Application of Fuzzy Sliding Approach for Speed Control in the Field-Oriented Process and to Reduce Chattering of an Induction Motor

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Abstract- Sliding mode control has long proved its interests. Among them, relative simplicity of design, control of independent motion (as long as sliding conditions are maintained), invariance to process dynamics characteristics and external perturbations, wide variety of operational modes such as regulation, trajectory control, model following and observation. This paper presents a robust control technique for a field oriented induction motor drive. Sliding Mode Controller (SMC) and Fuzzy Sliding Mode Controller (FSMC) are designed for the speed loop of the drive, the approach of softened several ramps based on Ben Ghalia's technical is introduced, in order to reduce the chattering phenomenon and also to perform the control obtained with sliding mode control of an induction motor squirrel cage. In practical applications, the main disadvantage associated with the command is the phenomenon of chattering. In order to minimize the amplitude of the corresponding oscillations, we propose a new technic of variable structure control which is softened several ramps based on Ben ghalia's fuzz sliding approach. Simulation results will reveal some very interesting features.

Key-Words: Induction motor, field-oriented control, sliding mode control, fuzzy control.

1. INTRODUCTION

Sliding mode (SM) control has long proved its interests. Among them, relative simplicity of design, control of independent motion (as long as sliding conditions are maintained), invariance to process dynamics characteristics and external perturbations, wide variety of operational modes such as regulation, trajectory control, model following and observation.

The SM-control method ensures that the state converges to the sliding mode in a finite time, but in order to guarantee the finite time convergence the SM input includes the sign function in the control, which may yield chattering in practice.[1-2]

On the other hand, thanks to the progress in the field of power electronics components and the different control techniques applied to the induction machines; most of the recent industrial applications and control motor drivers are based on induction motor and make such processes as performing as DC machines [3].

In this context, "vector control" was the first technique to be used. This technique allows obtaining a decoupled dynamic model similar to the model of the machine to separate DC excitation [4-5-6].

In practice, the use of conventional correction schemes of field oriented control for induction motor, where the model is nonlinear and depends on the motor parameters [5-7], which makes it very sensitive to any changes in parametric variations.

That is why, for decades the research is oriented to other types of robust controllers, like sliding mode controller and fuzzy controller. So this work is structured in three stages:

In the first step, will be devoted to the design of indirect vector control scheme based on a classic PI regulator. So, in this context and to do this, the basic principles of this technical type of orientation of rotor flux control will be presented.

Second, we will have a look at the basic concepts of variables structures control and it will be used for the detailed design of a sliding mode control with the prior the first discontinuous control law which is: the boundary layer.

Thereafter and to reduce the chattering phenomenon, a new control law based on the softened several ramps of the discontinuous control law will be presented.

In the third step, the fuzzy variables structures control approach based on Ben ghalia's fuzzy sliding mode control technic will be used.

In this context, the fuzzyfication of the softened several ramps control is introduced to get the limits of the several ramps.

Finally, numerical simulations and comparisons between the obtained results will be presented with the aim of validation the proposed approach.

2. Field oriented control

A. Model of the induction motor

The equations of the voltage PWM source inverter fed induction motor with current control, in the synchronous reference frame (d–q), using rotor fluxes as state variables are given by [7-8]:

$$v_{ds} = \sigma L_s \frac{d \iota_{ds}}{d t} + R_s \iota_{ds} - \sigma L_s \omega_s \iota_{qs} - \frac{L_m}{T_r} \omega_r \Phi_{qr}$$

$$v_{qs} = \sigma L_s \frac{d \iota_{qs}}{d t} + R_s \iota_{qs} + \sigma L_s \omega_s \iota_{ds} + \frac{L_m}{T_r} \omega_r \Phi_{dr}$$

$$\frac{d\Phi_{dr}}{dt} = \frac{-1}{T_r}(\Phi_{dr} - L_m \cdot \iota_{ds}) + \omega_{sl} \cdot \Phi_{qr}$$

