Adaptive Field-Oriented Control for the Asynchronous Machine

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Abstract: The method of groping, to find the parameters of a regulator PI, is very tiring, because of that. In this paper, one proposed a PI adaptif regulator with reference model based on the optimization of a criterion performance to apply to the Field-Oriented Control for asynchronous machine.

Key–Words: Field-Oriented Control (FOC); PI Adaptive regulator; reference model; Asynchronous Machine.

1 Introduction

Effect, the asynchronous machines, because of their low cost and their robustness, currently constitutes the machine the most used to carry out drives at variable speeds. However, to effectively control the dynamics of the couple of an asynchronous machine, it is necessary to employ more elaborate strategies of control. Thus progresses them of data processing, of the power electronics and of the automatic, changes caused significant in the systems design of control/regulator. This development pushed several research laboratories of automatic towards structures of control much more advanced based on methods of automatic to knowing the vectorial - control, adaptive, nonlinear, predictive . . . .

The bases of the theory on vectorial control or Field-Oriented Control (FOC) were developed by BLASCHKE [1], since 1972, this type of control makes it possible to consider a decoupling between the couple and the flux of the machine and to control lead comparable with that of the machines with D.C. current.

Several research tasks use the method of groping [2, 3, 4, 5, 6, 7], to find the parameters of the regulators but this technique is very tiring, or traditional method [8]. In this work, one proposed adaptif PI with model of reference based on the optimization of a criterion performance to apply to the FOC for the asynchronous machine. In the following section, one synthesis FOC where we propose PI adaptif with model of reference based on the optimization of a criterion of performance; after one studies the regulator by simulation and one concludes with the results.

2 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 [9].

$$\begin{aligned}
\begin{bmatrix} \dot{i}_{sd} \\ \dot{i}_{sq} \\ \dot{\psi}_{rd} \\ \dot{\psi}_{rq} \end{bmatrix} &= \begin{bmatrix} -\gamma & \omega_s & \frac{K}{T_r} & pK\Omega \\ -\omega_s & -\gamma & -pK\Omega & \frac{K}{T_r} \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & \omega_s - p\Omega \\ 0 & \frac{M}{T_r} & -(\omega_s - p\Omega) & -\frac{1}{T_r} \end{bmatrix} \\
& \begin{bmatrix} i_{sd} \\ i_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \\
\dot{\Omega} &= \frac{p}{J}\frac{M}{L_r}\left(i_{sq}\psi_{rd} - i_{sd}\psi_{rq}\right) - \frac{f_v}{J}\Omega - \frac{T_l}{J} \\
\dot{T}_l &= 0
\end{aligned} \tag{1}$$

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 machine. We will use for establishment, the following equation:

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

In these equations:

- 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.

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 [9].

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 [10] :

$$\left\{\begin{array}{lcl} \dot{i_{sd}} & = & -\gamma i_{sd} + \omega_s i_{sq} + \frac{K}{T_r}\psi_r + \frac{1}{\sigma L_s}V_{sd} \\ \dot{i_{sq}} & = & -\omega_s i_{sd} - \gamma i_{sq} - pK\Omega\psi_r + \frac{1}{\sigma L_s}V_{sq} \\ \dot{\psi_r} & = & \frac{M}{T_r}i_{sd} - \frac{1}{T_r}\psi_r \\ 0 & = & \frac{M}{T_r}i_{sq} - (\omega_s - p\Omega)\psi_r \\ \dot{\Omega} & = & \frac{p}{J}\frac{M}{L_r}i_{sq}\psi_{rd} - \frac{f_v}{J}\Omega - \frac{T_l}{J} \end{array}\right. \tag{3}$$

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

$$\left\{\begin{array}{lcl} V_{sd} & = & v_{sd} - e_{sd} \\ V_{sq} & = & v_{sq} - e_{sq} \end{array}\right. \tag{4}$$

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

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

and orders it uncoupling

$$\left\{\begin{array}{lcl} v_{sd} & = & \sigma L_s\left(\dot{i_{sd}} + \gamma i_{sd}\right) \\ v_{sq} & = & \sigma L_s\left(\dot{i_{sq}} + \gamma i_{sq}\right) \end{array}\right. \tag{6}$$

