{J}_2 \quad .$$

The stator pulsation is not exploitable since ψ_r is null with the starting of the machine. We will use for establishment, the following equation:

$$\omega_s = \frac{d\theta_s}{dt} = p\Omega + \frac{M}{T_r}\frac{i_{sq}}{\psi_r + \varepsilon} \tag{2}$$

The vectorial field-oriented control is based on an orientation of the turning reference mark of axes (d, q) such as the axis d that is to say confused with the direction of ψ_r [1].

The flux ψ_r being directed on the axis d, the equation of state (1) us allows to express V_{sd}, V_{sq}, ψ_r and ω_s with $\psi_{rq} = 0$ and $\psi_{rd} = \psi_r$. The following equations are obtained [2] :

$$\begin{cases} \dot{i}_{sd} = -\gamma i_{sd} + \omega_s i_{sq} + \frac{K}{T_r}\psi_r + \frac{1}{\sigma L_s}V_{sd} \\ \dot{i}_{sq} = -\omega_s i_{sd} - \gamma i_{sq} - pK\Omega\psi_r + \frac{1}{\sigma L_s}V_{sq} \\ \dot{\psi}_r = \frac{M}{T_r}i_{sd} - \frac{1}{T_r}\psi_r \\ 0 = \frac{M}{T_r}i_{sq} - (\omega_s - p\Omega)\psi_r \\ \dot{\Omega} = \frac{p}{J}\frac{M}{L_r}i_{sq}\psi_{rd} - \frac{f_v}{J}\Omega - \frac{T_l}{J} \end{cases} \tag{3}$$

Closely connected of uncoupled the two first equations from the system (3). We define two new variables of order

v_{sd} and v_{sq} :

$$\begin{cases} V_{sd} = v_{sd} - e_{sd} \\ V_{sq} = v_{sq} - e_{sq} \end{cases} \quad (4)$$

Where v_{sd} and v_{sq} are the terms of coupling given by :

$$\begin{cases} e_{sd} = \sigma L_s \left(\omega_s i_{sq} + \frac{K}{T_r}\psi_r\right) \\ e_{sq} = \sigma L_s \left(\omega_s i_{sd} + pK\Omega\psi_r\right) \end{cases} \quad (5)$$

and orders it uncoupling

$$\begin{cases} v_{sd} = \sigma L_s \left(\dot{i_{sd}} + \gamma i_{sd}\right) \\ v_{sq} = \sigma L_s \left(\dot{i_{sq}} + \gamma i_{sq}\right) \end{cases} \quad (6)$$

Transfer functions of this system uncoupled while taking as in-puts $v_{sd}, \ v_{sq}$ and as out-puts $i_{sd}, \ i_{sq}$ and :

$$\begin{cases} \dfrac{i_{sd}}{v_{sd}} = \dfrac{1}{\sigma L_s (s+\gamma)} \\ \dfrac{i_{sq}}{v_{sq}} = \dfrac{1}{\sigma L_s (s+\gamma)} \end{cases} \quad (7)$$

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

Flux regulator :

The combination enters the third equation of the system (3) and the first of the system (7), we will have

$$\psi_r = \frac{M}{L_s T_r \sigma} \cdot \frac{1}{\left(s+\frac{1}{T_r}\right)(s+\gamma)} v_{sd} \quad (8)$$

We wish to obtain in closed loop a response of the type 2^{nd} order. To achieve this objective, one takes an adaptive proportional-derive regulator with MRAC of the type:

$$PD_{\psi}(s) = k_{D\psi} s + k_{P\psi} = \rho_1 s + \rho_2 \quad (9)$$

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

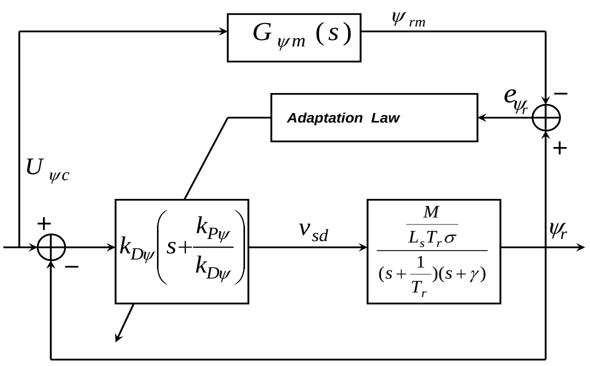

Figure 1: Diagram block in closed loop of PD adaptive regulator with model reference of flux.

