New Approach of Adaptive Field-Oriented Control with MRAC Regulator for the Asynchronous Motor

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Abstract: In this article, one gives a new approach to calculate the gain adjustment parameters of the Field-Oriented Control (FOC) based on regulator Model Reference Adaptative Control (MRAC), where the derivative of the performance function is function $signe$. This technique enables us to eliminate all the motor parameters in the adaptation law. What facilitates the adjustment, the convergence of the paces and gives good performances.

Key–Words: Field-Oriented Control (FOC); Model Reference Adaptative Control (MRAC); Asynchronous Motor.

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 motor 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].

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

$$\begin{aligned} \dot{\Omega} &= \frac{p}{J}\frac{M}{L_r}(i_{sq}\psi_{rd} - i_{sd}\psi_{rq}) - \frac{f_v}{J}\Omega - \frac{T_l}{J} \\ \dot{T_l} &= 0 \end{aligned} \qquad (1)$$

The parameters are defined as follows:

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

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

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

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] :

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

Closely connected of uncoupled the two first equations from the system (3). We define two new variables of order v_{sd} and v_{sq} :

$$\begin{cases} V_{sd} = v_{sd} - e_{sd} \\ V_{sq} = v_{sq} - e_{sq} \end{cases} \tag{4}$$

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

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

and orders it uncoupling

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

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

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

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

$$\Psi = \frac{M}{L_s T_r \sigma}.\frac{1}{\left(s+\frac{1}{T_r}\right)(s+\gamma)} v_{sd} \tag{8}$$

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

$$v_{sd}(s) = \rho_1 U_{\psi c} - \rho_2 \Psi \tag{9}$$

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

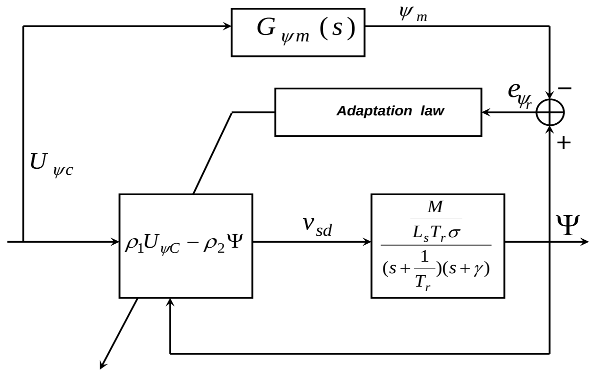

Figure 1: Diagram block in closed loop of MRAC regulator of flux.

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

$$G_{\psi m}(s) = \frac{b_{\psi m}}{s^2 + a_{1\psi m}s + a_{0\psi m}}$$

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

$$J(e) = |e| \tag{10}$$

Its derivative is :

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

The out-put is written:

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

With $K_\psi = \frac{M}{L_s T_r \sigma}$. The error $e = \Psi - \psi_m$, its derivative compared to the parameters gives :

$$\frac{\partial e}{\partial \rho_1} = \frac{K_\psi}{s^2 + \left(\frac{1}{T_r} + \gamma\right)s + \frac{\gamma}{T_r} + \rho_2 K_\psi} U_{\psi c}(s) \tag{13}$$

$$\begin{aligned} \frac{\partial e}{\partial \rho_2} &= \frac{-\rho_1 K_\psi^2}{\left(s^2 + \left(\frac{1}{T_r} + \gamma\right)s + \frac{\gamma}{T_r} + \rho_2 K_\psi\right)^2} U_{\psi c}(s) \\ &= \frac{-K_\psi}{s^2 + \left(\frac{1}{T_r} + \gamma\right)s + \frac{\gamma}{T_r} + \rho_2 K_\psi} \\ &\quad \frac{\rho_1 K_\psi}{s^2 + \left(\frac{1}{T_r} + \gamma\right)s + \frac{\gamma}{T_r} + \rho_2 K_\psi} U_{\psi c}(s) \end{aligned} \tag{14}$$

For $e = 0 \Rightarrow \Psi = \psi_m$ then $\frac{\gamma}{T_r} + \rho_2 K_\psi = a_{0\psi m}$, $\frac{1}{T_r} + \gamma = a_{1\psi m}$ and $\rho_1 K_\psi = b_{\psi m}$.