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

$$\left\{\begin{array}{lcl} \dfrac{i_{sd}}{v_{sd}} & = & \dfrac{1}{\sigma L_s\left(s+\gamma\right)} \\ \\ \dfrac{i_{sq}}{v_{sq}} & = & \dfrac{1}{\sigma L_s\left(s+\gamma\right)} \end{array}\right. \tag{7}$$

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

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

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

$$PI_\psi(s) = k_{p\psi} + \frac{k_{i\psi}}{s} = \theta_1 + \frac{\theta_2}{s} \tag{9}$$

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

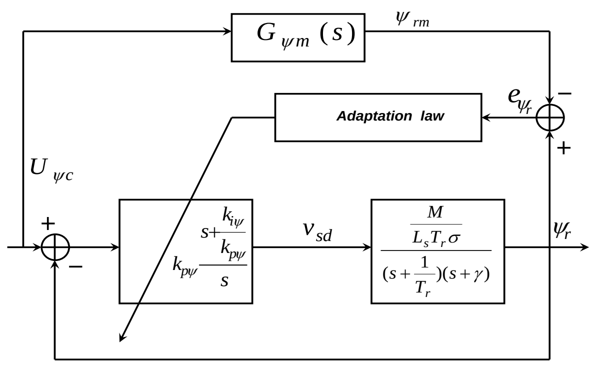

Figure 1: Diagram block in closed loop of PI adaptive regulator with model reference of flux.

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

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

That is to say the optimality criterion $J(e)$ of the adjustment loop is expressed by the quadratic integral [11]:

$$J(e) = \frac{1}{2}\int_0^T e^2(\tau)d\tau \tag{10}$$

Its derivative is :

$$\begin{array}{rcl} \dfrac{\partial J(e)}{\partial e} & = & \dfrac{\partial}{\partial e}\left(\dfrac{1}{2}\displaystyle\int_0^T e^2(\tau)d\tau\right) \\ & = & \dfrac{1}{2}\displaystyle\int_0^T \dfrac{\partial}{\partial e}e^2(\tau)d\tau = \displaystyle\int_0^T e(\tau)d\tau \end{array} \tag{11}$$

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

$$\frac{1}{T_r} = \frac{k_{i\psi}}{k_{p\psi}} = \frac{\theta_2}{\theta_1} \Rightarrow \theta_2 = \frac{\theta_1}{T_r} \tag{12}$$

In open loop, the transfer function is written:

$$G_{BO\psi}(s) = \frac{\theta_1 K_\psi}{s\,(s+\gamma)} \text{ with } K_\psi = \frac{M}{L_s T_r \sigma} \tag{13}$$

And in closed loop:

$$G_{BF\psi}(s) = \frac{\theta_1 K_\psi}{s^2 + \gamma s + \theta_1 K_\psi} \tag{14}$$

If the condition (12) is not considered, therefore one will have

$$G_{BF\psi}(s) = \frac{(\theta_1 s + \theta_2)\,K_\psi}{s\left(s + \frac{1}{T_r}\right)(s+\gamma) + K_\psi\,(\theta_1 s + \theta_2)} \tag{15}$$

One calculates the adjustable parameters θ_1 and θ_2:

$$\frac{\partial G_{BF\psi}(s)}{\partial \theta_1} = \frac{a_{\psi m}}{s^2+\gamma s + a_{\psi m}} . \frac{1}{\theta_1} . \frac{s}{s^2+\gamma s + a_{\psi m}} \tag{16}$$

$$\frac{\partial G_{BF\psi}(s)}{\partial \theta_2} = \frac{a_{\psi m}}{s^2+\gamma s + a_{\psi m}} . \frac{1}{\theta_2\,(T_r s + 1)} \frac{s\,(s+\gamma)}{s^2+\gamma s + \theta_2 T_r K_\psi} \tag{17}$$

Taking into account (11), (16) and (17), one can write the equation of gradient θ_1 and θ_2:

$$\mathcal{L}\left\{\frac{d\theta_1}{dt}\right\} = -\kappa_{\psi 1}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \theta_1} \tag{18}$$

$$\begin{aligned} \theta_1 &= -\frac{\kappa_{\psi 1}}{s}\left(\int_0^T e(\tau)d\tau\right)\frac{\partial G_{BF\psi}(s)}{\partial\theta_1} U_{\psi c}(s) \\ \theta_1 &= -\frac{\kappa_{\psi 1}}{s}\left(\int_0^T e(\tau)d\tau\right) . \frac{1}{\theta_1} \frac{a_{\psi m}}{s^2+\gamma s + a_{\psi m}} . \frac{s}{s^2+\gamma s + a_{\psi m}} U_{\psi c}(s) \\ &= -\frac{\kappa_{\psi 1}}{s}\left(\int_0^T e(\tau)d\tau\right) . \frac{1}{\theta_1} . \psi_m(s) \frac{s}{s^2+\gamma s + a_{\psi m}} \end{aligned} \tag{19}$$