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

$$G_{\psi m}(s) = \frac{b_{\psi m}}{s + a_{\psi m}}$$

That is to say the optimality criterion $J(e)$ of the adjustment loop is expressed by the quadratic integral [3]:

$$J(e) = |e| \quad (10)$$

Its derivative is :

$$\frac{\partial J(e)}{\partial e} = sign(e) \quad (11)$$

The out-put is written:

$$\Psi(s) = \frac{(\rho_1 s + \rho_2) K_{\psi}}{s^2 + \left(\frac{1}{T_r} + \gamma\right) s + \frac{\gamma}{T_r} + (\rho_1 s + \rho_2) K_{\psi}} U_{\psi c}(s) \quad (12)$$

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

$$\frac{1}{T_r} = \frac{k_{P\psi}}{k_{D\psi}} = \frac{\rho_2}{\rho_1} \quad (13)$$

In open loop, the transfer function is written:

$$G_{BO\psi}(s) = \frac{\rho_1 K_{\psi}}{s+\gamma} \text{ with } K_{\psi} = \frac{M}{L_s T_r \sigma} \quad (14)$$

And in closed loop:

$$G_{BF\psi}(s) = \frac{\rho_1 K_{\psi}}{s + \gamma + \rho_1 K_{\psi}} \quad (15)$$

If the condition (13) is not considered, therefore one will have

$$G_{BF\psi}(s) = \frac{(\rho_1 s + \rho_2) K_{\psi}}{\left(s+\frac{1}{T_r}\right)(s+\gamma) + K_{\psi}(\rho_1 s + \rho_2)} \quad (16)$$

One calculates the adjustable parameters ρ_1 and ρ_2:

$$\frac{\partial G_{BF\psi}(s)}{\partial \rho_1} = \frac{b_{\psi m}}{s + a_{\psi m}} \cdot \frac{s}{\rho_1 s + \rho_2} \cdot \frac{s + a_{\psi m} - b_{\psi m}}{s + a_{\psi m}} \quad (17)$$

$$\frac{\partial G_{BF\psi}(s)}{\partial \rho_2} = \frac{1}{\rho_1 s + \rho_2} \cdot \frac{s + a_{\psi m} - b_{\psi m}}{s + a_{\psi m}} \cdot \frac{b_{\psi m}}{s + a_{\psi m}} \quad (18)$$

Where $b_{\psi m} = \rho_1 K_{\psi}$ and $a_{\psi m} = \gamma + \rho_1 K_{\psi}$.

Taking into account (11), (17) and (18), one can write the equation of gradient ρ_1 and ρ_2:

$$\mathcal{L}\left\{\frac{d\rho_1}{dt}\right\} = -\kappa_{\psi 1}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \rho_1} \qquad (19)$$

$$\rho_1 = -\frac{\kappa_{\psi 1}}{s}.sign(e).\frac{\partial G_{BF\psi}(s)}{\partial \rho_1}U_{\psi c}(s)$$

$$\rho_1 = -\frac{\kappa_{\psi 1}}{s}sign(e).\frac{1}{\rho_1}.\frac{s+a_{\psi m}-b_{\psi m}}{s+a_{\psi m}}.\frac{b_{\psi m}}{s+a_{\psi m}}.U_{\psi c}(s)$$

$$\rho_1 = -\frac{\kappa_{\psi 1}}{s}.sign(e).\frac{1}{\rho_1}.\frac{s+a_{\psi m}-b_{\psi m}}{s+a_{\psi m}}.\psi_m(s) \qquad (20)$$

