International Symposium on Technology & Sustainable Industry Development, ISTSID'19
EL OUED, ALGERIA, 24 - 26 February 2019

Reduction of the Chattering Phenomenon By Using Softened Several Ramps Mode Control of an Induction Machine

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***Abstract*—The principal objective of this paper consists in introducing the sliding mode control concepts in the speed's regulations control scheme of the induction machine powered by static converters. The control by sliding mode is an interesting technique for solving the problem of robustness of the adjustment with respect to the variation of the load. So, the control law in this technic is expressed mainly from the quantity to be regulated and the number of derivatives. In practical applications, the main disadvantage associated with the command is the phenomenon of chattering. In order to minimize the amplitude of oscillations, we propose a technique of variable structure control which is softened several ramps control. In this context, firstly, we will be introducing some general notions on nonlinear systems as well as the design of sliding mode control. Secondly, they will try to establish a methodology for designing this control (conventional control and softened several ramps control). Each stage of such study is illustrated and validated by simulation results. Finally, we will be conducting robustness testing to evaluate our order.**

Keywords—Sliding Mode Control; Softened Several Ramps Control; Induction Machine; Phenomenon of chattering.

I. INTRODUCTION

The advantages of robust control with variables structures or sliding mode control are important, well known and appreciated since the early 1980s, namely very high precision, good stability, simplicity, very low response time and particularly robustness…, etc [1], [2], [3]. This allows it to be particularly adapted to the treatment of systems whose models are imprecise.
This imprecision may be due to two reasons:
1) Imprecision and variation of parameters: identification problems,
2) Simplification of the dynamic model of the system: modelling problem.
One of the simplest approaches to robust control is sliding mode control which allows very good performance (response time, accuracy) in the presence of uncertainties on the parameters of the system and their variations on the one hand, And the uncertainties on the models of the system on the other hand [4]. These performances are obtained at the price of a very strong control activity which can result in very strong oscillations called "Chattering". The design of the controllers by sliding mode takes into account the problems of stability and consequently, good performances in its approach will be ensured.

II. CONTROL DESIGN BY SLIDING MODE

This design is done in three stages [5]:
1) Choice of control's sliding mode surfaces,
2) Determination of the control law,
3) Establishing conditions of existence and convergence.

II.1. Selection of sliding surfaces

In general, for a system defined by the following state's matricial form:

$$\dot{X} = [A(x)][X] + [B][U] \tag{1}$$

Choose "m" sliding surfaces for a vector [U] of dimension "m". The researcher J.J. Slotine proposed a simplest and general equation to determine the required sliding mode surfaces that ensure the convergence of a state variable x to its reference value x_{ref} [6].

$$S= \lambda_1 e^{(x)} + \lambda_2 e^{(x)} + \lambda_3 e^{(x)} + \ldots\ldots\ldots \lambda_m e^{(m)} \quad (2)$$

With :

x : Variable to be regulated,

$e^{(x)}$: The $(x)^{th}$ derivation of the variable which will be regulated ($x_{ref}(t) - x(t)$),

λ_i(i=1… m) : constants.

II.2. Condition of existence and convergence

The convergence conditions allow the control variables of the system to converge towards the sliding surface:
Therefore, it is necessary to formulate a positive scalar function for the state variables of the system and to choose a control law that will decrease this function $(\dot{V}(x) < 0)$ [7][3].
By defining the Lyapunov function [3]:

$$V(x) = \frac{1}{2} S^2(x) \quad (3)$$

Its corresponding derivative expression will be:

$$\dot{V}(x) = S(x).\dot{S}(x) \quad (4)$$

In order to ensure the stability of the control, Lyapunov function must be applied:

$$\dot{V}(x) = S(x).\dot{S}(x) < 0 \quad (5)$$

This condition is necessary, neither to estimate the performance of the control, the robustness study and to guarantees the stability of the nonlinear system [2].

II.3. Calculation of the control law:

Once the sliding surface has been chosen, as well as the convergence velocity, it remains to determine the control necessary to attract the variable to be checked towards the surface and then towards its equilibrium point (origin of the phase plane) while maintaining the condition of the existence of the mode of sliding [2]. One of the essential assumptions in the design of variable structure systems for slip mode control is that the control must switch between U_{max} and U_{min} instantaneously (infinite frequency) as a function of the sign of the sliding surface (Fig 1).

