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# *Comparison of Two Techniques for Control Nonlinear Systems : The PI Regulator and Sliding Mode Control*

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***Abstract*- This article presents a comparison of two techniques of control for asynchronous motor MAS: Control by a PI controller and the sliding mode control (SMC). A control uncoupled from the various exits as well as the stability of the system, we will ensure used a linearization input/output.**

***Keywords- Regulator PI, linearization input/output, Sliding Mode, IM torque control.***

## I. INTRODUCTION

The control of the asynchronous machine proves to be difficult. In other words, compared to the machine with D.C., qualities of the asynchronous motor, electric actuator with high performances, can be exploited only with definitely complex or evolved/moved strategies of order. Those are dependent on the one hand, with certain variable parameters and/or being able to be not accessible and on the other hand to the nonlinear multivariable dynamic behavior from these machines [ 1 ].

It during, the traditional and modern theories of order makes it possible to order with precision of the no disturbed linear processes and with known parameters. Example, the proportional-integral controller (PI) is largely answered in many applications of order because of its simplicity and effectiveness.

The principal disadvantage of controller pi is the weak possibility of treating the uncertainty of system, c-a-d, the variations of parameters and the disturbances external [ 2-3 ].

The variable-structure and associated sliding mode control [4] is the subject of studies detailed during these thirty last years. This theory is a robust control with respect to uncertainties on the model, of the disturbances and the radial forces handled. The sliding mode was largely used to control the nonlinear systems [5-6]

The principal characteristic of SMC is the robustness counters variations of parameter and disturbances external [7-8].

In order to apply the SMC for the nonlinear system, one will use the method of linearization input/output. The system obtained after this transformation, is a linear system uncoupled with *m* entered [ 9-10 ].

The disadvantage associated with the order by sliding mode is the appearance of the phenomenon "chattering".

To avoid chattering different approaches have been proposed, PID sliding mode control [11–12].

The objective of our work, is to study the behavior of the asynchronous machine by a setting in equation of the engine [ 13-14 ].This approach, we will bring to prepare the machine with the establishment of the law of order by a regulator PI and the law of order to variable structure by sliding mode to control flow and the electromagnetic couple.

The results obtained by simulation on Matlab, represent a comparative study between the SMC and control it by a regulator PI.

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## II. MODELING OF THE MAS

Before describing the asynchronous machine general equations, some simplifying assumptions most usually accepted on the machine, are possible:

- The air-gap between the rotor surfaces and the stator is constant.

- The magnetic circuits saturation, hysterics, the Foucault currents and the magnetic field to the ends of the machine dispersion are neglected.

### A. *Electric equation*

$$V_{dS} = R_S I_{dS} + \frac{d\phi_{dS}}{dt} - w_S \phi_{qS}$$

$$V_{qS} = R_S I_{qS} + \frac{d\phi_{qS}}{dt} + w_S \phi_{dS} \tag{1}$$

$$0 = R_r I_{dr} + \frac{d\phi_{dr}}{dt} - w_{Sl} \phi_{qr}$$

$$0 = R_r I_{qr} + \frac{d\phi_{qr}}{dt} + w_{Sl} \phi_{dr}$$

With

$$\phi_{dS} = L_S I_{dS} + L_m I_{dr}$$
$$\phi_{qS} = L_S I_{qS} + L_m I_{qr}$$
$$\phi_{dr} = L_m I_{dS} + L_r I_{dr} \tag{2}$$
$$\phi_{qr} = L_m I_{qS} + L_r I_{qr}$$

The synchronization speed is defined by:

$$w_S = 2\pi f = \frac{d\theta_S}{dt} \tag{3}$$

The sliding angular speed is defined by:

$$w_{Sl} = w_S - w_r \tag{4}$$

$L_S$ : Cyclic clean inductance of the stator.

$L_r$ : Cyclic clean inductance of the rotor.

$L_m = M_{sr}$ : Cyclic mutual inductance between stator and rotor.

