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Contribution to study Performance of the Induction Motor by Sliding Mode Control and Field Oriented Control

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Abstract—**The induction motor squirrel cage that is deemed by its strength, high torque mass, and its relatively low cost ... etc, meanwhile, it benefited from the support of industry since its invention. Despite these advantages, the induction motor has complex dynamic systems that exhibit a strong nonlinearity, which makes them difficult to be controlled. The use of control algorithms is therefore desirable that both stabilization trajectory tracking. This paper seeks to analyze dynamical performances and sensitivity to motor parameter changes of two techniques of induction motor, Sliding Mode Control and Field Oriented Control. Comparison between the two techniques is made through computer simulations.**

Index Terms— **Indirect Field Oriented Control (IFOC), Induction Motor (IM), nonlinear sliding surface, Sliding Mode Control (SMC).**

Nomenclature

r, s	: Subscripts stand for rotor and stator;
R_r, R_s	: Rotor and stator resistances;
L_r, L_s, L_m	: Rotor, stator and mutual inductances;
C_{em}	: Electromagnetic torque;
σ	: Total leakage coefficient;
J	: Moment of inertia;
v, i	: Voltage and current;
ϕ	: Flux linkage;
ω_r	: Electrical angular rotor speed;
ω_s	: Synchronously rotating angular speed;
p	: Number of poles pair.

I. INTRODUCTION

INDUCTION motors are suitable electromechanical systems for a large spectrum of industrial applications. However, induction motors are multivariable nonlinear and strongly coupled time-varying systems, mainly, in variable speed applications [1]. However, its dynamic control requires complex control algorithms, facing its structural simplicity [2], since there is a complex coupling between the input variables, output variables and the internal variables of the machine [3].

So with the invention of power electronics, and advances in computing, has made a radical revolution. Its goal is to develop control strategies for asynchronous motors, namely the field oriented control [5]; this method is based on the principle of decoupling between the flux and torque of the machine, however, this technique requires the use of a mechanical sensor on the shaft of the machine and has a weakness against the parametric variations of the machine [1], [4]. For this and overcome the problems of vector control, the sliding mode control is nonlinear nature, has this robustness, [9].

The sliding mode control is a nonlinear control and based on the switching functions of state variables, used to create a variety or hyper sliding surface, whose purpose is to force the system dynamics to correspond with the defined by the equation of the hyper-surface. When the state is maintained on the hyper surface, the system is in sliding regime [10]. Its dynamic is so insensitive to external disturbances and parametric conditions as sliding regime are carried out [6]. In the synthesis of the control law by way of sliding, the sliding surface is defined as an independent and stable linear system. However, the dynamics imposed by such a system is slower than that imposed by a non-linear system, hence the importance of using the latter type of systems to synthesize the sliding surface in some applications [13].

The paper is organized as follows: in the third section ,the considered induction motor nonlinear model is presented. In the forth section the field oriented control technique is recalled and in the fifth section the sliding mode control design is presented. The comparison simulation results and comments are presented in the sixth and final section; they have been validated by numerical simulations in Matlab/Simulink interface.

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II. NONLINEAR INDUCTION MOTOR MODEL

Induction motor as various electric machines constitutes a theoretically interesting and practically important class of nonlinear dynamic systems. Induction motor is known as a complex nonlinear system in which time-varying parameters entail additional difficulty for induction motor system control, conditions monitoring and faults diagnosis. Based on the fact that the nonlinear model of the induction motor system can be significantly simplified, if only one applies the d-q Park transformation, different structures of the nonlinear model are investigated. The choice of a model depends on measurement possibilities, selected state variables of the machine and the problem at hand [1]. In this paper, the considered induction motor model has stator current, rotor flux and rotor angular velocity as selected state variables. The control inputs are the stator voltage and load torque. The available stator current measurements are the induction motor system outputs. The nonlinear state space model of the induction motor is expressed as the following:

$$\begin{cases} \dot{x} = f(x) + g(x).v \\ y = h(x) \end{cases} \tag{1}$$

With: $v = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \end{bmatrix}^T = \begin{bmatrix} U_1 & U_2 \end{bmatrix}^T$

$$x = \begin{bmatrix} i_{s\alpha} & i_{s\beta} & \phi_{r\alpha} & \phi_{r\beta}\,\Omega_r \end{bmatrix}^T = \begin{bmatrix} x_1 & x_2 & x_3 & x_4\, x_5 \end{bmatrix}^T$$

Such as:

x : State vector.

v : Vector control.

y : Output selected.