$$\begin{aligned} \frac{\partial e}{\partial \rho_1} &= \frac{1}{\rho_1}.\frac{b_{\psi m}}{s^2 + a_{1\psi m}s + a_{0\psi m}}U_{\psi c}(s) \\ &= \frac{1}{\rho_1}.\psi_m \qquad (15) \end{aligned}$$

$$\begin{aligned} \frac{\partial e}{\partial \rho_2} &= \frac{-1}{\rho_1}.\frac{(\rho_1 K_\psi)^2}{\left(s^2 + \left(\frac{1}{T_r} + \gamma\right)s + \frac{\gamma}{T_r} + \rho_2 K_\psi\right)^2}U_{\psi c}(s) \\ &= \frac{-1}{\rho_1}.\frac{b_{\psi m}^2}{(s^2 + a_{1\psi m}s + a_{0\psi m})^2}U_{\psi c}(s) \\ &= \frac{-1}{\rho_1}.\frac{b_{\psi m}}{s^2 + a_{1\psi m}s + a_{0\psi m}}.\psi_{\psi m} \qquad (16) \end{aligned}$$

Taking into account (11), (15) and (16), one can write the equation of gradient ρ_1 and ρ_2:

$$\mathcal{L}\left\{\frac{d\rho_1}{dt}\right\} = -\kappa_{\psi 1}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \rho_1} \qquad (17)$$

$$\rho_1 = -\frac{\kappa_{\psi 1}}{s}sign(e).\frac{1}{\rho_1}.\psi_m \qquad (18)$$

And

$$\mathcal{L}\left\{\frac{d\rho_2}{dt}\right\} = -\kappa_{\psi 2}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \rho_2} \qquad (19)$$

$$\begin{aligned} \rho_2 &= \frac{\kappa_{\psi 2}}{s}sign(e)\frac{1}{\rho_1}.\psi_m \\ &\quad .\frac{b_{\psi m}}{s^2 + a_{1\psi m}s + a_{0\psi m}} \qquad (20) \end{aligned}$$

Speed regulator:

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

$$\Omega = \frac{1}{Js + f_v}(T_{em} - T_l) \qquad (21)$$

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

$$T_{em} = \frac{pM}{L_r}i_{sq}\psi_{rd} \qquad (22)$$

While replacing, i_{sq} the system (7) in the torque (22)

$$T_{em} = \frac{pM}{L_r}\psi_{rd}.\frac{1}{\sigma L_s(s+\gamma)}.v_{sq} \qquad (23)$$

Therefore, equation (21) becomes :

$$\Omega = \frac{\frac{pM}{\sigma L_s L_r}\psi_{rd}}{(Js + f_v)(s+\gamma)}.v_{sq} - \frac{1}{Js + f_v}T_l \qquad (24)$$

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

$$v_{sq}(s) = \varrho_1 U_{\Omega c} - \varrho_2 \Omega \qquad (25)$$

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

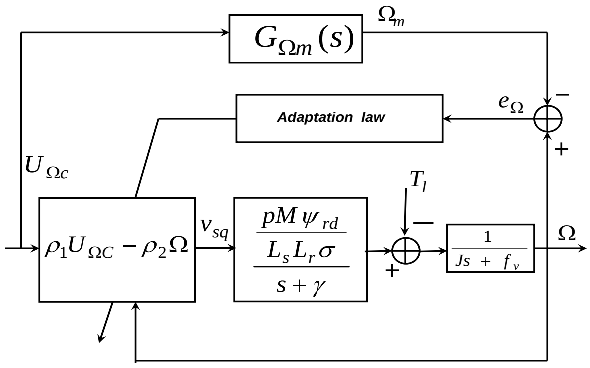

Figure 2: Diagram block in loop closed of MRAC regulator of rotating speed .