And

$$\mathcal{L}\left\{\frac{d\theta_2}{dt}\right\} = -\kappa_{\psi 2}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \theta_1} \tag{20}$$

$$\begin{aligned} \theta_2 &= -\frac{\kappa_{\psi 2}}{s}\left(\int_0^T e(\tau)d\tau\right)\frac{\partial G_{BF\psi}(s)}{\partial\theta_2} U_{\psi c}(s) \\ \theta_2 &= -\frac{\kappa_{\psi 2}}{s}\left(\int_0^T e(\tau)d\tau\right) . \frac{1}{\theta_2\,(T_r s+1)} \frac{a_{\psi m}}{s^2+\gamma s + a_{\psi m}} . \frac{s\,(s+\gamma)}{s^2+\gamma s + \theta_2 T_r K_\psi} U_{\psi c}(s) \\ &= -\frac{\kappa_{\psi 2}}{s}\left(\int_0^T e(\tau)d\tau\right) . \frac{1}{\theta_2\,(T_r s+1)} . \psi_m(s) \frac{s\,(s+\gamma)}{s^2+\gamma s + \theta_2 T_r K_\psi} \end{aligned} \tag{21}$$

Speed regulator:

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

$$\Omega = \frac{1}{Js + f_v}\,(T_{em} - T_l) \tag{22}$$

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

$$T_{em} = \frac{pM}{L_r} i_{sq} \psi_{rd} \tag{23}$$

While replacing, i_{sq} the system (7) in the torque (23)

$$T_{em} = \frac{pM}{L_r}\psi_{rd} . \frac{1}{\sigma L_s\,(s+\gamma)} . v_{sq} \tag{24}$$

Therefore, equation (22) becomes :

$$\Omega = \frac{\frac{pM}{\sigma L_s L_r}\psi_{rd}}{(Js + f_v)\,(s+\gamma)} . v_{sq} - \frac{1}{Js + f_v} T_l \tag{25}$$

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

$$PI_\Omega(s) = k_{p\Omega} + \frac{k_{i\Omega}}{s} = \vartheta_1 + \frac{\vartheta_2}{s} \tag{26}$$

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

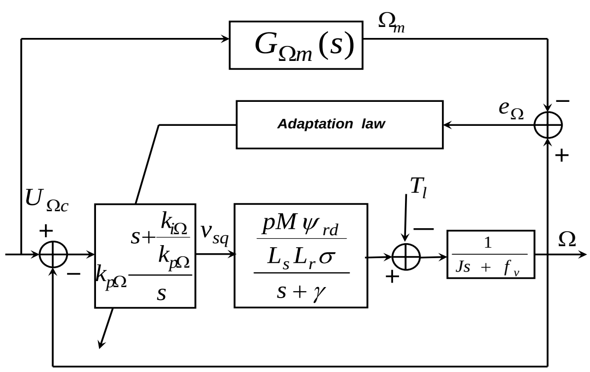

Figure 2: Diagram block in loop closed of PI adaptive regulator to model reference speed .

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

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

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

$$\frac{f_v}{J} = \frac{k_{i\psi}}{k_{p\psi}} = \frac{\vartheta_2}{\vartheta_1} \Rightarrow \vartheta_2 = \frac{f_v}{J}\vartheta_1 \tag{27}$$

In open loop, the transfer function is written:

$$G_{BO\Omega}(s) = \frac{\vartheta_1 K_\Omega \psi_{rd}}{s(s+\gamma)} \text{ avec } K_\Omega = \frac{pM}{JL_sL_r\sigma} \quad (28)$$

And in closed loop:

$$G_{BF\Omega}(s) = \frac{\vartheta_1 K_\Omega \psi_{rd}}{s^2+\gamma s+\vartheta_1 K_\Omega} \quad (29)$$