$h(x)$: An analytic function.

$$f(x) = \begin{bmatrix} a_{11}\cdot x_1 + a_{13}\cdot x_3 + a_{14}\cdot x_4.x_5 \\ a_{11}\cdot x_2 - a_{14}\cdot x_3.x_5 + a_{13}\cdot x_4 \\ a_{31}\cdot x_1 + a_{33}\cdot x_3 + a_{34}\cdot x_4.x_5 \\ a_{31}\cdot x_2 - a_{34}\cdot x_3.x_5 + a_{33}\cdot x_4 \\ \mu\cdot(x_2\cdot x_3 - x_1\cdot x_4) - \frac{c_r}{J} \end{bmatrix}; \quad g(x) = \begin{bmatrix} b_{11} & 0 \\ 0 & b_{11} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Such as:

$a_{11} = -\left[\frac{1}{\sigma\cdot T_s} + \frac{1}{T_r}\cdot\left(\frac{1-\sigma}{\sigma}\right)\right]$, $a_{13} = \frac{1-\sigma}{\sigma}\cdot\frac{1}{M\cdot T_r}$, $a_{14} = \frac{1}{M}\cdot\frac{1-\sigma}{\sigma}\cdot p$,

$a_{31} = \frac{M}{T_r}$, $a_{33} = -\frac{1}{T_r}$, $a_{34} = -p$, $b_{11} = \frac{1}{L_s.\sigma}$,

$\sigma = 1 - \frac{M^2}{L_s.L_r}$, $T_s = \frac{L_s}{R_s}$, $T_r = \frac{L_r}{R_r}$, $\mu = \frac{p\cdot M}{J\cdot L_r}$.

III. FIELD ORIENTED CONTROL STRUCTURE

The choice of the reference model of the asynchronous machine from the template in the Park transformation is such that the axis'd' coincides with the direction of the flux guide, or stator or rotor air gap. Therefore, it is clear that the current focus on the axis'd' is one that generates the flux (fig.1) [6], [11]:

$$\phi_d = \phi_r\,, \phi_q = 0 \tag{2}$$

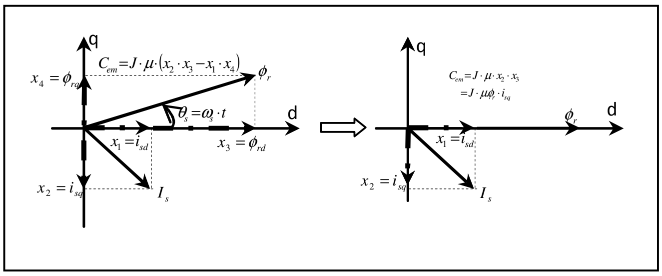

Fig. 1. Angular relations of current vectors [11].

The strategy of the vector control is to independently control the flux term and the current term to impose a couple. Keeping the control variables as (V_{sd}, V_{sq}) and state variables such as stator currents (i_{sd}, i_{sq}), the flux ϕ_r and the mechanical speed. When an electric motor drives a mechanical load it is essential to properly control the dynamics of it, to master the instantaneous torque of it. The thrust of the vector control is to have the asynchronous machine for a couple proportional to flux engine and a current like the DC machine. So, let's take the expression of the electromagnetic torque of the induction machine. So, let's take the expression of the electromagnetic torque of the induction machine:

$$C_{em} = J\cdot\mu\cdot(x_2\cdot x_3 - x_1\cdot x_4) \tag{3}$$

In the reference dq which are projected the rotor flux and the stator current running at the speed of the rotating field, either in: $\theta_s = \omega_s\cdot t$

In order to have expression analogous to that electromagnetic torque of a DC motor the axis will be directed of the rotor flux, air gap torque of the expression becomes:

$$C_{em} = J\cdot\mu\cdot x_2\cdot x_3 \tag{4}$$

By imposing the condition (2) to state the model of IM (1) supplied with voltage equations at the following reduced system is realized, [11]:

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$$\begin{cases} i_{sq} = \dfrac{L_r}{P \cdot M} \cdot \dfrac{C_{em}^*}{\phi_r^*} \\ i_{sd} = \dfrac{1}{M} \cdot \left[T_r \cdot \dfrac{d\phi_r^*}{dt} + \phi_r^* \right] \\ \omega_r = \dfrac{M}{T_r} \cdot \dfrac{i_{sq}}{\phi_r^*} \\ \omega_s = \omega_m + \omega_r \\ v_{sd} = R_s \cdot \left[\sigma \cdot L_s \dfrac{di_{sd}}{dt} + i_{sd} + T_s \dfrac{(1-\sigma)\cdot \phi_r^*}{M} - \sigma \cdot T_s \cdot \omega_s \cdot i_{sq} \right] \\ v_{sq} = R_s \cdot \left[\sigma \cdot T_s \dfrac{di_{sq}}{dt} + i_{sq} + T_s \dfrac{(1-\sigma)\cdot \phi_r^*}{M} - \sigma \cdot T_s \cdot \omega_s \cdot i_{sd} \right] \end{cases} \quad (5)$$

The diagram of vector control with a flux model is given in Figure (1):

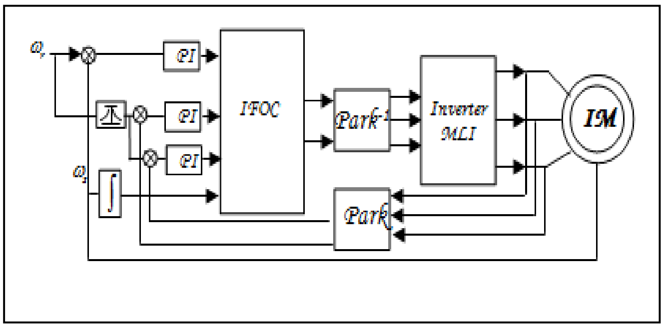

Fig. 2. Block diagram of indirect field oriented control structure.

IV. CONDITION EXISTENCE OF SLIDING MODE CONTROL

The sliding mode exists when the switching takes place continuously between U_{max} and U_{min}. This is illustrated in figure (3) for the case of a control system of the second order with two state variables x_1 and x_2 , [14].

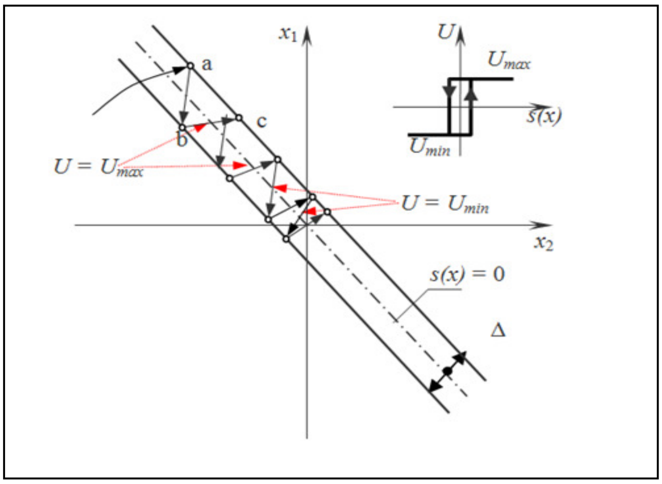

Fig. 3. Path of steady state sliding mode

V. SLIDING MODE CONTROL DESIGN

The implementation of sliding mode control requires three main steps, [7]:

- The choice of the surface.
- The establishment of the conditions of existence of convergence.
- The determination of the control law.

A. *The choice of the surface*

The choice of the sliding surface for the necessary number and shape, depending on the application and purpose. In general, for a system defined by the state equation (1), choose'' m'' sliding surfaces for a vector of dimension "m", [13], with:

$$y(x) = \begin{bmatrix} y_1(x) \\ y_2(x) \end{bmatrix} = \begin{bmatrix} \Phi_r \\ \Omega_r \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\left(x_3^2 + x_4^2\right) \\ x_5 \end{bmatrix} \quad (6)$$

The surface $S(x)$ represents the desired dynamic behavior of the system. J. J Slotine [7], [9]; proposes a form of general equation to determine the sliding surface which ensures the convergence of a variable towards its desired value $x_{i\ ref}$.