The mechanical equation is defined by:

$$C_{em} = \frac{3}{2} p \frac{M_{Sr}}{L_r} \left(\phi_{dr}.I_{qS} - \phi_{qr}.I_{dS}\right) \tag{5}$$

It is the reference orientation mark (dq) with the axis (d) related to rotor flow. In this case one can write:

$$\phi_{dr} = \phi_r \quad \text{et} \quad \phi_{qr} = 0 \tag{6}$$

Under this orientation action allowing obtaining a significant starting torque, certain members of the preceding equations are simplified:

$$C_{em} = \frac{3}{2} p \frac{M_{Sr}}{L_r} \phi_r.I_{qS} \tag{7}$$

### B. *Synthesis Regulators*

The state equations of the induction machine are:

$$\frac{dI_{Sd}}{dt} = -C_1 I_{Sd} + w_S I_{Sq} + C_2 \phi_{rd} + C_3 p \Omega_m \phi_{rq} + C_4 V_{Sd} \tag{8}$$

$$\frac{dI_{Sq}}{dt} = C_1 I_{Sq} + w_S I_{Sd} + C_2 \phi_{rq} - C_3 p \Omega_m \phi_{rd} + C_4 V_{Sq} \tag{9}$$

$$\frac{d\phi_{rd}}{dt} = C_5 I_{Sd} - C_6 \phi_{rd} + \left(w_S - p\Omega_m\right)\phi_{rq} \tag{10}$$

$$\frac{d\phi_{rq}}{dt} = C_5 I_{Sq} - C_6 \phi_{rq} - \left(w_S - p\Omega_m\right)\phi_{rd} \tag{11}$$

$$\frac{d\Omega_m}{dt} = C_7 \left(\phi_{rd} I_{Sq} - \phi_{rq} I_{sd}\right) - C_8 \Omega_m - C_9 C_r \tag{12}$$

With $\sigma = 1 - \frac{M_{Sr}^2}{L_S L_r}$

### C. *Control loop of the rotor flux.*

The decoupling carried out by directed flow and the relation (3) make it possible to give:

$$\frac{d\phi_{rd}}{dt} = \frac{M_{Sr} R_r}{L_r} I_{Sd} - \frac{R_r}{L_r} \phi_{rd} \tag{13}$$

From where the direct stator current is determined by:

$$I_{Sd} = \frac{1}{M_{Sr}} \left( \phi_{rd} + \frac{L_r}{R_r} \frac{d\phi_{rd}}{dt} \right) \tag{14}$$

with

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- $T_r = \frac{L_r}{R_r}$: rotor time-constant.

- $T_S = \frac{L_S}{R_S}$ :stator time-constant.

The relations (7) and (13) make it possible to have:

$$V_{sd} = \frac{R_S}{M_{Sr}}\left(\phi_{rd} + (T_S + T_r)\frac{d\phi_{rd}}{dt}\right) + \sigma T_S T_r \frac{d^2\phi_{rd}}{dt^2} - w_S \sigma L_S I_{Sq} = V_{Sdf} + V_{Sdc} \qquad (15)$$

To ensure decoupling between the two axes, the term should be compensated for $V_{Sdc}$

$$V_{Sdf} = \frac{R_S}{M_{SR}}\left(\phi_{rd} + (T_S + T_r)\frac{d\phi_{rd}}{dt}\right) + \sigma T_S T_r \frac{d^2\phi_{rd}}{dt^2} \qquad (16)$$

$$V_{Sdc} = -w_S \sigma L_S I_{Sq}$$

The transfer function of the system is:

$$G(p) = \frac{\phi_{rd}(p)}{V_{Sdf}(p)} = \frac{M_{Sr}}{R_S}\frac{1}{1 + (T_S + T_r)p + \sigma T_S T_r p^2} \qquad (17)$$

Are $p_1$ and $p_2$ the roots of denominator, such as $p_2 >> p_1$.

$$p_1 = \frac{2\sigma T_S T_r}{T_S + T_r + \Delta} \; ; \qquad p_2 = \frac{2\sigma T_S T_r}{T_S + T_r - \Delta}$$

To compensate for the dominant time-constant $p_2$. The regulator of flow is of type PI.

$$F(p) = K_f \frac{R_S}{M_{Sr}} \frac{1 + T_f p}{p}$$

The transfer function in closed loop is:

$$H_F(p) = \frac{\phi_{rd}(p)}{\phi_{rd\_réf}(p)} = \frac{1}{1 + \frac{2z}{w_n}p + \frac{1}{w_n^2}p^2}$$

with

$$T_f = p_2 \; ; \qquad w_n = \sqrt{\frac{k_f}{p_1}} \; ; \qquad z = \frac{1}{2}\sqrt{\frac{k_f}{p_1}}$$

To ensure a fast establishment of flow leading to a just oscillating system, one chooses $z = \frac{1}{\sqrt{2}}$.