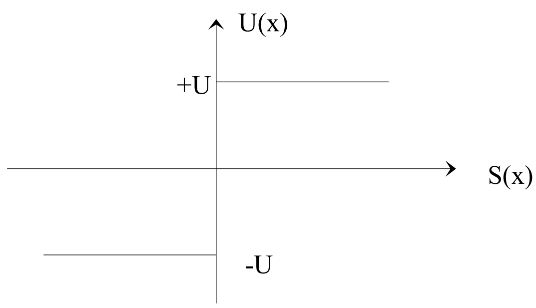

Fig. 1: Applied control of the system.

There are several types of control systems with variable structures of which the most frequently used are those corresponding to what is called: Equivalent control that was used in our work.
The structure of a controller, in this case, has two parts, a first concerning the exact linearization and a second stabilizer, representing the dynamics of the system during the convergence mode. The latter is very important in the non-linear control technique because it is used to eliminate the imprecision effects of the model and the external perturbations we pose, therefore: [2] [3] [4].

$$U = U_{eq} + U_n \quad (6)$$

U_{eq} corresponds to the linearization control proposed by *Fillipov* and *Utkin* (equivalent control), making it possible to have the trajectory of the deviation on the sliding surface $S(x) = 0$.

The equivalent command can be interpreted as the average (continuous) value of the command when the fast switching between U_{max} and U_{min} [2] (Figure 2) takes place and is

obtained by recognizing that the dynamic behaviour during slip is described by:

$$S(x) = 0 \quad (7)$$

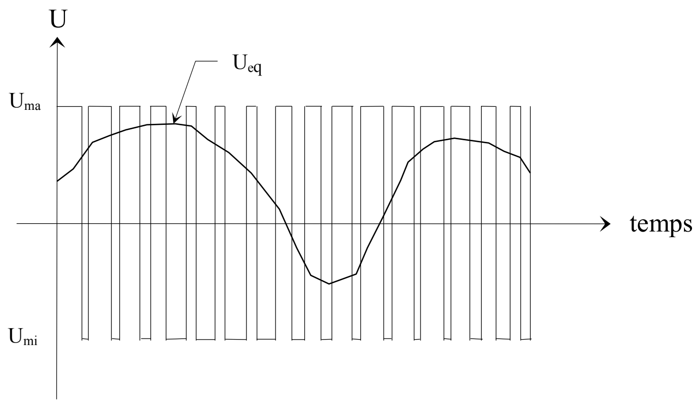

Fig. 2: The continuous value *(U_{eq})* taken by the control during switching between U_{min} *and* U_{max}.

Moreover, the control One is determined to guarantee the attraction of the variable to be controlled towards the surface and to satisfy the convergence condition $S(x).\dot{S}(x) < 0$. In other words, to define the dynamic behaviour of the system during the convergence mode given by:

$$U_n = \dot{S}(x) \quad (8)$$

III. The phenomenon of chattering

In order to reduce the oscillations, we will present two solutions based on the variation of the value of the control A as a function of the distance between the state variable and the sliding surface. These consist in framing the surface by a band with one or two thresholds so as to diminish or eliminate the

effect of the original $U_n = K.signe(S(x))$, function of the Chattering [8], [1].
The simplest form that U_n can take is that of a relay represented by the Figure (3).

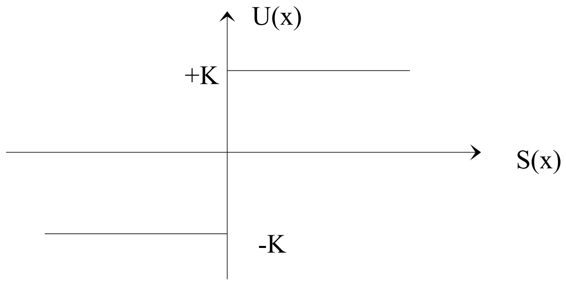

Fig. 3: Definition of the function U_n.

The choice of the constant K is very influential because if the constant K is very small the response time is too long and if it is too large, the "Chattering" appears.