If x_i a variable to controlled, associated with the following surface:

$$S_i(x_i) = \left(\frac{d}{dt} + \lambda_i\right)^{r-1} \cdot e_i(x_i) / i = 1,2. \quad (7)$$

With :

λ_i : is a positive constant.

r : is the relative degree [8], [9].

The difference between the controlled variable and its reference is:

$$e_i(x) = x_i - x_{i\ ref} \quad (8)$$

The purpose of this paper is to determine a control law to force the system states, ie, the rotor flux and the electromagnetic torque to follow the sliding surface as: $S = [S_1 \quad S_2]^T$.

B. *Area Calculation*

After the calculation of the relative degree, the sliding surfaces of the equation [12], can be determined as follows:

$$\begin{cases} S_1 = \lambda_1 \cdot e_1 + \dot{e}_1 \\ S_2 = \lambda_2 \cdot e_2 + \dot{e}_2 \end{cases} \quad (9)$$

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With :
$$\begin{cases} e_1 = \Phi_r - \Phi_{r\ ref} \\ e_2 = \Omega_r - \Omega_{r\ ref} \end{cases} \quad (10)$$

Are successively error flux (e_1) and error rate (e_2).

When substituting (1) and (10) into (9) the following result is as follows:

$$\begin{cases} S_1 = \lambda_1 \cdot (\Phi_r - \Phi_{rref}) + a_{31} \cdot (x_1 \cdot x_3 + x_2 \cdot x_4) + 2 \cdot a_{33} \cdot \Phi_r - \dot{\Phi}_{rref} \\ S_2 = \lambda_2 \cdot (\Omega_r - \Omega_{rref}) + \mu \cdot (x_2 \cdot x_3 - x_1 \cdot x_4) - \frac{c_r}{J} - \frac{f}{J}\Omega_r - \dot{\Omega}_{rref} \end{cases} \quad (11)$$

However, to continue $\Phi_{r\ ref}$ and $\Omega_{r\,ref}$, it suffices to make the sliding surface attractive and invariant.

C. Equivalent command for the invariance

Once the sliding surface is chosen, it remains to determine the control necessary to attract the controlled variable to the surface and then to his balance point, the relation will be as follows:

$$u = u_{eq} + u_n \quad (12)$$

The necessary condition for the system states follow the path defined by the sliding surfaces is:

$$\dot{S} = 0 \quad (13)$$

The ideal diet is almost never possible. Therefore must use the second term of the command to restore the system state to the surface whenever it deviates. Thus, it should be taken:

$$u_n = M_i \cdot sign(S_i(x)) \quad (14)$$

$S(x)$ Slip function is selected such that it is a solution of the following differential equation:

$$\dot{S}_i(x) = -M_i \cdot sign\ (S_i(x)) \quad / \quad i = 1,2. \quad (15)$$

According to the equations (13), (14) and (15) the equivalent command for this invariance cans determined as:

$$u = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = G^{-1} \cdot \begin{bmatrix} X \\ Y \end{bmatrix} \quad (16)$$

With:

$$G = \begin{bmatrix} -b_{11} \cdot x_3 & -b_{11} \cdot x_4 \\ b_{11} \cdot x_4 & -b_{11} \cdot x_3 \end{bmatrix} \quad (17)$$

In taking into consideration the condition transversal matrix (16), then:

$$\det G \neq 0 \quad (18)$$

Therefore: $b_{11}^2 \cdot (x_3^2 + x_4^2) \neq 0$

With:
$$\begin{cases} x_3 = \phi_{r\alpha} \\ x_4 = \phi_{r\beta} \end{cases} \quad (19)$$

The diagram of sliding mode control is given in Figure (3):

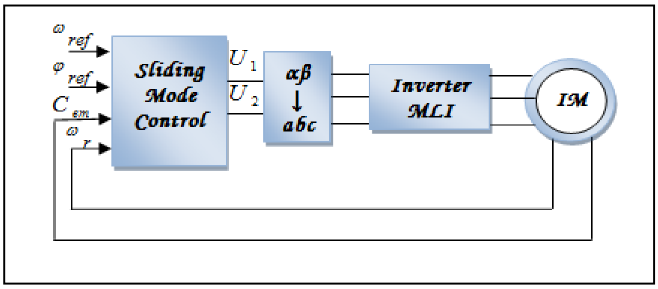

Fig. 4. Block diagram of the sliding mode control.