The error of flow is $\varepsilon = e_{2\_PI} = \phi_{rd\_réf} - \phi_{rd}$.

The following figure represents the functional diagram of the loop of regulation of flow.

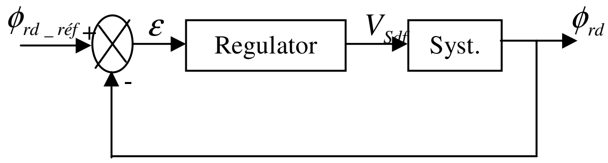


Fig. 1. *Control loop of the rotor flux*

*D. Control loop of the electromagnetic torque*

That is to say the response of flow is faster than the response of the couple then flow reaches its end value $\phi_{rd} = \phi_{rd0}$, from where the couple is given by the following expression:

$$C_{em} = \frac{3}{2}\frac{M_{sr}p}{L_r}\phi_{rd0} I_{sq} \qquad (18)$$

The equation of the tension $V_{Sq}$ becomes:

$$V_{Sq} = R_S I_{Sq} + \sigma L_S \frac{dI_{Sq}}{st} + \phi_{rd} w_S \frac{M_{Sr}}{L_r} + \sigma L_S w_S I_{Sd} \qquad (19)$$

That is to say

$$V_{Sq} = V_{Sqt} + V_{Sqc} \qquad (20)$$

The component $V_{Sqc}$ represents a term of decoupling which one must compensate for.

$$V_{Sqc} = \phi_{rd} w_S \frac{M_{Sr}}{L_r} + \sigma L_S w_S I_{Sd} \qquad (21)$$

$$V_{Sqt} = R_S I_{Sq} + \sigma L_S \frac{dI_{Sq}}{dt}$$

The transfer functions of the system:

$$G(p) = \frac{C_{em}(p)}{V_{Sqt}(p)} = \frac{3M_{Sr}P\phi_{rd0}}{2L_r R_S (1 + \sigma T_S p)} \qquad (22)$$

One chooses a regulator PI, his transfer function is given by:

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$$F(p)=\frac{2L_rR_S}{3M_{Sr}P\phi_{dr0}}.\frac{K_C(1+T_Cp)}{p} \qquad (23)$$

Maybe $T_C=\sigma T_S$, the transfer function in closed loop is:

$$H_F(p)=\frac{C_{em}(p)}{C_{em\_réf}(p)}=\frac{1}{1+\frac{1}{K_C}p} \qquad (24)$$

The error of torque is $\varepsilon=e_{1\_PI}=C_{em\_réf}-C_{em}$.

The following figure represents the functional diagram of the loop of regulation of the torque.

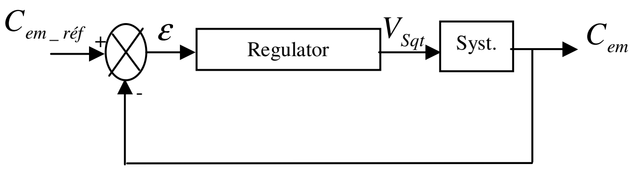


Fig. 2. *Control loop of the electromagnetic torque*

## III. LINEARISATION INPUT/OUTPUT

The technique of input/output linearization is a transformation into open loop of a nonlinear dynamic system to a linear system uncoupled to m entered (in our case m=2) having all its poles in the beginning. The fundamental idea of this approach makes it possible to express the system variables according to the entry sizes thanks to a nonlinear state return.

$$X'=f(X)+D(X).u \ ; \ y=h(X) \qquad (25)$$

with:

- $f$ and $h$ are applications respectively of $R^n$ in $R^n$ and $R^m$.