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

$$G_{\Omega m}(s) = \frac{b_{\Omega m}}{s^2 + a_{1\Omega m}s + a_{0\Omega m}}$$

The out-put is written:

$$\Omega(s) = \frac{\varrho_1 K_\Omega \Psi}{s^2 + \left(\frac{f_v}{J} + \gamma\right)s + \frac{\gamma f_v}{J} + \varrho_2 K_\Omega \Psi}U_{\Omega c}(s) \quad (26)$$

With $K_\Omega = \frac{pM}{JL_sL_r\sigma}$. The error $e = \Omega - \Omega_m$, its derivative compared to the parameters gives :

$$\frac{\partial e}{\partial \varrho_1} = \frac{K_\Omega \Psi}{s^2 + \left(\frac{f_v}{J} + \gamma\right)s + \frac{\gamma f_v}{J} + \varrho_2 K_\Omega \Psi}U_{\Omega c}(s) (27)$$

$$\begin{aligned} \frac{\partial e}{\partial \varrho_2} &= \frac{-\varrho_1 (K_\Omega \Psi)^2}{\left(s^2 + \left(\frac{f_v}{J} + \gamma\right)s + \frac{\gamma f_v}{J} + \varrho_2 K_\Omega \Psi\right)^2}U_{\Omega c}(s) \\ &= \frac{-\varrho_1 K_\Omega \Psi}{s^2 + \left(\frac{f_v}{J} + \gamma\right)s + \frac{\gamma f_v}{J} + \varrho_2 K_\Omega \Psi}U_{\Omega c}(s) \\ &\quad .\frac{K_\Omega \Psi}{s^2 + \left(\frac{f_v}{J} + \gamma\right)s + \frac{\gamma f_v}{J} + \varrho_2 K_\Omega \Psi} \qquad (28) \end{aligned}$$

So that $e = 0 \Rightarrow \Omega = \Omega_m$ then $\frac{\gamma f_v}{J} + \varrho_2 K_\Omega \Psi = a_{0\Omega m}$; $\frac{f_v}{J} + \gamma = a_{1\Omega m}$ and $\varrho_1 K_\Omega \Psi = b_{\Omega m}$.

$$\begin{aligned} \frac{\partial e}{\partial \varrho_1} &= \frac{1}{\varrho_1}.\frac{b_{\Omega m}}{s^2 + a_{1\Omega m}s + a_{0\Omega m}}U_{\Omega c}(s) \qquad (29) \\ &= \frac{1}{\varrho_1}.\Omega_m \qquad (30) \end{aligned}$$

$$\begin{aligned} \frac{\partial e}{\partial \varrho_2} &= \frac{-b_{\Omega m}}{s^2 + a_{1\Omega m}s + a_{0\Omega}}U_{\Omega c}(s) \\ &\quad \frac{1}{\varrho_1}.\frac{b_{\Omega m}}{s^2 + a_{1\Omega m}s + a_{0\Omega m}} \\ &= -\frac{1}{\varrho_1}.\frac{b_{\Omega m}}{s^2 + a_{1\Omega m}s + a_{0\Omega m}}.\Omega_m(s) \qquad (31) \end{aligned}$$

Taking into account (11), (30) and (31), one can write the equation of gradient ϱ_1 and ϱ_2:

$$\mathcal{L}\left\{\frac{d\varrho_1}{dt}\right\} = -\kappa_{\Omega 1}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \varrho_1} \quad (32)$$

$$\varrho_1 = -\frac{\kappa_{\Omega 1}}{s}.sign(e).\frac{1}{\varrho_1}.\Omega_m \quad (33)$$

And

$$\mathcal{L}\left\{\frac{d\varrho_2}{dt}\right\} = -\kappa_{\Omega 2}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \varrho_2} \quad (34)$$

$$\varrho_2 = \frac{\kappa_{\Omega 2}}{s}sign(e).\frac{1}{\varrho_1}.\Omega_m(s) \cdot \frac{b_{\Omega m}}{s^2 + a_{1\Omega m}s + a_{0\Omega m}} \quad (35)$$