If the condition (27) is not considered, therefore one will have

$$G_{BF\psi}(s) = \frac{(\vartheta_1 s+\vartheta_2) K_\Omega \psi_{rd}}{s(Js+f_v)(s+\gamma)+K_\Omega \psi_{rd}(\vartheta_1 s+\vartheta_2)} \quad (30)$$

The adjustable parameter is calculated ϑ_1 and ϑ_2 :

$$\begin{aligned} \frac{\partial G_{BF\psi}(s)}{\partial \vartheta_1} &= \frac{a_{\Omega m}}{s^2+\gamma s+a_{\Omega m}}.\frac{1}{\vartheta_1}.\frac{s}{s^2+\gamma s+a_{\Omega m}} \quad (31) \\ \frac{\partial G_{BF\psi}(s)}{\partial \vartheta_2} &= \frac{a_{\Omega m}}{s^2+\gamma s+a_{\Omega m}}.\frac{1}{\vartheta_2}.\frac{f_v}{Js+f_v} \\ & \frac{s(s+\gamma)}{s^2+\gamma s+\vartheta_2 \frac{K_\Omega \psi_{rd}}{f_v}} \quad (32) \end{aligned}$$

Taking into account (11), (31) and (32), one can write the gradient equation ϑ_1 and ϑ_2 :

$$\begin{aligned} \mathcal{L}\left\{\frac{d\vartheta_1}{dt}\right\} &= -\kappa_{\Omega 1}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \vartheta_1} \quad (33) \\ \vartheta_1 &= -\frac{\kappa_{\Omega 1}}{s}\left(\int_0^T e(\tau)d\tau\right)\frac{\partial G_{BF\Omega}(s)}{\partial \vartheta_1}U_{\Omega c}(s) \\ \vartheta_1 &= -\frac{\kappa_{\Omega 1}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{\vartheta_1} \\ & \frac{a_{\Omega m}}{s^2+\gamma s+a_{\Omega m}}.\frac{s}{s^2+\gamma s+a_{\Omega m}}U_{\Omega c}(s) \\ &= -\frac{\kappa_{\Omega 1}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{\vartheta_1}.\Omega_m(s) \\ & \frac{s}{s^2+\gamma s+a_{\Omega m}} \quad (34) \end{aligned}$$

And

$$\begin{aligned} \mathcal{L}\left\{\frac{d\vartheta_2}{dt}\right\} &= -\kappa_{\Omega 2}\frac{\partial J(e)}{\partial e}\frac{\partial e}{\partial \vartheta_2} \quad (35) \\ \vartheta_2 &= -\frac{\kappa_{\Omega 2}}{s}\left(\int_0^T e(\tau)d\tau\right)\frac{\partial G_{BF\Omega}(s)}{\partial \vartheta_2}U_{\Omega c}(s) \\ \vartheta_2 &= -\frac{\kappa_{\Omega 2}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{\vartheta_2}.\frac{f_v}{Js+f_v} \\ & \frac{a_{\Omega m}}{s^2+\gamma s+a_{\Omega m}}.\frac{s(s+\gamma)}{s^2+\gamma s+\vartheta_2\frac{K_\Omega \psi_{rd}}{f_v}}U_{\Omega c}(s) \\ &= -\frac{\kappa_{\Omega 1}}{s}\left(\int_0^T e(\tau)d\tau\right).\frac{1}{\vartheta_2}.\frac{f_v}{Js+f_v}.\Omega_m(s) \\ & \frac{s(s+\gamma)}{s^2+\gamma s+\vartheta_2\frac{K_\Omega \psi_{rd}}{f_v}} \quad (36) \end{aligned}$$

3 Simulation and results

The proposed regulator has been simulated for a three-phase 1.5kw asynchronous machine(see [12]), whose parameters are depicted in Table 1.

Pole pair motor	p	2
Frequency	f	$50hz$
Stator inductance cyclic	L_s	$0.464H$
Rotor inductance cyclic	L_r	$0.464H$
Cyclic mutual inductance	M	$0.4417H$
Stator resistance	R_s	5.717Ω
Rotor resistance	R_r	3Ω
Rotor inertia	J	$0.00049Nm$
Coefficient of friction	f_v	0.0001

Table 1: Asynchronous machine parameters used in simulations.