$$f(x)=[f_1(x) \quad f_2(x) \quad f_3(x) \quad f_4(x)]^T=A.X \qquad (26)$$

with

$$f_1(X)=-\frac{R_r}{L_r}\phi_{dr}+M_{Sr}\frac{R_r}{L_r}i_{dS}$$

$$f_2(X)=(w_S-P\Omega_m)\phi_{dr}+M_{Sr}\frac{R_r}{L_r}i_{qS}$$

$$f_3(X)=\frac{M_{Sr}R_r}{\sigma L_SL_r^2}\phi_{dr}-\frac{1}{\sigma L_S}\left(R_S+\frac{M_{Sr}^2R_r}{L_r^2}\right)i_{dS}+w_Si_{qS}$$

$$f_4(X)=-\frac{M_{Sr}}{\sigma L_SL_r}P\Omega_m\phi_{dr}+w_Si_{dS}+\frac{1}{\sigma L_S}\left(R_S+\frac{M_{Sr}^2R_r}{L_r^2}\right)i_{qS}$$

- X is the vector of state of dimension n=4.

$$X=[\phi_{dr} \quad \phi_{qr} \quad i_{dS} \quad i_{qS}]^T \qquad (27)$$

- $u$ is the vector of entry of dimension m=2.

$$u=[V_{dS} \quad V_{qS}]^T \qquad (28)$$

- D(x) is a matrix of dimension nxm whose columns are fields of vectors $d_i(x)$.

$$D(x)=[d_1(x) \quad d_2(x)] \qquad (29)$$

$$d_1=\begin{bmatrix}0 & 0 & \frac{1}{\sigma L_S} & 0\end{bmatrix}^T$$

$$d_2=\begin{bmatrix}0 & 0 & 0 & \frac{1}{\sigma L_S}\end{bmatrix}^T$$

- $y=h(x)$ is the vector of exit of the system of dimension m

The elements of the vector of exit $h(x)=[h_1(x) \quad h_2(x)]^T$ are respectively the electromagnetic torque $h_1(x)$ and rotor flow $h_2(x)$.

$$h(x)=[h_1(x) \quad h_2(x)]^T=[C_{em} \quad \phi_r]^T$$

To obtain the linearization input/output of the system, it is necessary to as many derive time by the derivative of Dregs and the relative degree [ 15-16 ]:

$$y_i^{(ri)}=L_f^{ri}h_i(x)+\sum_{j=1}^{m}L_{dj}.L_f^{ri-1}.h_i(x).u_j \qquad (30)$$

- The system input/output.

$$y_d=[y_{d1} \quad y_{d2} \quad y_{d3} \quad y_{d4} \quad y_{d5}]^T$$
$$=\left[C_{em} \quad \phi_{dr} \quad \phi_{dr}' \quad \int(y_{d1\_réf}-y_{d1})dt \quad \int(y_{d2\_réf}-y_{d2})dt\right] \qquad (31)$$

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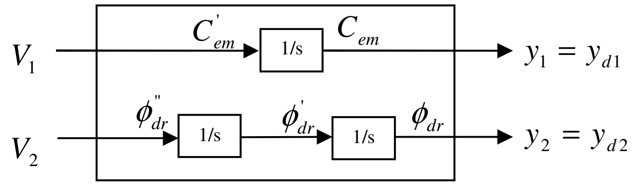


Fig. 3. *System obtained after application of the linearization input/output*

The control by sliding mode used consists in bringing the system state trajectory towards a slip surface where logic of adapted commutation will make it oscillate on both sides of this one until convergence towards the balance point located on this surface [17].

The generation of the vector control $V_d$ is carried out by using the following law of rallying.

$$S' = -Q\,\mathrm{sgn}(S) - L\lambda(S) = 0 \tag{32}$$

With

$$Q = diag[q_1, \quad q_2, \quad \ldots \quad , q_m], \quad q_i > 0$$
$$L = diag[l_1, \quad l_2, \quad \ldots \quad , l_m], \quad l_i > 0$$
$$\lambda(S) = [\lambda_1(S_1), \quad \lambda_2(S_2), \quad \ldots \quad , \lambda_m(S_m)]^T,$$
$$S_i\lambda_i(S_i) > 0, \quad \lambda_i(0) = 0$$

The discontinuous component Q.sgn(S) is a term of high frequency commutation. The coefficients of the matrix Q are null when the trajectory of state evolves/moves in the vicinity of the sliding surface.