$$\frac{d\Phi_{qr}}{dt} = \frac{-1}{T_r}(\Phi_{qr} - L_m \cdot \iota_{qs}) + \omega_{sl} \cdot \Phi_{dr}$$ (1)

$$\frac{d\Omega}{dt} = \frac{1}{J} \cdot (T_{em} - T_L - f_r \cdot \Omega)$$

$$T_{em} = \frac{3}{2} \frac{pL_m}{L_r} \cdot (\Phi_{dr} \cdot \iota_{qs} - \Phi_{qr} \cdot \iota_{ds})$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad ; \quad T_r = \frac{L_r}{R_r}$$

For a rotor-flux orientation, the regulator imposes the orientation of the rotor flux (Φr) with respect to the d-axis, giving $\Phi r = \Phi dr$ and $\Phi qr = 0$. Substituting these relations in (2), leads to the field-oriented model of the motor which is given by the following equation system:

$$v_{ds} = \sigma L_s \frac{d \iota_{ds}}{d t} + R_s \iota_{ds} - \sigma L_s \omega_s \iota_{qs} - \frac{L_m}{T_r} \omega_r \Phi_r$$

$$v_{qs} = \sigma L_s \frac{d \iota_{qs}}{d t} + R_s \iota_{qs} + \sigma L_s \omega_s \iota_{ds} + \frac{L_m}{T_r} \omega_r \Phi_r$$ (2)

$$\frac{d\Phi_r^*}{dt} + \frac{1}{T_r} \cdot \Phi_r^* = \frac{L_m}{T_r} \cdot \iota_{ds}^*$$

$$\omega_{sl}^* = \frac{L_m \cdot \iota_{qs}^*}{T_r \cdot \Phi_r^*}$$

$$T_{em}^* = \frac{3}{2} \frac{pL_m}{L_r} \Phi_r^* \cdot \iota_{qs}^*$$

The field-oriented controller is based on the inversion of the above equation system. The command variables (ids*, iqs*, vds*, vqs*) are generated here respectively by regulators as it is shown in Fig.1.

The rotor flux is estimated by means of stator current
and speed measurements (direct method) as follows:

$$\frac{d \iota_{ds}}{d t} = \frac{1}{\sigma L_s} \left[v_{ds} - \left(R_s + \left(\frac{L_m}{T_r} \right)^2 \right) \cdot \iota_{ds} + \right.$$

$$\left. + \sigma L_s \omega_s \iota_{qs} + \frac{L_m}{T_r} \omega_r \Phi_r \right]$$ (3)

$$\frac{d \iota_{qs}}{d t} = \frac{1}{\sigma L_s} \left[v_{qs} - \left(R_s + \left(\frac{L_m}{T_r} \right)^2 \right) \cdot \iota_{qs} \right.$$

$$\left. - \sigma L_s \omega_s \iota_{ds} + \frac{L_m}{T_r} \omega_r \Phi_r \right]$$

The corresponding position is given by:

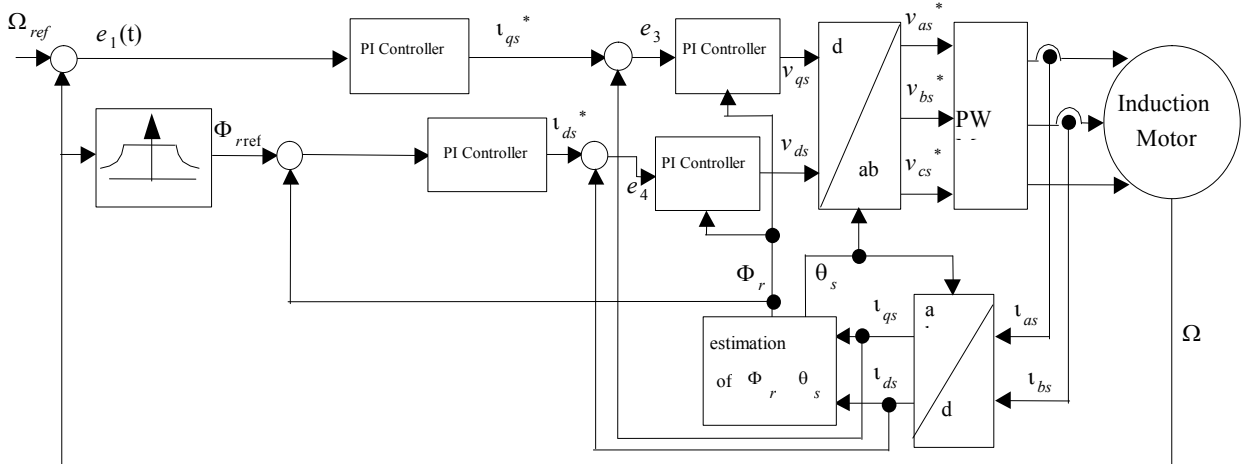$$\theta_e = \int (p \cdot \Omega + \omega_{sl}^*) \, dt$$ (4)

Fig. 1 . Vector control scheme of an induction motor.

3. Variables Structures Control Technical

The basic principle of the variables structures control also called the sliding mode control consists in moving the state trajectory of the system toward a predetermined surface called sliding or switching surface and in maintaining it around this latter with an appropriate switching logic. This is similar to a feed-forward controller that provides the control that should be applied to track a desired trajectory, which is in this case, the user-defined sliding surface itself.

So, the design of a sliding mode controller has two steps, the definition of the adequate switching surface $S(.)$ and the development of the control law or the switching logic U. Concerning the development of the switching logic, it is divided into two parts, the equivalent control U_{eq} and the attractivity or reachability control U_n. The equivalent control is determined off-line with a model that represents the plant as accurately as possible and calculated by imposing the derivative of sliding mode surface equal to zero. If the plant is exactly identical to the model used for determining U_{eq} and there are no disturbances, there would be no need to apply an additional control U_n.

However, in practice there will be discrepancy between the model and the actual system control.

Therefore, the control component U_n is necessary and it will always guarantee that the state is attracted to the switching surface by satisfying the following attractivity condition.

$$S(\cdot) \cdot \dot{S}(\cdot) < 0 \qquad (5)$$

Therefore, the basic switching law is of the form:

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

With: $U_n = -M(\cdot) \cdot \text{Sgn}(S(\cdot))$

$M(S)$: the magnitude of the attractivity control law U_n,
Sgn: the sign function.

In a conventional variables structures control (VSC), the reachability control generates a high control activity as it depends on the magnitude $M(.)$, 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 [9-12]. However, in practice, chattering can only be reduced.

Generally to reduce chattering was to introduce a boundary layer around the sliding surface Fig.(2) and to use a smooth function to replace the discontinuous part of the control action as follows [13-16]:

$$U_n = \begin{cases} \dfrac{K}{\varepsilon} \cdot S(x) & \text{if} \quad |S(x)| < \varepsilon \\ \\ K \cdot Sgn\ (S(x)) & \text{if} \quad |S(x)| > \varepsilon \end{cases} \qquad (7)$$
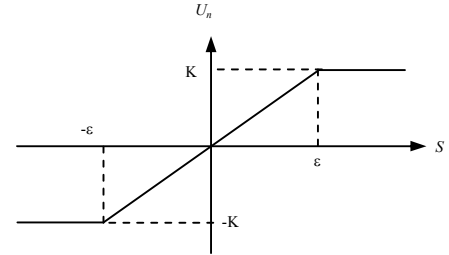

Fig. 2 . Sliding mode with boundary layer and the modified switching law.

The constant K is linked to the speed of convergence towards the sliding surface of the process the reaching Mode). 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, a proposed approach will be described in the following section which is able to reduce this latter.