The vector of machine state is initialized whit $\begin{bmatrix} i_{sd} & i_{sq} & \psi_{rd} & \Omega \end{bmatrix}^T = \begin{bmatrix} 0 & 0 & 0.2 & 0 \end{bmatrix}^T$, 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.4). We show a detailed scheme SIMULINK of the control with PI adaptive regulator in Fig.5.

The figure (FIG.3) show the pace of desired flux and the flux of the machine; we notice that this last follows very well the flux wished with small disturbances at the moments $t = 1.2s$ and $t = 2.5s$ where speed changes its direction. The error mean of flux is equal to $-3.6mWb$ with a variance 4.11×10^{-4} to see the figure (FIG.6).

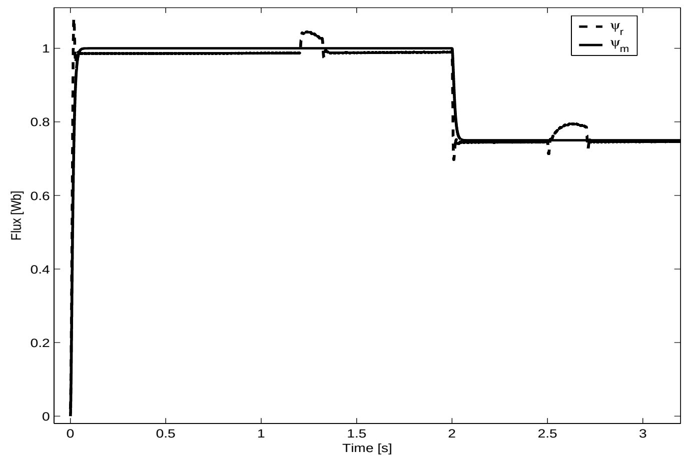

Figure 3: Flux performance.

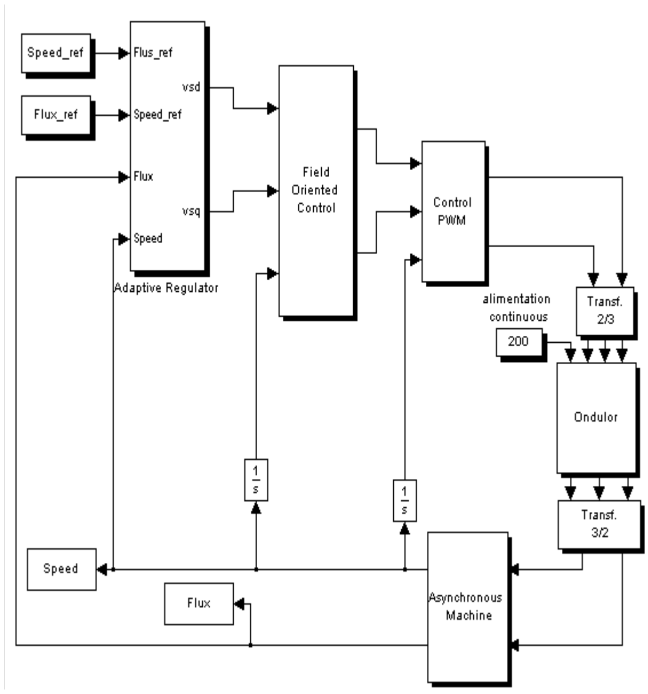

Figure 4: Diagram general of FOC with PI adaptatif regulator with reference model.

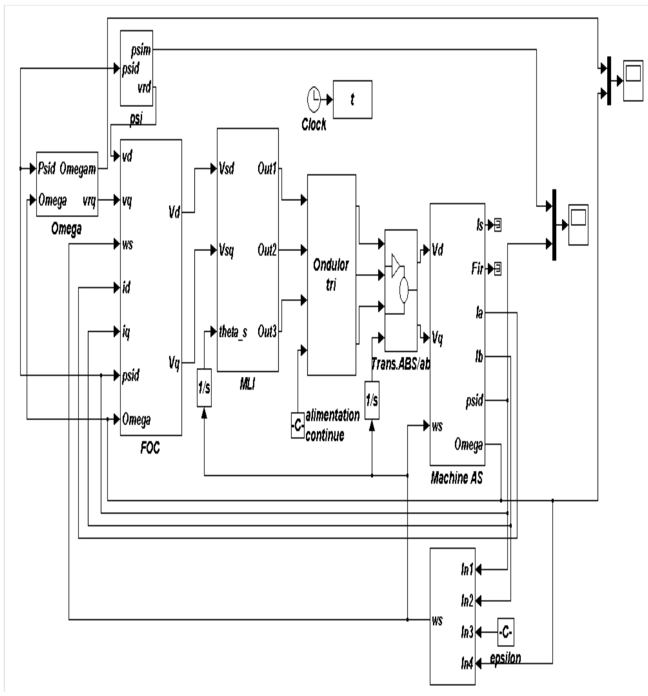

Figure 5: Simulink of FOC with PI adaptatif regulator with reference model.