When one moves away too much from there, then the term in Q.sgn(S) becomes active and brings back with a great dynamics the trajectory of state towards the sliding surface. Once the operation point reaches the surface, it oscillates around it. In theory, the commutation control must be at an infinite frequency and null amplitude.

*A. Definition of the hyper surface of commutation*

The general form suggested in [18-19-20] to determine the sliding surface is:

$$S(x) = \left(\frac{d}{dt} + \alpha\right)^n \left(\int e\right) \tag{33}$$

n **:** order of system;

e **:** error enters the exit and the desired exit;

$\alpha$ **:** coefficient, $\alpha \succ 0$.

The two components of the hyper surface of commutation are defined as follows:

$$S_1 = \left(\frac{d}{dt} + \alpha\right)^{n1} \left(\int e\right) = e_1 + \alpha \int e_1 \tag{34}$$
$$= e_1 + \alpha \int e_1 = K_1\left(y_{d1\_réf} - y_{d1}\right) + K_2 y_{d4}$$

$$S_2 = \left(\frac{d}{dt} + \alpha\right)^{n2} \left(\int e\right) = e'_2 + 2.\alpha.e_2 + \alpha^2.\int e_2 \tag{35}$$
$$= -K_3 y_{d3} + K_4\left(y_{d2\_réf} - y_{d2}\right) + K_5 y_{d5}$$

with: $n_1 = 1$ and $n_2 = 1$.

- $e_1$ and $e_2$ are respectively the errors of torque and flow:

$$e_1 = C_{em\_réf} - C_{em} \tag{36}$$
$$e_2 = \phi_{dr\_réf} - \phi_{dr} \tag{37}$$

*B. Condition of existence of a sliding mode*

Indeed, to bring and maintain the operation point on the sliding surface or its vicinity, the S(t) function must check the sliding mode existence condition [21-22-23]:

$$S.S' \leq 0 \tag{38}$$

*C. Equivalent control calculation*

By defining the function $\lambda(S) = S$, the relation (14) makes it possible to deduce the equivalent control from it $V_d$.

The components $V_1$ and $V_2$ of the vector control $V_d$ linear system, definite by:

$$v_1 = K_1.K_3\left[-K_2.e_1 + q_1.\mathrm{sgn}(S_1) + l_1.S_1\right] \tag{39}$$
$$v_2 = K_1.K_3\left[-K_5.e_2 + q_2.\mathrm{sgn}(S_2) + l_2.S_2\right] \tag{40}$$

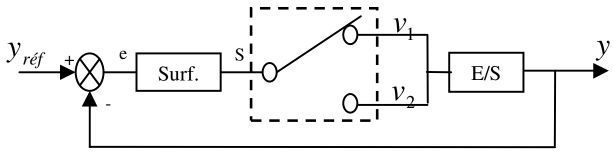


Fig. 4. General principle diagram of the control by sliding mode

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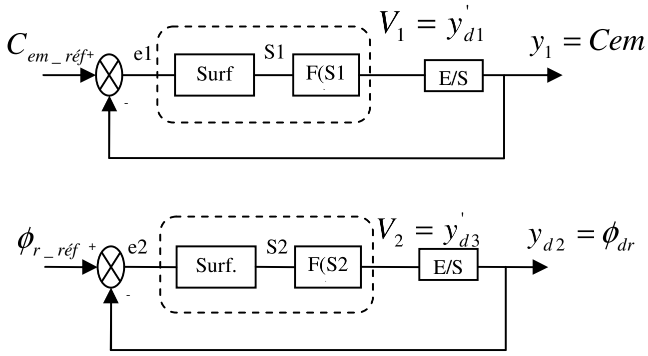


Fig. 5. *General diagram of the control by sliding mode of torque and flow.*

## IV. SIMULATION RESULTS

To show the theoretical results, we will use the Matlab/Simulink software to simulate in real time the applied control. represent the sliding mode adjustment performance defined by:

- Stability in steady operation.
- Speed of the answer.
- A relatively small static error.