2 Results and Simulations

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

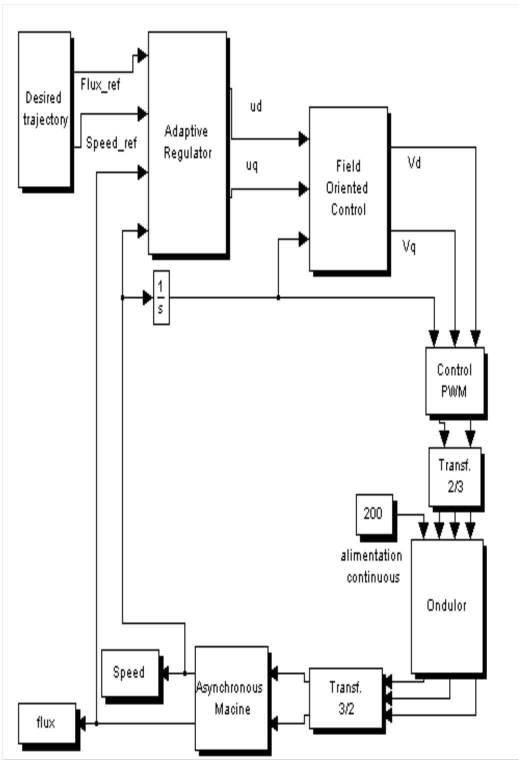

Figure 3: Diagram general of FOC with MRAC regulator.

2.1 Simulation Block Diagrams, Motor 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 motor 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 motor.[4]

2.2 Powerful of MRAC based FOC

The vector of motor 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 motor of which a direct starting.

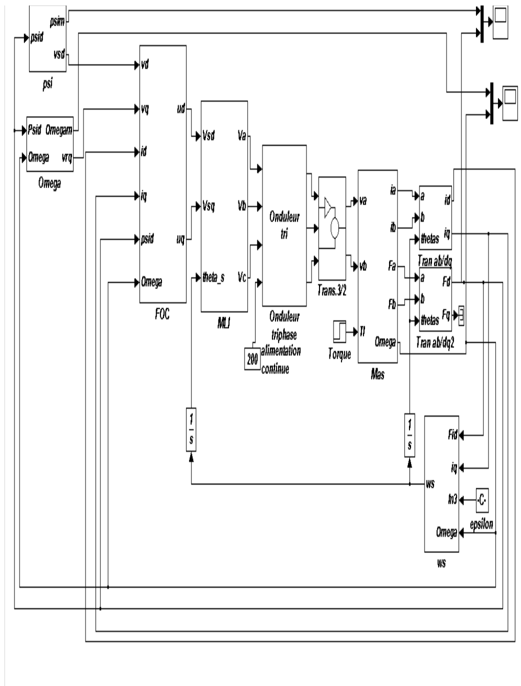

Figure 4: SIMULINK of FOC with MRAC regulator.

In the figure (FIG.5); the pace controlled flux carefully follows the flux wished with a small respect to the transient states at the moments $t_1 = 1.2s$ and $t_2 = 2.5s$. After flux stabilizes itself definitively; the error mean is -5.8049×10^{-4} with a variance of 4.9×10^{-3} to see the figure (FIG.6)

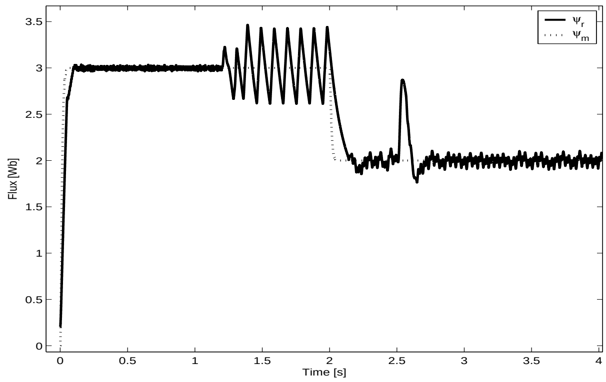

Figure 5: Flux performance.

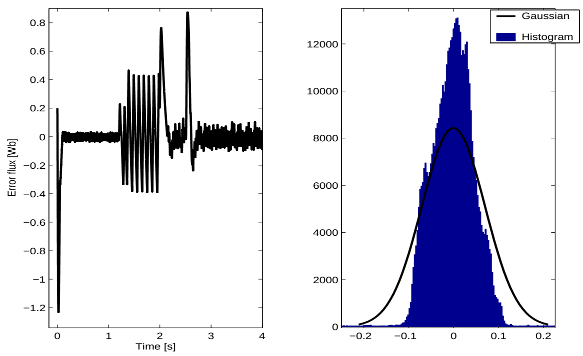

Figure 6: Mean and variance flux errors of control.