And

$$\mathcal{L}\left\{\frac{d\rho_2}{dt}\right\} = -\kappa_{\psi 2}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \rho_2} \qquad (21)$$

$$\rho_2 = -\frac{\kappa_{\psi 2}}{s}sign(e)\frac{\partial G_{BF\psi}(s)}{\partial \rho_2}U_{\psi c}(s)$$

$$\rho_2 = -\frac{\kappa_{\psi 1}}{s}sign(e).\frac{1}{\rho_1 s+\rho_2}.\frac{s+a_{\psi m}-b_{\psi m}}{s+a_{\psi m}}.\frac{b_{\psi m}}{s+a_{\psi m}}.U_{\psi c}(s)$$

$$\rho_2 = -\frac{\kappa_{\psi 2}}{s}.sign(e).\frac{1}{\rho_1 s+\rho_2}.\frac{s+a_{\psi m}-b_{\psi m}}{s+a_{\psi m}}.\psi_m(s) \qquad (22)$$

Speed regulator:

According to the mechanical equation of the machine (3); we have :

$$\Omega = \frac{1}{Js+f_v}\left(T_{em}-T_l\right) \qquad (23)$$

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

$$T_{em} = \frac{pM}{L_r}i_{sq}\psi_{rd} \qquad (24)$$

While replacing, i_{sq} the system (7) in the torque (24)

$$T_{em} = \frac{pM}{L_r}\psi_{rd}.\frac{1}{\sigma L_s\left(s+\gamma\right)}.v_{sq} \qquad (25)$$

Therefore, equation (23) becomes :

$$\Omega = \frac{\frac{pM}{\sigma L_s L_r}\psi_{rd}}{\left(Js+f_v\right)\left(s+\gamma\right)}.v_{sq} - \frac{1}{Js+f_v}T_l \qquad (26)$$

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

$$PD_\Omega(s) = k_{P\Omega}+k_{D\Omega}s = \varrho_1 s+\varrho_2 \qquad (27)$$

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

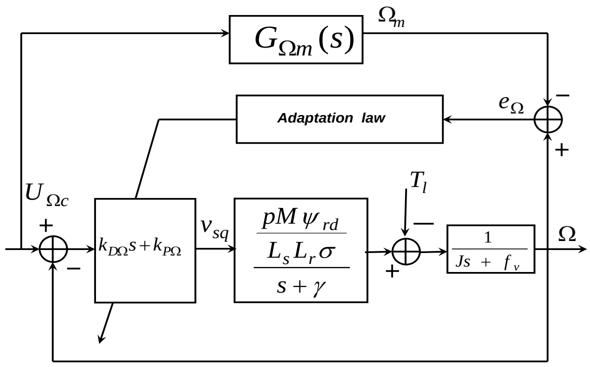

Figure 2: Diagram block in loop closed of PD adaptive regulator to model reference speed .

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

$$G_{\Omega m}(s) = \frac{b_{\Omega m}}{s+a_{\Omega m}}$$

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

$$\frac{f_v}{J} = \frac{k_{P\Omega}}{k_{D\Omega}} = \frac{\varrho_2}{\varrho_1} \qquad (28)$$

In open loop, the transfer function is written:

$$G_{BO\Omega}(s) = \frac{\varrho_1 K_\Omega \psi_{rd}}{s+\gamma} \text{ with } K_\Omega = \frac{pM}{JL_sL_r\sigma} \qquad (29)$$

And in closed loop:

$$G_{BF\Omega}(s) = \frac{\varrho_1 K_\Omega \psi_{rd}}{s+\gamma+\varrho_1 K_\Omega\psi_{rd}} \qquad (30)$$