III.1. Conventional Control

This control is characterized by a threshold function expressed as follows (Fig.4) [10]:

$$U_n = \begin{cases} 0 & \text{if } |S(x)| < \varepsilon \\ K \text{ signe}(S(x)) & \text{if } |S(x)| \geq \varepsilon \end{cases} \tag{9}$$

Although the control cancels the effect of the sign function in a band around the surface, it is not widely used for two reasons. In the presence of a disturbance, the dynamics of the system leaves the sliding surface and the band around it, therefore U_n intervenes with all its value to reduce the dynamics on the surface and the chattering phenomenon persists in the steady-state operation of the system on the one hand, and on the other hand it remains impracticable in practice where the physical limitation of the switches intervenes. U_n softening the control U_n thus proves necessary.

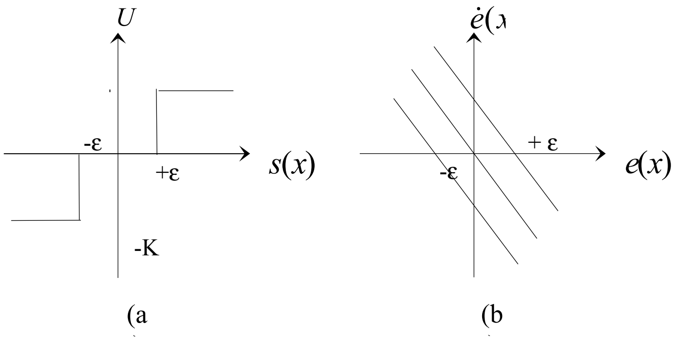

Fig. 4: Conventional control: a) sign function, b) band which surrounds the surface in the phase plane.

In a conventional, the variables structures control, the reachability control generates a high control activity as it depends on the magnitude since it was first taken as constant, a relay function, which is very harmful to the actuators and may excite the unmodeled dynamics of the system. This is known as a chattering phenomenon. Ideally, to reach the sliding surface, this phenomenon should be eliminated [9-11]. However, in practice, chattering can only be reduced.
To reduce chattering was to introduce a boundary layer around the sliding surface and to use a smooth function to replace the discontinuous part of the control action as follows [12-13]:

$$U_n = \begin{cases} (K/\varepsilon)\, S(x) & \text{if } |S(x)| < \varepsilon \\ K \text{ signe}(S(x)) & \text{if } |S(x)| \geq \varepsilon \end{cases} \tag{10}$$

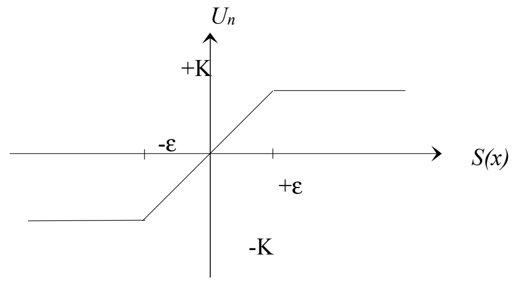

Fig.5 : Sliding mode with boundary layer and the modified switching law.

The constant K is linked to the speed of convergence towards the sliding surface of the process the reaching mode). A compromise must be made when choosing this constant, since if K is very small the time response is important, whereas when K is too big,
the chattering phenomenon increases so, in this paper, we proposed an approach which is able to reduce this latter and will be described in the following section.

III.2. Softened Several Ramps Control

In order to further reduce the chattering, the idea consists to approach gradually the control state of the sliding mode surface. So, we propose to use a softened several ramps discontinuous control law given in eq.11. Thus, this control law must be based on the approach of the state toward the surface in the region that borders the latter, and that following several slopes with a pass through the origin in the $(S(x), U_n)$
in order to avoid a discontinuity of operation as it is shown in the figure.6 [11].

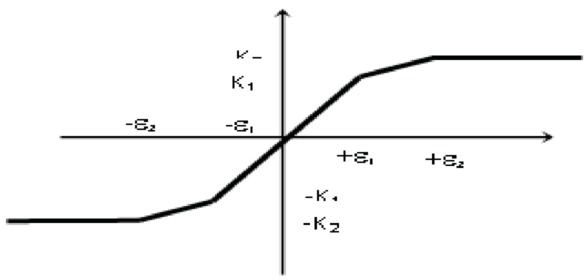

Fig.6: Sign function control with several ramps.