On the other hand, in order to reduce the chattering, the authors propose here an idea that consists to approach gradually the control state of the sliding mode surface ($S(.)=0$). So, by the use of a softened several ramp discontinuous control law given in eq.8. Thus, this control law must be ensured a softened approach of the controller variable towards the sliding surface and leading to reduction of the chattering phenomenon. This control law will also, avoid a discontinuity of operation as it is shown in Fig.3 [11].
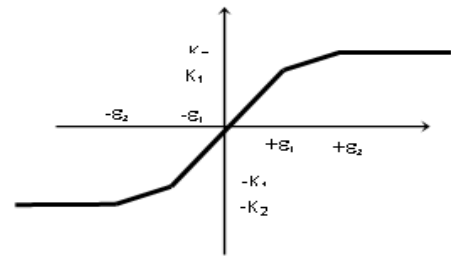

Fig.3. Sign function control with several ramps.

The expression that corresponds to such a control law given in the above figure is given by [17]:

$$U_n = M(S) \cdot sign(s) \qquad (8)$$

with:

$$M(S) = \begin{cases} +K_2 & S(x) > +\varepsilon_2 \\ ((K_2-K_1)/(\varepsilon_2-\varepsilon_1)) \cdot S(x) & \varepsilon_1 < |S(x)| < +\varepsilon_2 \\ (K_1/\varepsilon_1) \cdot S(x) & -\varepsilon_1 < |S(x)| < \varepsilon_1 \\ ((K_1-K_2)_1/(\varepsilon_1-\varepsilon_2)) \cdot S(x) & -\varepsilon_2 < |S(x)| < -\varepsilon_1 \\ -K_2 & |S(x)| < -\varepsilon_2 \end{cases}$$

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

4. Conception of the Speed variables structures controller

In this paper, only the PI speed controller of the figure.1 is replaced by variables structures one. Fig.4. Its corresponding parameters are defined as follows:

1) Design of the switching surface

The sliding mode surface is defined as:

$$S(\Omega) = (\Omega_{ref} - \Omega) + m_1 \int (\Omega_{ref} - \Omega) dt \qquad (9)$$

With: Ω_{ref} being respectively the reference variable of the rotor speed.

2) Development of the control law:

By using the equation system (2), the speed regulator control laws are obtained as follows:

$$S(\Omega) \cdot \dot{S}(\Omega) < 0 \implies \iota_{qs} = \iota_{qseq} + \iota_{qsn} \qquad (10)$$

With:

$$\iota_{qseq} = \frac{J \cdot \dfrac{d\Omega_{ref}}{dt} + T_L}{\dfrac{3}{2} p \dfrac{L_m}{L_r} \cdot \Phi_r}$$

Concerning the discontinuous control law it is considered as it was defined in eq 6, 7 and 8 respectively.

5. Validation of the Sliding Mode Controller

In order to verify the effectiveness of the softened several ramps control law given in eq.7 compared to the boundary layer one of eq. 6, a numerical 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 $\Omega_{ref} = 100$ rad/sec. Then a torque load (TL = 10 Nm) is applied at t = 1 sec. The results are shown in "Fig.5 and 6".