VI. SIMULATIONS RESULTS AND DISCUSSIONS

Comparison developed between the two techniques, Sliding Mode Control (SMC) and field oriented control (FOC).Tto evaluate these properties, different simulation is realized , Test of robustness for a variation of rotor resistance, speed variation and load variation, see the following figures:

Developed comparison between the two techniques, Sliding Mode Control (SMC) and field-oriented control (FOC). In evaluating these properties, realizing different simulation test robustness for a change in resistance of the rotor speed variation and load variation, see the following figures:

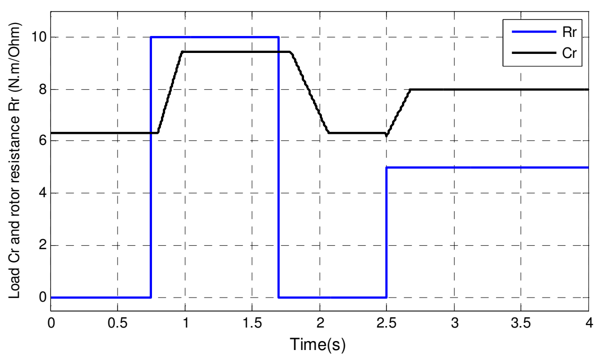

Fig. 5. Load and rotor resistance variations

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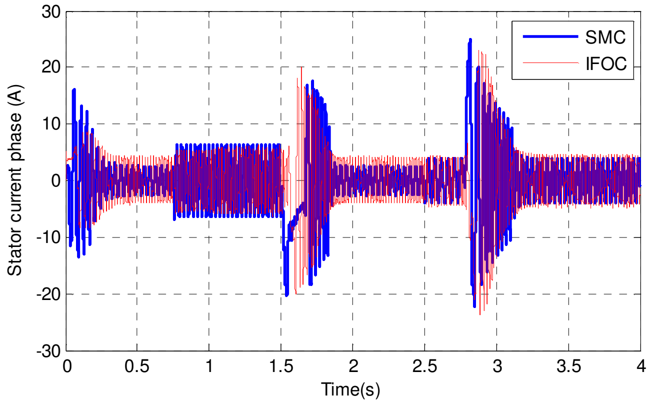