The expression that corresponds to it is given by:

$$U_n = M(S).sign(s) \tag{11}$$

With:

$$M(S) = \begin{cases} +\mathrm{K2} & \mathrm{S(x)} > +\varepsilon 2 \\ ((\mathrm{K}_2 - \mathrm{k}_1)/(\varepsilon_2 - \varepsilon_1)).\mathrm{S(x)} & \varepsilon 1 < |\mathrm{S(x)}| < + \\ (\mathrm{K}_1/\varepsilon_1).\mathrm{S(x)} & -\varepsilon_1 < |\mathrm{S(x)}| < \varepsilon_1 \\ ((\mathrm{K}_1 - \mathrm{k2})_1/(\varepsilon_1 - \varepsilon_2)).\mathrm{S(x)} & -\varepsilon 2 < |\mathrm{S(x)}| < -\varepsilon 1 \\ -\mathrm{K}_2 & |\mathrm{S(x)}| < -\varepsilon_2 \end{cases}$$

To satisfy the stability condition of the system, the gains K_1 and K_2 should be taken positively by selecting the appropriate values.

Whatever; the softened several ramps method used to limit the Chattering phenomenon, we notice that the higher the threshold, the less switching, but if it is too large, the response time of the variables becomes large.

IV. Application of the control by sliding mode for the induction machine

In order to protect the machine and the converter, the current absorbed must be limited to a maximum permissible value. To do this; we consider a cascade structure of the overall control scheme. This latter imposes a choice of two surfaces on each axis. The inner loop controls the currents " i_{ds} and i_{qs} " and the external loop the velocity and flux " Ω_r, Φ_r ", (Fig.7).

Figure 7 shows the cascade structure of the speed control of the induction machine. The application of this control strategy begins with the determination of the relative degree of the variables to be regulated. The variables are the flux and the direct current for the d-axis and the velocity and the quadrature current for the q axis. The output's value of the external loop represents the current references of the internal loop. The outputs of the latter represent the direct and quadrature control voltages to be applied to the machine.

IV.1 Application of the U_n command in relay mode (Simulation and interpretation)

The surfaces chosen for each of the axes (figure 4) are [12] :

$$\text{Axes } d : \begin{cases} S(\Phi_r) = \Phi_{r\,\mathrm{ref}} - \Phi_r \\ S(i_{ds}) = i_{ds\,\mathrm{ref}} - i_{ds} \end{cases} \tag{12}$$

$$\text{Axes } q : \begin{cases} S(\Omega_r) = \Omega_{r\,\mathrm{ref}} - \Omega_r \\ S(i_{qs}) = i_{qs\,\mathrm{ref}} - i_{qs} \end{cases} \tag{13}$$

The calculation of the control values will be done on the basis of the electrical and mechanical equations (4) of the system, and of the equivalent control definition (7),

To satisfy the convergence criterion, the gains (K_d, K_f, K_w, K_q) must always be positive. The choice of these gains will be made in such a way as to impose the desired value at the output of the regulator.

We have simulated the dynamics of the control strategy by considering the switching function as a relay one. The test which is done consists on starting with no-load, followed by an application of C_r= 5Nm between t=0.7s and t=1.3s (Fig 8).

In this figure, it is clear that the speed of the machine is established after 0.15 s, for a set speed which is equal to 100 rad / s. The direct component of the rotor flux is 0.15 s. From this figure, we also notice an orientation of the rotor flux along the d axis with a component in zero quadrature. By applying a load between instants t = 0.7s and 1.3s (Cr = 5N.m), it can be seen that the electromagnetic torque of the machine becomes larger to compensate for the load. In our case where U_n is defined by a function in the relay, we can see:

- Low response time.

-The electromagnetic torque C_{em} and the rotor flux are perfectly independent of one another, so the decoupling is carried out successfully.

- The waveforms of large oscillations, this is due to the phenomenon of "Chattering".