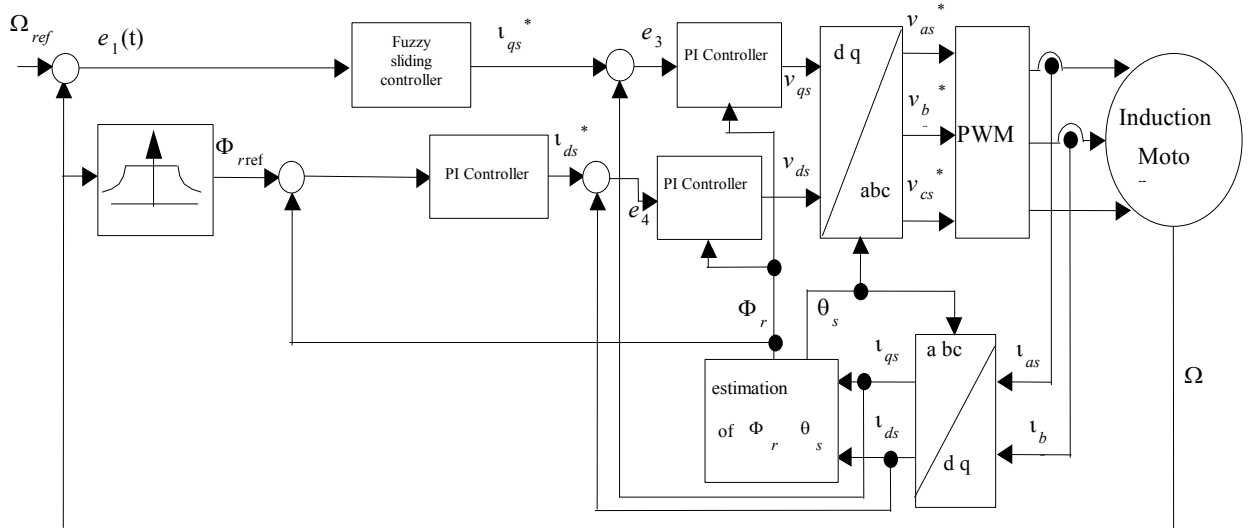Note that the parameters of the induction motor used are given in Appendix.

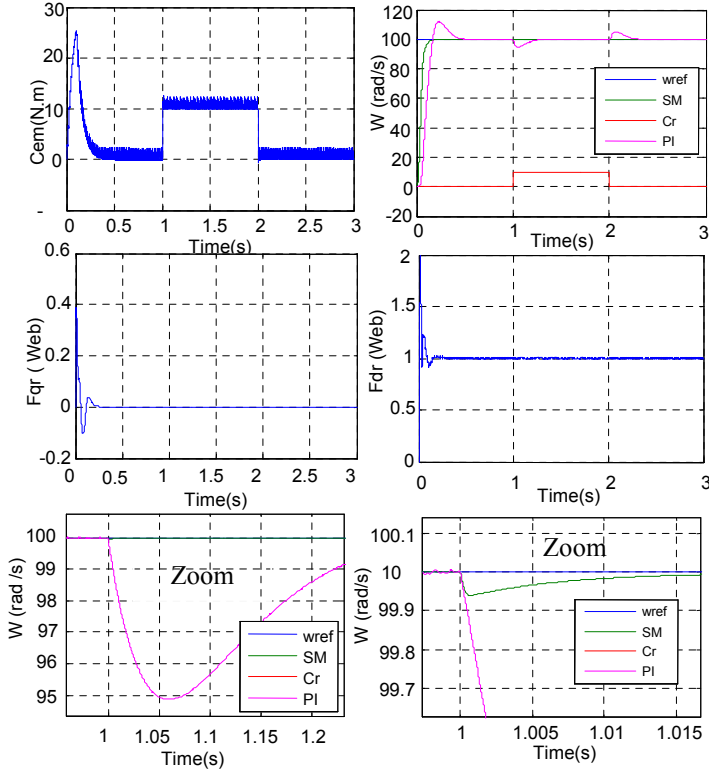Fig. 4 . Vector control scheme of an induction motor with Fuzzy sliding

Fig. 5. Dynamics simulation of induction machine with a perturbation of a load torque of 10 Nm with a boundary layer**.**