If the condition (28) is not considered, therefore one will have

$$G_{BF\Omega}(s) = \frac{\left(\rho_1 s+\varrho_2\right)K_\Omega\psi_{rd}}{\left(s+\frac{f_v}{J}\right)\left(s+\gamma\right)+K_\Omega\psi_{rd}\left(\varrho_1 s+\varrho_2\right)} \qquad (31)$$

The adjustable parameter is calculated ϱ_1 and ϱ_2 :

$$\frac{\partial G_{BF\Omega}(s)}{\partial \varrho_1} = \frac{b_{\Omega m}}{s+a_{\Omega m}}.\frac{1}{\varrho_1}.\frac{s+a_{\Omega m}-b_{\Omega m}}{s+a_{\Omega m}} \qquad (32)$$

$$\frac{\partial G_{BF\Omega}(s)}{\partial \varrho_2} = \frac{1}{\varrho_1 s+\varrho_2}.\frac{s+a_{\Omega m}-b_{\Omega m}}{s+a_{\Omega m}}.\frac{b_{\Omega m}}{s+a_{\Omega m}} \qquad (33)$$

Where $b_{\Omega m} = \varrho_1 K_\Omega \psi_{rd}$ and $a_{\Omega m} = \gamma + \varrho_1 K_\Omega \psi_{rd}$.

Taking into account (11), (32) and (33), one can write the gradient equation ϱ_1 and ϱ_2 :

$$\begin{aligned}
\mathcal{L}\left\{\frac{d\varrho_1}{dt}\right\} &= -\kappa_{\Omega 1}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \varrho_1} && (34)\\
\varrho_1 &= -\frac{\kappa_{\Omega 1}}{s}.sign(e)\frac{\partial G_{BF\Omega}(s)}{\partial \varrho_1}U_{\Omega c}(s)\\
\varrho_1 &= -\frac{\kappa_{\Omega 1}}{s}.sign(e).\frac{1}{\varrho_1}.\frac{s+a_{\Omega m}-b_{\Omega m}}{s+a_{\Omega m}}.\\
&\quad \frac{b_{\Omega m}}{s+a_{\Omega m}}.U_{\Omega c}(s)\\
&= -\frac{\kappa_{\Omega 1}}{s}.sign(e).\frac{1}{\varrho_1}.\frac{s+a_{\Omega m}-b_{\Omega m}}{s+a_{\Omega m}}.\Omega_m(s) && (35)
\end{aligned}$$

And

$$\begin{aligned}
\mathcal{L}\left\{\frac{d\varrho_2}{dt}\right\} &= -\kappa_{\Omega 2}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \varrho_2} && (36)\\
\varrho_2 &= -\frac{\kappa_{\Omega 2}}{s}.sign(e).\frac{\partial G_{BF\Omega}(s)}{\partial \varrho_2}U_{\Omega c}(s)\\
\vartheta_2 &= -\frac{\kappa_{\Omega 2}}{s}.sign(e).\frac{1}{\varrho_1 s+\varrho_2}.\frac{s+a_{\Omega m}-b_{\Omega m}}{s+a_{\Omega m}}.\\
&\quad \frac{b_{\Omega m}}{s+a_{\Omega m}}U_{\Omega c}(s)\\
&= -\frac{\kappa_{\Omega 2}}{s}.sign(e).\frac{s+a_{\Omega m}-b_{\Omega m}}{s+a_{\Omega m}}.\\
&\quad \frac{1}{\varrho_1 s+\varrho_2}.\Omega_m(s) && (37)
\end{aligned}$$

2 Results and Simulations

We conceived simulation by carrying out the diagram general in blocks as the figure shows it (Fig.3).

2.1 Simulation Block Diagrams, Machine Data and a Benchmark

We ride a detailed scheme SIMULINK of the MRAC regulator in figure (FIG.4).

In addition to that, we perform a simulation with MATLAB-SIMULINK by using the benchmark in (FIG. 3) and the asynchronous machine parameters given in Table 1.