The engine is started initially in neutral with t=60s is reverse the direction of rotation and t=100s is coupled with a load Cr=20Nm. the existence of the oscillations (phenomenon of "chattering") will be represented by the Fig. 6.

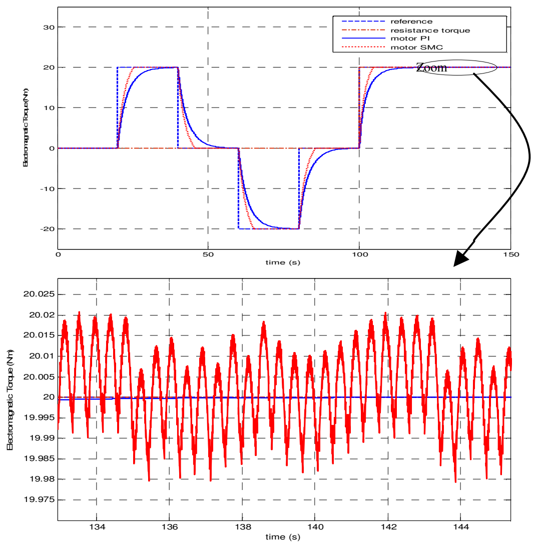


Fig. 6. *Evolution of the electromagnetic torque by sliding mode and PI regulator*

The Fig. 6. represents the evolution of the electromagnetic torque considered, real and reference of the asynchronous motor in the presence of radial force Cr=20N à t=100s.

It is noted that the electromagnetic torque does not admit oscillations and reaches steady operation with a response time $Tr_{PI} = 2.95\ s$ et $Tr_{SMC} = 1.96\ s$. The machine answers successfully the inversion of its direction of rotation.

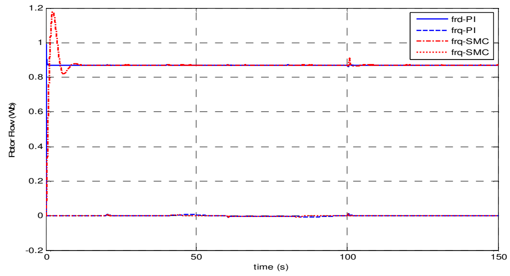


Fig. 7. *Reponse of rotor flow*

The Fig. 7. shows the influence of controls applied to the response of flow along the two axes (d, q):

- Along the axis (d): control by sliding mode integrated is less sensitive to the reversal of direction of rotation or the introduction of load that the PI controller.
- Along the axis (q): the flow is zero regardless of the order.

changes in the motor flux demonstrates the robustness of the control slide, it follows exactly the desired set point without overshoot and without static error even when the impact load torque or reversal of direction of rotation.

The evolution of direct rotor flux is not a static error with short response time;

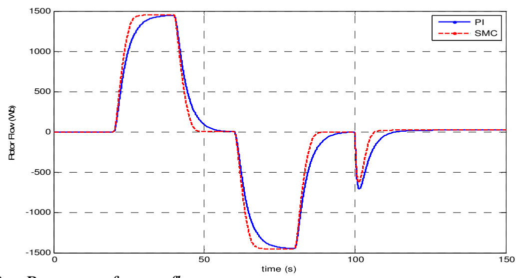


Fig. 8. *Reponse of rotor flow*

The Fig. 8. is a representation of the evolution of the speed of asynchronous techniques for both commands.

The response speed of the MAS shown in figure 9 is similar to that of a first order system without overshoot, steady and stable with a response time of the order of 4.19 seconds for

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the speed defined by the PI controller and 3.02 seconds for the speed determined by the sliding mode. The evolution of the velocity shows the introduction of charge (t = 100s) the robustness of the order sliding mode with respect to the PI.