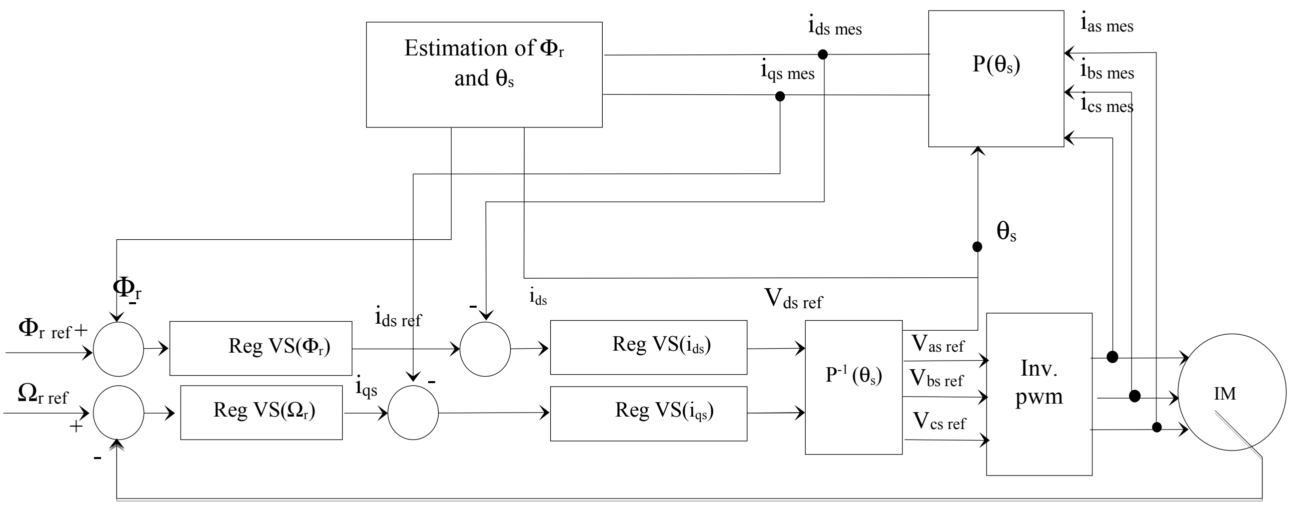

Fig. 7: Diagram of the cascade structure of the induction machine control by sliding mode.

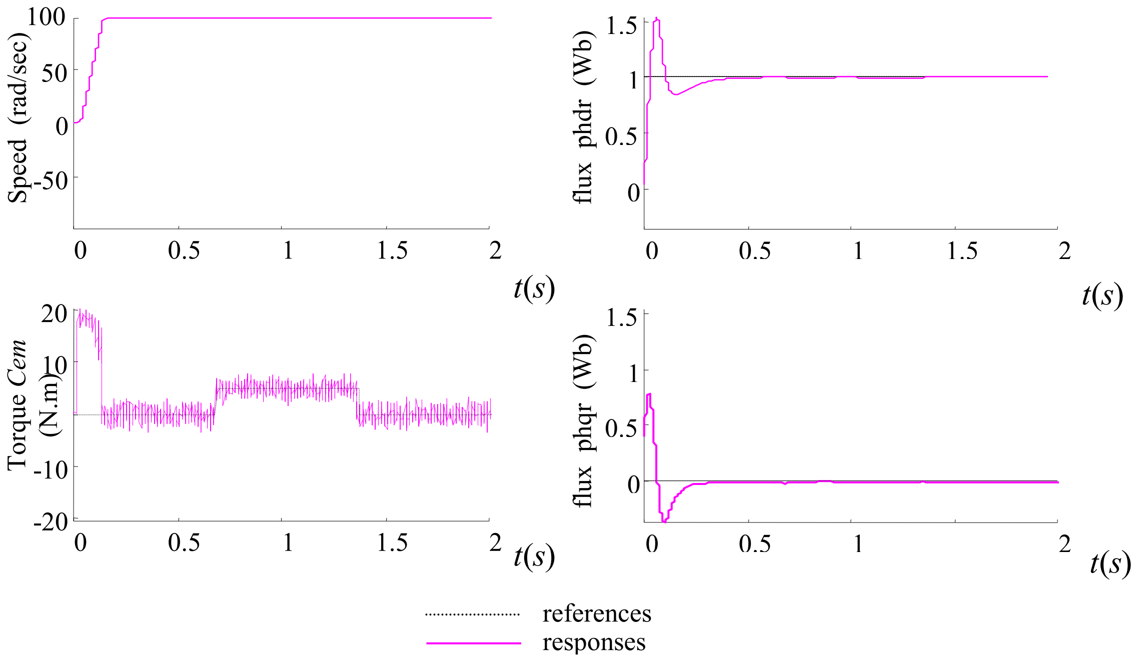

Fig.8: Simulation results on machine load using sliding mode control with U_n in the relay.