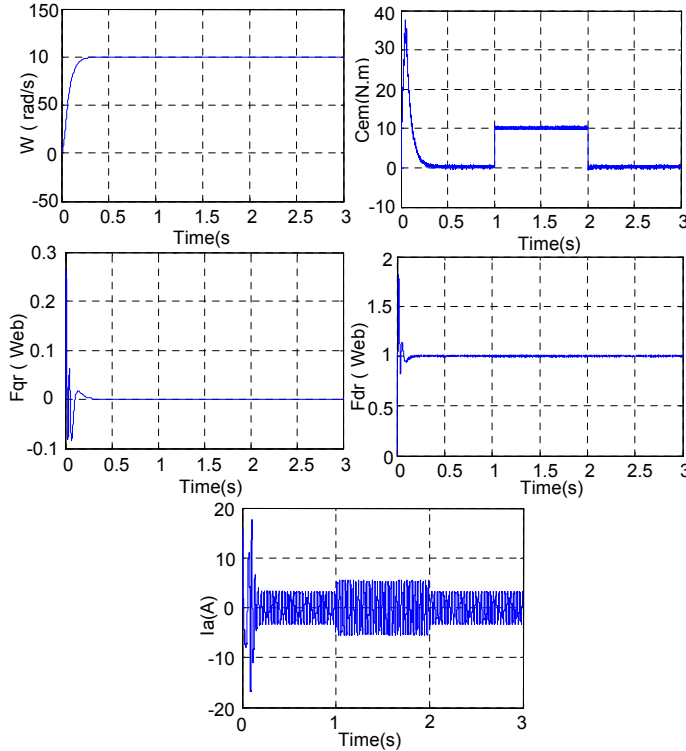Fig. 6.Dynamics simulation of induction machine with a perturbation of a load torque of 10 Nm with softened several ramps.

It is noticed that the vector control is maintained with $\Phi_{qr} = 0, \Phi_{dr} = 1$ wb, the speed follows perfectly the reference value and the regulator compensates all disturbances without any effect on the variation of the flux.

Thus, the aim of the field-oriented control is achieved, and the introduction of perturbations is immediately rejected by the control system, the transient torque is about $5*I_n$ (nominal current) which is permeable in the induction motor (Fig.6).

The comparison of performance between PI and SM controller shows a better robustness and pursues of the regulator SM vs PI.

A marked reduction of the chattering phenomenon appears in the torque response (Fig.5) due to the discontinuous characteristic of the controller with the second discontinuous control law is noticed (Fig.6), because the second technique allow to attract gradually the variable control to the desired state. So, we can see that our objective is attempted with great success.

On the other hand, in order to find the required constants k_1, k_2 ε_1 and ε_2 , we propose to fuzzify the softened several ramps.

6. Conception of the Fuzzy Variables Structures Speed Controller

In this section, we propose to fuzzify the sign function Fig (7) in several ramps given in the previous section based on the approach of Ben Ghalia and al [16].
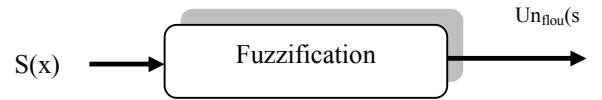

Fig. 7**.** Bloc of fuzzyfication of sign function

Indeed, this function is closely related to these upper limits k_1, k_2, ε_1 et ε_2 which represents the limits of the slopes that make up this function. It is difficult to find the optimal limits which will given the best performances of the overall controlled process and providing a reduction of chattering phenomenon. So to solve this problem, we proposed to fuzzify the function sign (S), and to display the number of ramps by adapting the form of sets of the membership functions based on Ben Ghalia approach [16].

In fact, Ben Ghalia [15-16-17] has noted that if one takes the absolute value of the sign function is located with the boundaries fuzzy function.
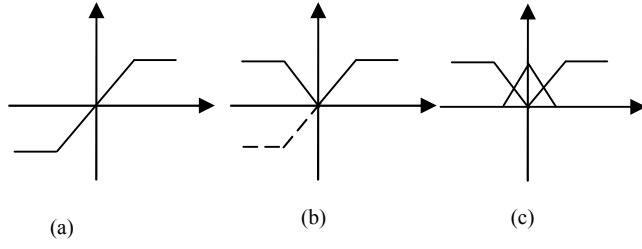
Fig.8. The basic principle of the approach of Ben-Ghalia

Fig. 11.Sign function of the fuzzy control several ramps

In this proposal, increasing the number of membership functions of Fig 8c, give the appropriate controller based on the function with several ramps with the optimal constants.