Parameters	Notation	Value	Unit
Poles pairs	p	2	
Stator resistance	R_s	9.65	Ω
Rotor resistance	R_r	4.3047	Ω
Stator inductance	L_s	0.4718	H
Rotor inductance	L_r	0.4718	H
Mutual Inductance	M	0.4475	H
Rotor inertia	J	0.0293	$Kg.m^2$
viscous damping coefficient	f_v	0.0001	$Nm.s/rad$
Resistive torque	T_l	0	$N.m$

Table 1: Parameters of the asynchronous machine.[4]

2.2 Powerful of MRAC based FOC

The vector of machine state is initialized whit $\begin{bmatrix} i_{s\alpha} & i_{s\beta} & \psi_{r\alpha} & \psi_{r\alpha} & \Omega \end{bmatrix}^T = \begin{bmatrix} 0 & 0 & 0.2 & 0 & 0 \end{bmatrix}^T$, and the results are given for the machine of which a direct starting.

The figure (FIG.5) shows the pace of desired flux and flux reference. One notices desired flux follows very well his reference with a respect to the transient state and the moment $t = 2s$ where speed changes its direction. The means flux error is $-32.2mWb$ with a variance 14.9×10^{-3} to see the figure (FIG.6)

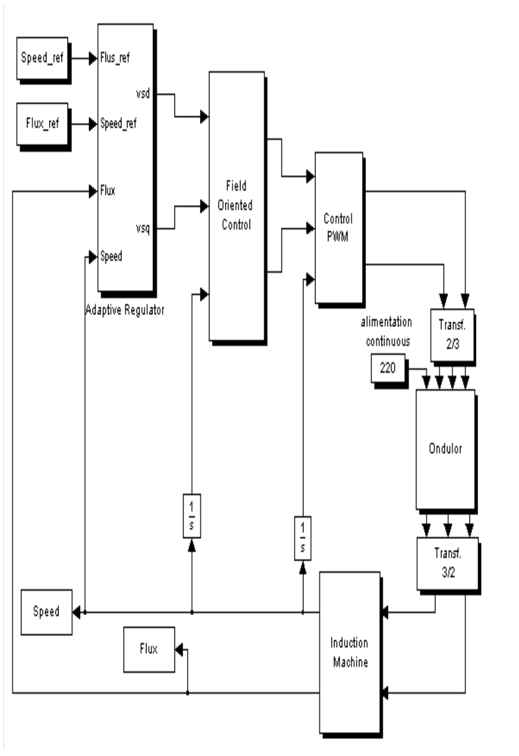

Figure 3: Diagram general of FOC with MRAC regulator.

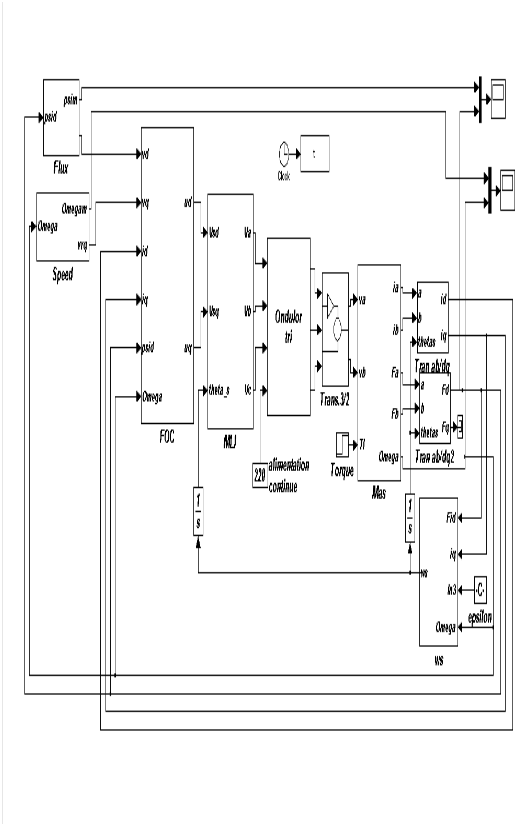

Figure 4: SIMULINK of FOC with MRAC regulator.