IV.2 Application of the Softened Several Ramps Control (Simulation and interpretation)

In order to verify the effectiveness of the softened several ramps control law (eq.11) compared to the boundary layer one (eq. 10), a simulation of the dynamic of the process is done by considering the following tests:

The first test concerns a no-load starting of the motor with a reference speed w_{ref} = 100 rad/sec. Then a torque load (Cr = 5 Nm) is applied between t=0.7s and t=1.3s. The results are shown in (fig.9).

The chattering phenomenon appears in the torque response due to the discontinuous character of the controller and a marked reduction of such a phenomenon with the second discontinuous control law is noticed. So, we can see that our objective is attempted with great success.

IV.3 Robustness Tests

The robustness of a control is its ability to overcome the uncertainty about the model to be controlled. These uncertainties can be either with respect to the parameters (identification problem) or with respect to the simplification of the dynamics of the model (modelling problem).

In this part, the study will deal with the uncertainties of the rotori electric time constant by changing the value of Rr. In order to check the robustness of the calculated control algorithms, simulations have been made with a variation of the resistance (R_r= 150% R_r) (Fig .10).

From these results, we can say that this type of control is robust compared to the case of vector control with PI regulators.

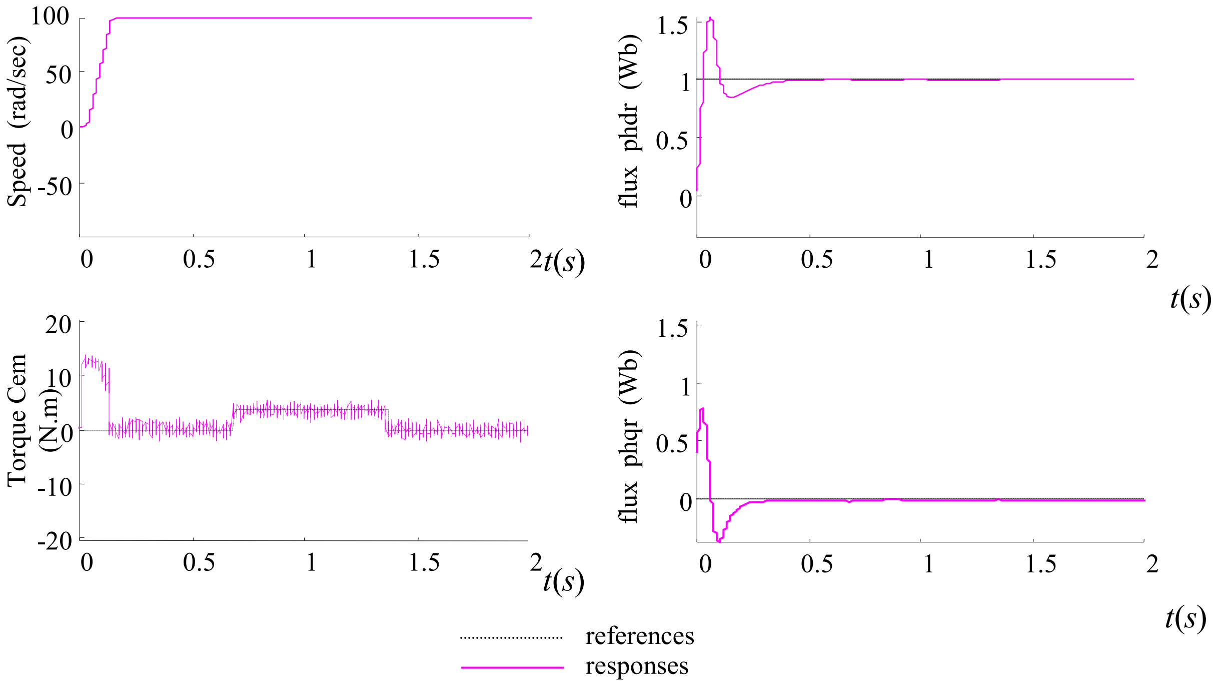

Fig.9: Simulation results under the load of the machine using the softened several ramps control by sliding mode with U_n.