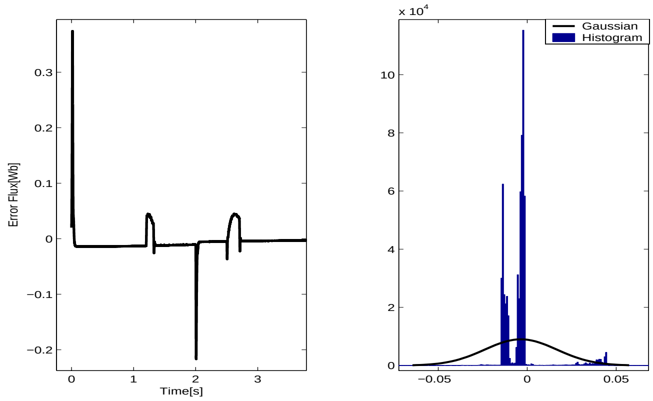

Figure 6: Mean and variance flux errors of control.

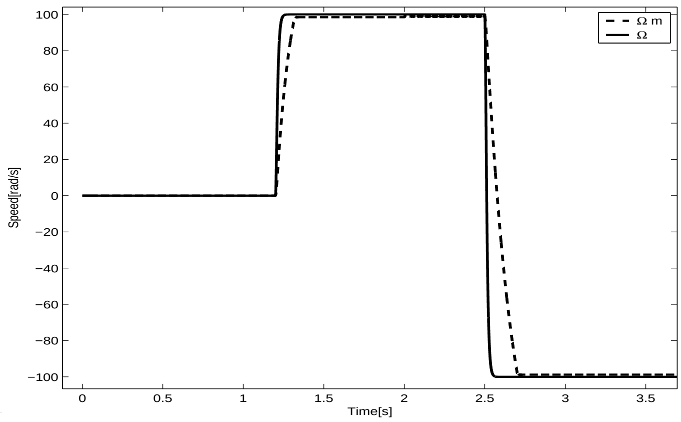

Figure 7: Speed performance.

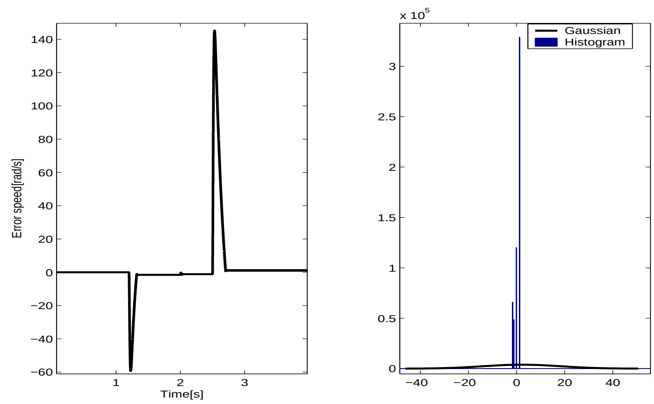

Figure 8: Mean and variance speed errors of control.

The figure (FIG.7) give the curve speed reference and the machine speed ; it is noted that speed follows well the instruction speed with shifts in the transient states ($t = 1.2s$ and $t = 2.5s$). The average of error speed is equal to

$2.1620 rad/s$ with a variance 260.0776 to see the figure (FIG.8).

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

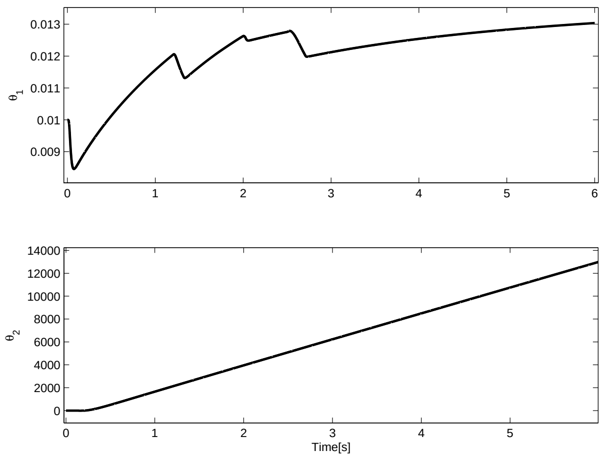

Figure 9: Parameters θ_1 and θ_2.