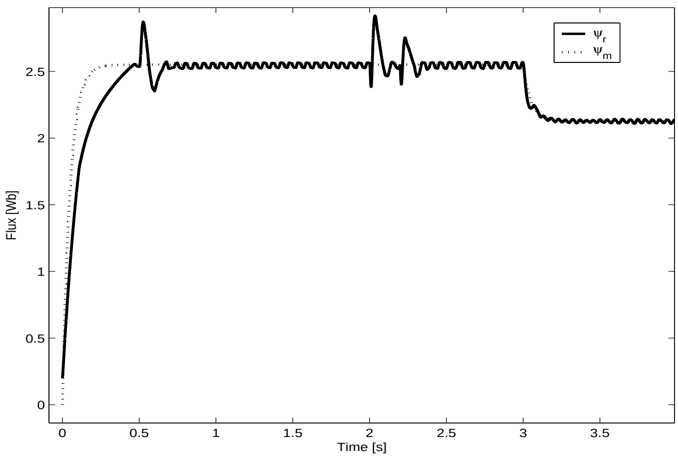

Figure 5: Flux performance.

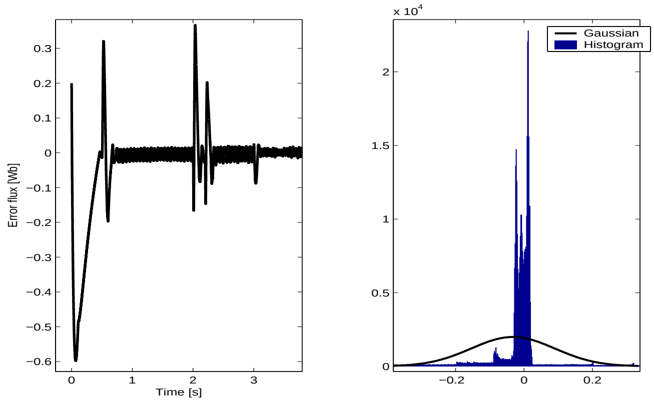

Figure 6: Flux errors of control.

The curves of the figure (FIG.7) give desired speed and controlled speed; there are differences right in the transient states at moment $t = 0.5s$ and $t = 2s$, with a very weak means of error which is $-0.6441 rad/s$ and variance 99.497 to go up to the figure (FIG.8).

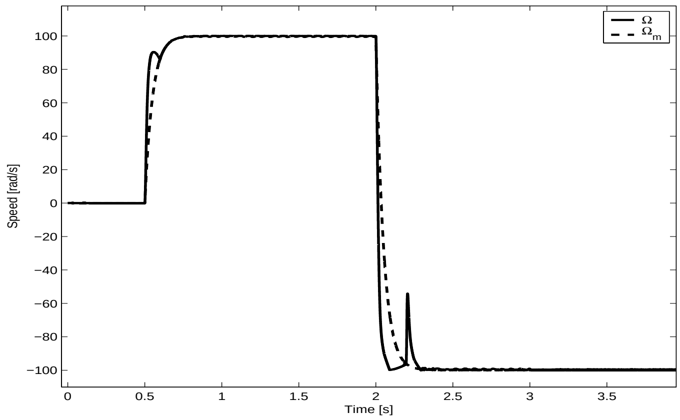

Figure 7: Speed performance.