Thus, here and in order to reduce the chattering as well as possible the following classes for the output fuzzy sign (S) is defined:
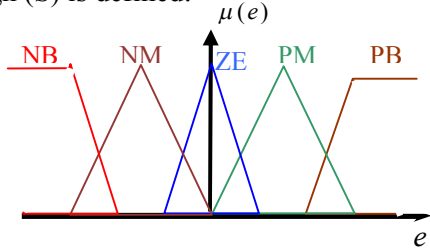

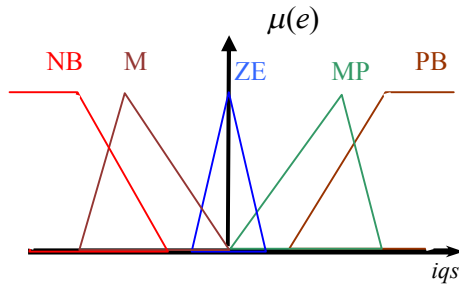Fig. 9.Membership functions of input variables e (Ω).

Fig. 10.Membership functions of fuzzy output variables sign (s).

In Fig (9), each interval is associated to a membership function whose form is chosen by the designer in order to define fuzzy sets on the functions sign (S) [18]

The table of fuzzy rules generating the sign (S) that results is

e(Ω)	NB	NM	ZE	PM	PB
i_{qs}*	Negative Big	Negative medium	Zero	Positive medium	Positive Big

TABLE 1.The table of fuzzy rules generating the sign (s)

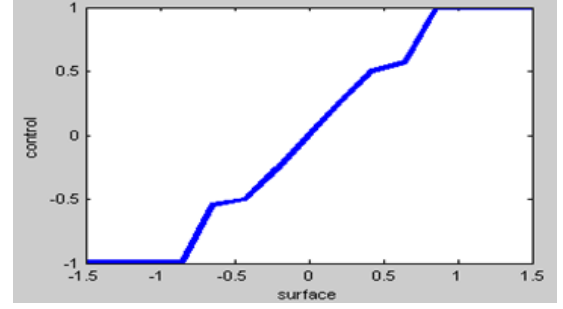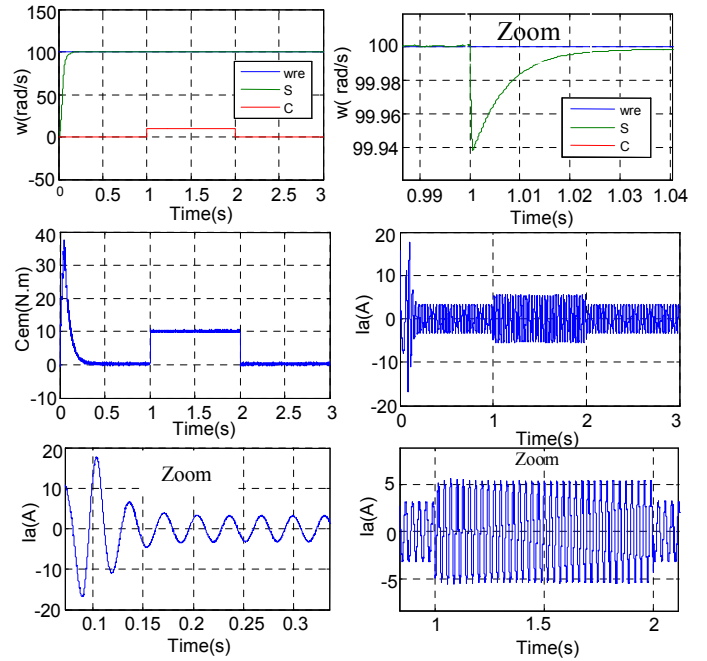In order to see the contribution of this technical, a simulation under the same conditions as above is made

Fig. 12.Dynamics simulation of induction machine with a perturbation of a load torque of 10 Nm with fuzzy softened several ramps.