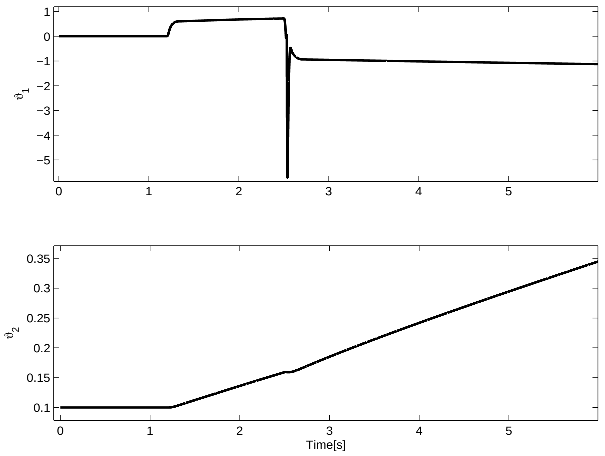

Figure 10: Parameters ϑ_1 and ϑ_2.

4 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 PI adaptive in the control loops of the rotor flux and of rotating speed. The results are very well. Simulations show the effectiveness of adaptation.

References:

[1] F. Blaschke, The principle of field orientation as applied to the new Transvektor closed-loop control system for rotating field machines. *Siemens Review XXXIX* (5), pp:217-220, 1972.

[2] R. Marino, S. Peresada and P. Valigi, Adaptive input-output linearizing control of induction motors, *IEEE Transactions on Automatic Control*, vol(38), N2, pp:208-221, 1993.

[3] T. VanRaumer, J.M. Dion, L. Dugard and J.L. Thomas, Applied nonlinear control of induction motor using digital signal processing, *IEEE Transactions on Control Systems Technology*, vol(2), N4, pp:327-335, 1994.

[4] Chouya Ahmed. Linearizing control of the asynchronous motor with an interconnected observers for sopecial class of nolinear system. *procedings of the 13th WSEAS International Conference on Applied mathimatics . Puerto De La Cruz, Tenerife, Canary Islands, SPAIN.15-17 December 2008*.

[5] Ahmed Chouya, Mohamed Chenafa and Abdellah Mansouri. Sensorless speed non linear control of induction motor. *Advances in circuits, systems, signal and Telecommunications, Puerto Moreto, Mexico, January 29-31, 2011. pp:69-75*

[6] Ahmed Chouya, Mohamed Chenafa and Abdellah Mansouri. Design of an observer PI for an asynchronous machine without mecanical sensor. *International Journal of Systems applications, Engineering and Development.Volume 11, 2017 pp:195-201.*

[7] Ahmed Chouya, Mohamed Chenafa and Abdellah Mansouri. Sensorless Speed High Gain Observer Based on Field-oriented Control for the Asynchronous Machine. *WSEAS TRANSACTIONS on POWER SYSTEMS : Volume13, E-ISSN:2224-350X. pp:125-134, 2018*.

[8] AEK Meroufel. Commande de la machine asynchrone :Commande scalaire, commande vectorielle, commande directe du couple. *Université Djillali Liabès Sidi Bel-Abbès. Faculté des Sciences de l'Ingénieur. Département d'Electrotechnique. 2008-2009*

[9] Carlos Canudas de Wit. Modélisation controle vectoriel et DTC. *Commande des moteurs asynchrones. HERMES Science Publications. Volume 1. 2000*

[10] Carlos Canudas de Wit. Optimisation discrétisation et observateurs. *Commande des moteurs asynchrones 2. HERMES Science Publications. 2000*

[11] Mimoun Zelmat. Automatisation des processus industriels : Commande modale et adaptative. *Office des Publications Universitaires.Tome 2. 2000*

[12] Ahmed Chouya. Contribution à l'Observation de la machine Asynchrone. *These Doctorat, département de génie électrique . 2014-2015*