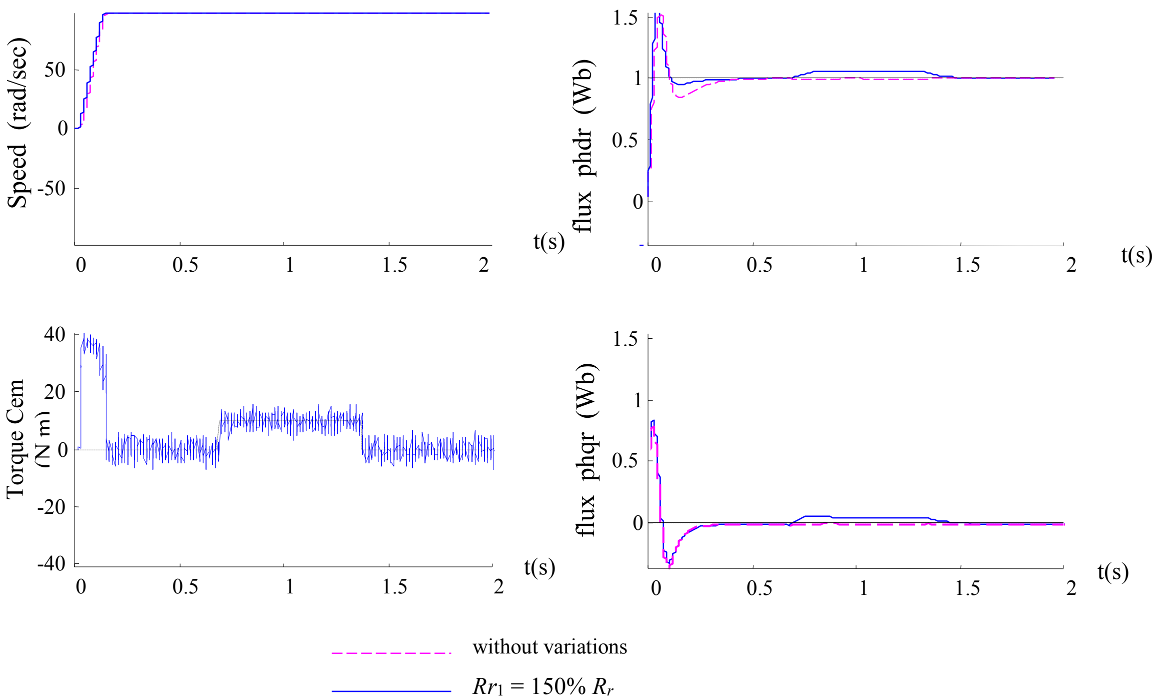

Fig.10: Results of simulation of the control by sliding mode with an application of resistant torque and a variation of the rotor resistance of 150%.

V. Conclusion

The application of the sliding mode control (softened several ramps control) to the induction machine made it possible to demonstrate the simplicity of design and good performance relative to that obtained with the rotor-oriented flux control.
We have seen that the switching of the control from one structure to another is effected by a so-called switching logic which imposes on the state a trajectory on which it must switch, thus enabling it to have certain robustness with respect to variations parameters and other disturbances.
Indeed, the advantage of this technic is that it uses all the force of the control to confront the external effects that could prove detrimental to the proper functioning of the system. Unfortunately, and in this sense, this control method very strongly forces the control members, especially those of the "inverter" stage, with a high frequency which could damage the latter. This phenomenon is called chattering.
Therefore and in order to decrease the "Chattering" a threshold command is applied. It is important to note that a judicious choice of this threshold is important.
Indeed, the greate of the threshold, the less commutation, but if it is too large, there is a problem of precision. The study of the robustness shows that control by sliding mode offers the advantage of the insensitivity of the control with respect to the internal parameters of the machine, a result which can be foreseen by the nature of this control.

VI. Appendix: Machine Parameters

Induction Machine of 1.5 KW, 220 V, 2 poles, 1420tr/min, 50 Hz.

Rs= 4.85 Ω; Rr= 3.805 Ω; Ls= 0.274 H; Lr= 0.274 H; M= 0.258 H; J= 0.031 Kg.m^2, f= 0.00114 Nms.

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