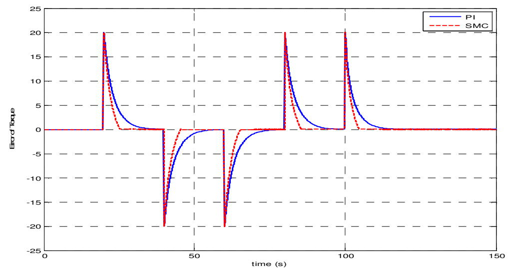


Fig. 9. *Characteristic of the error ( $e_1$ ; $e_{1\_PI}$ ) between the actual torque and the torque reference*

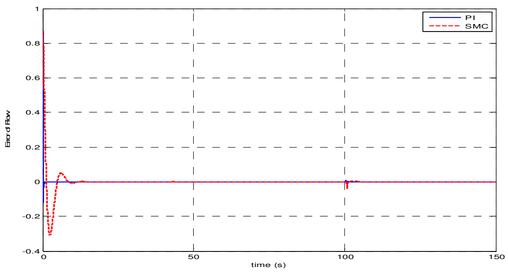


Fig. 10. *Characteristic of the error ( $e_2$;$e_{2\_PI}$ ) between the actual torque and the torque reference.*

Fig. 9. and 10. represents the errors of flux and torque. It is found that:
- The look of the error, or shows the stability of the system in steady state without overshoot and with a low response time.
- Control by sliding mode and PI are insensitive to load change (from zero torque to 20Nm).
- The instability of the system at startup.

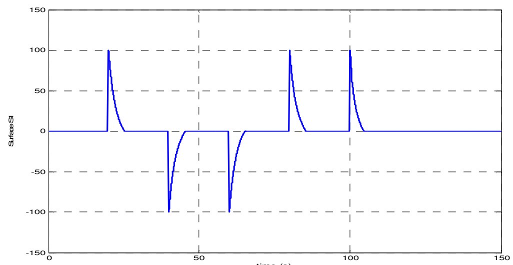


Fig. 11. *Changes in the sliding surface S1 as a function of time*

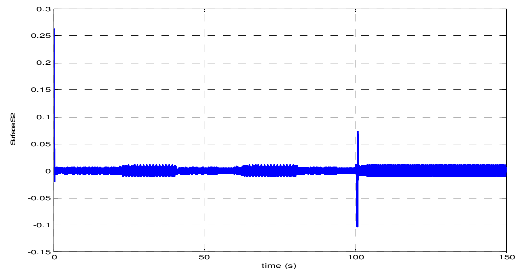


Fig. 12. *Changes in the sliding surface S2 function of time*

Fig. 11. and 12. show the evolution of the sliding surface over time.
The evolution of the surface S1 is going to zero for each load change in a quick time 5.25 (s).
The evolution of the surface S2 is going to zero in a very fast time 0.38 (s). We note that the error e2 is insensitive for the load variation.

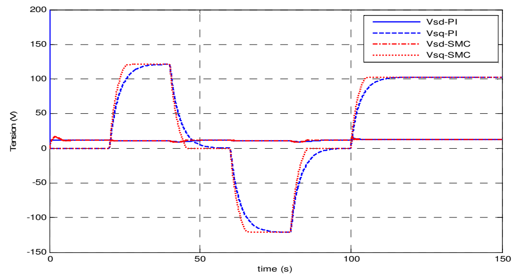


Fig. 13. *Changes in the voltage Vqs -Vds*

Fig. 13. represent the voltage Vds and Vqs to be applied to the machine for controlling the sliding mode and the PI controller.
There is evidence that air of tension reached the steady state with a response time:
- $tr_{SMC} = 2.13s$ ; $tr_{PI} = 3.11s$ ; For voltage Vqs
- $tr_{SMC} = 2.15s$ ; $tr_{PI} = 0.7s$ ; For voltage Vds
Note that the PI is more sensitive to start the command mode by sliding.

## V. CONCLUSION

A comparative study of two commands has been determined in this paper: PI control and control via sliding mode.

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To facilitate the design of the sliding mode control, it was determined the technique of linearization input /output which has the main advantage of completely decoupled system to control.
The simulation results show the speed response ($tr_{SMC} < tr_{PI}$) and the robustness of the method of setting the sliding mode vis-à-vis the disruption of the load. The main drawback of SMC is the presence of the phenomenon of "chattering", which is currently the subject of our research in order to eliminate the phenomenon of "chattering."

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