According to these figure (Fig.12), it is observed that the waveforms of each illustrated variable are typically the same as those observed with the control scheme based on speed variable structure controller, but with a better reduction of the phenomenon of chattering and higher performances which is due to the introduction of the fuzzification of the constants k_1, k_2 ε_1 and ε_2.

On the other hand, in order to test the of the fuzzy variable structure controller with respect to the PI, a robustness test is performed with several parametric variations (+50%J,+30%R_s). The results are given in Fig13.
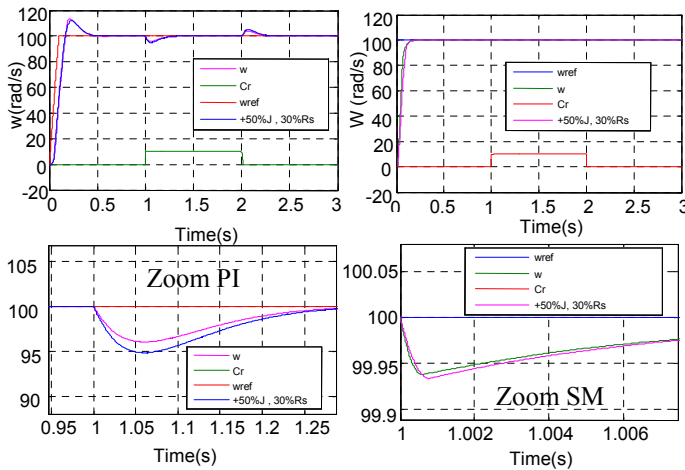
Fig. 13.Comparison between the two speed controllers with application of variations parametric and external disturbance.

From the obtained waveforms, it is clearly shown that the robustness of our system towards parameter's variations and external perturbation is ensured in all the sliding mode control processes which confirms the ability of these kind of structures variables control techniques to ensure the tracking and the robustness as it is cited by numerous other works.

7. Conclusion

The proposed approach has revealed very interesting features. In fact, the combination of the nonlinear control with the field oriented control maintains an effective decoupling between speed and flux for the whole range of speed which allows to obtain high dynamic performances for constant flux operation similar to that of DC motors. Further, these high performances are maintained above the nominal speed for the constant power operation, which is not the case in the conventional field oriented control. The addition of the sliding mode controllers has improved the robustness towards internal parameter variations, modelling uncertainties and external disturbances, and the fuzzyfication of the several ramps discontinuous control law function has minimized the phenomenon of chattering as it was shown clearly by the obtained results.

8. Appendix: Machine Parameters

Squirrel-cage induction motor of 1.5 Kw, 220 V, 2 poles, 1420 tr/min, 50 Hz. R_s = 4.85 Ω ; R_r = 3.805 Ω ; L_s= 0.274 H ; L_r =0.274 H; M = 0.258 H ; J = 0.031 Kg.m^2 ; f = 0.00114 Nms

9. Nomenclature

W_r: The rotor speed, in actual (mechanical) radians per second; W_s: Supply frequency; W_{ref}: Reference rotor speed.
T_{em}: Electromagnetic torque; C_r: Load torque.
p: Number of poles; J : Inertial constant.

I_d, I_q: Direct- and quadrature-axis components of the induction motor armature current.
V_d, V_q: Direct- and quadrature-axis components of the induction motor voltage.
$R_s,\ R_r$:: stator, rotor resistance.
$L_s,\ L_r$: stator inductance.
L_m: mutual inductance; Φ: Flux instantaneous; K_i: control constant

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