The figure (FIG.7) presents the controlled speed curve, which to follow perfectly desired speed except between moments $t_1 = 1.2s$ and $t_2 = 2.5s$ when there are untwistings because of the variations reciprocal of flux and speed. The figure (FIG.8) gives the speed error which has mean equal to $1.8189 rad/s$ and the variance of $22,9274$.

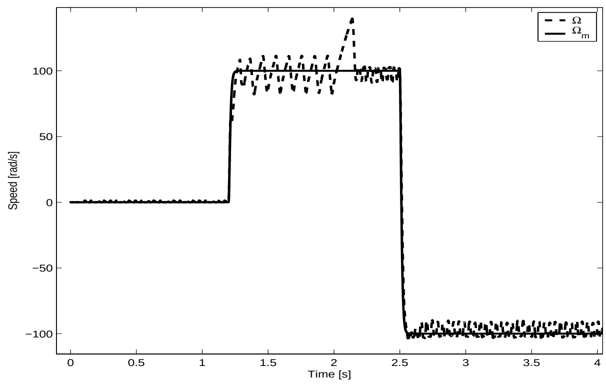

Figure 7: Speed performance.

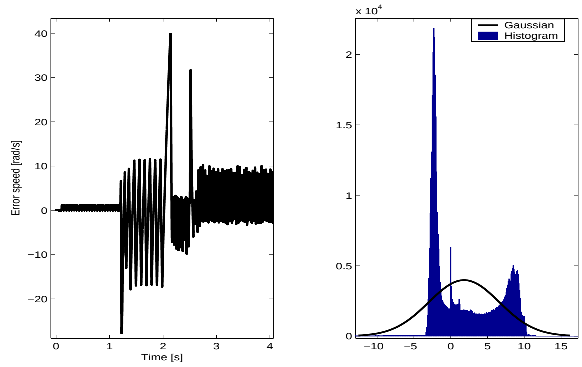

Figure 8: Mean and variance speed errors of control.

The adjustments parameters evolutions of rotor flux is shown in the figure (FIG.9) even for the speed adjustments parameters are shown by the paces of the figure (FIG.10).

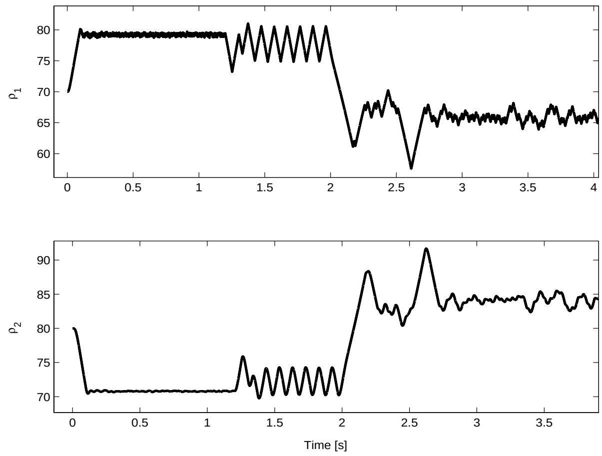

Figure 9: Parameters ρ_1 and ρ_2.

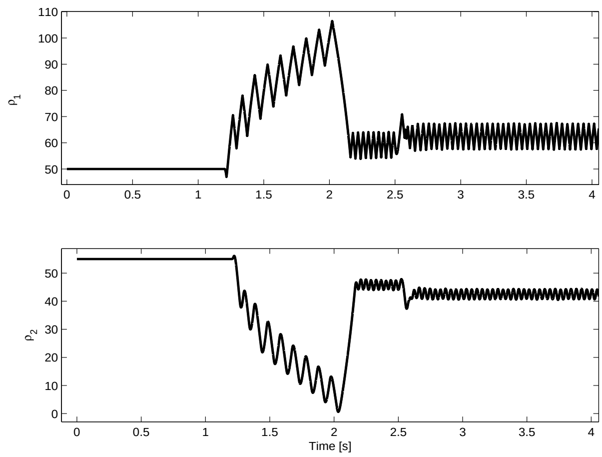

Figure 10: Parameters ϱ_1 and ϱ_2.

3 Conclusion

We showed a new technique which eliminates all the motor parameters in the adaptation law. Even although the performance function is a switching function it there chattering not. The simulation results are perfect.

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