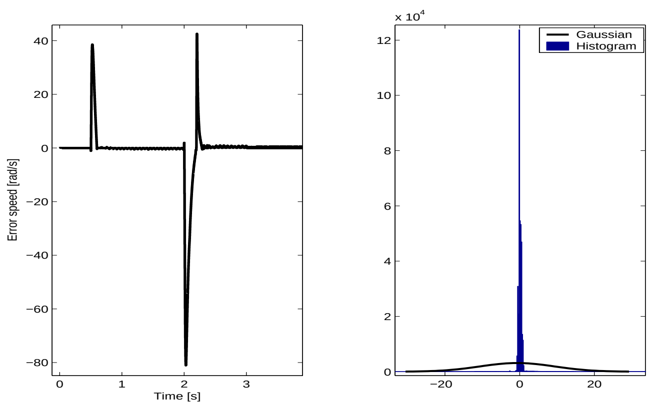

Figure 8: Speed errors of control.

The evolutions of the self-adjustable parameters ρ_1 and ρ_2 gave by the figure (FIG.9) and of the parameters ϱ_1 and ϱ_2 by the figure (FIG.10)

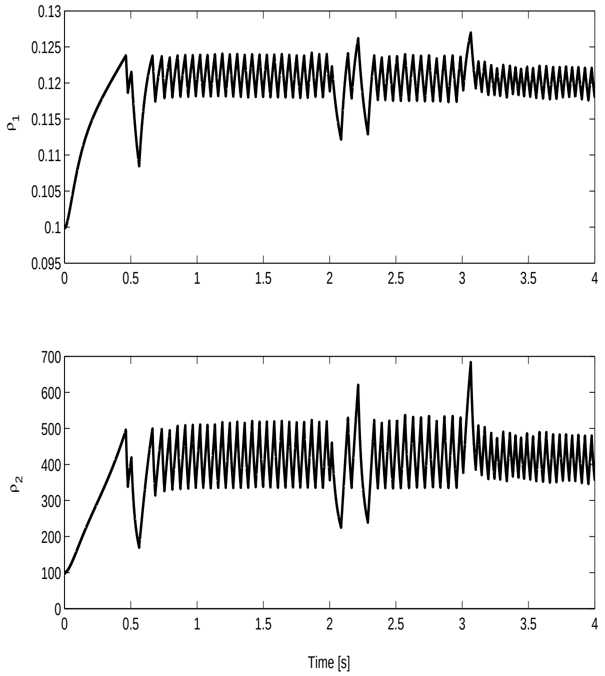

Figure 9: Parameters ρ_1 and ρ_2.

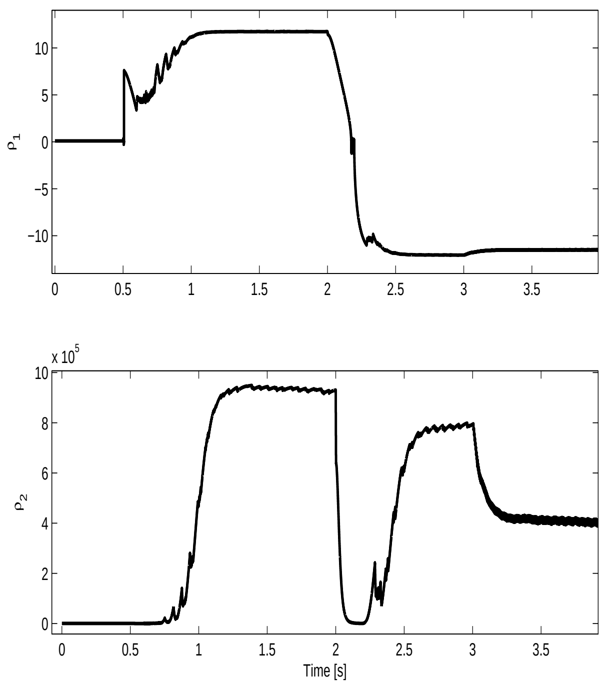

Figure 10: Parameters ϱ_1 and ϱ_2.

3 Conclusion

We clarified FOC control. The uncoupling control, us made it possible to use adaptive regulators and to have an effect uncoupled on the regulation from rotor flux and rotating speed.

The two regulators used are PD adaptive in the control loops of the rotor flux and of rotating speed. The results are very well. Simulations show the effectiveness of adaptation.

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