Fig. 6. Current of one phase

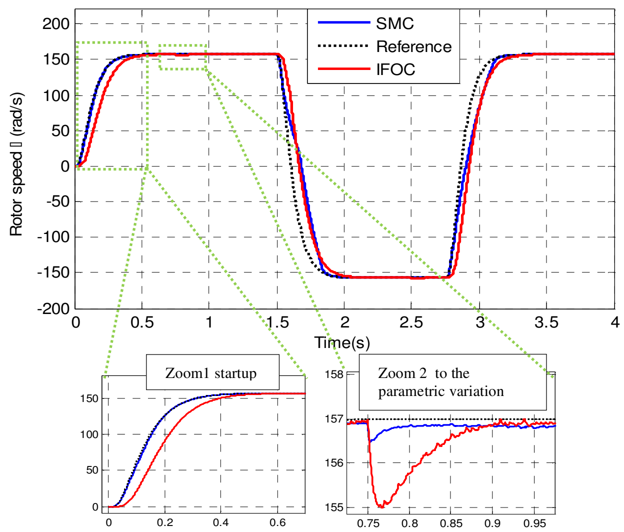

Fig. 9. Rotor speed tracking performance

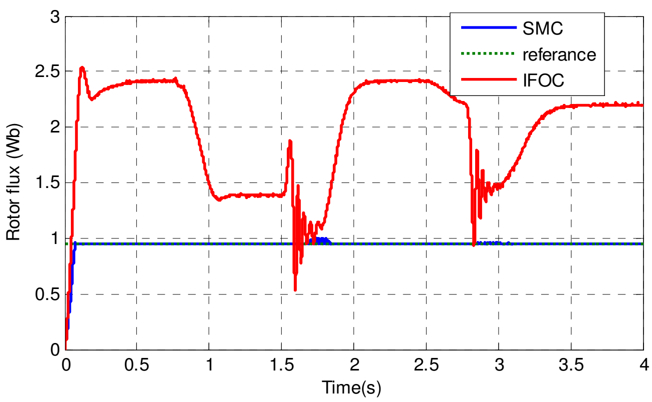

Fig. 7. Rotor flux tracking performance

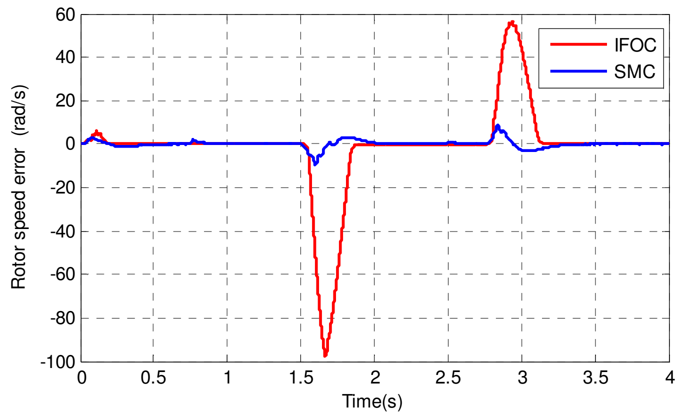

Fig. 10. Rotor speed error

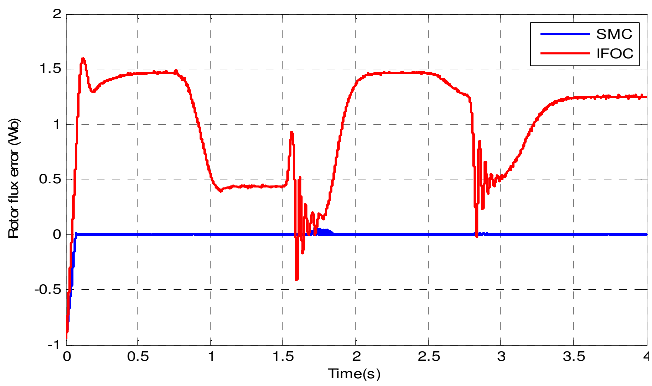

Fig. 8. Rotor flux error

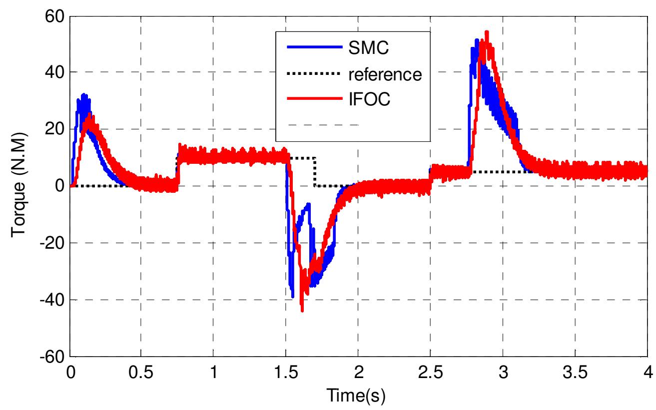

Fig. 11. Electromechanical torque to the load variation

Fig. 6, shows that a current of one phase of the MAS has a sinusoidal shape for both techniques, with peaks at inversion of speed.

Fig. 7 shows that the application of the load torque does not affect the flux control (SMC), the latter coincides with the reference rotor flux error which is zero see Fig.8, but for the second technique IFOC is influential.

Fig. 9 shows the dynamic pursuit of speed, and absence of the disturbance to the SMC technique because the static error is zero see Fig.10, and the application of the load torque and the variation of the rotor resistance see Fig .5 do not affect the speed, but for the second technique IFOC the parametric variation affects the speed as shown in Fig.9;

Fig.11, it is observed that the electromagnetic torque presents peaks (30% of the load torque for SMC and 20% for IFOC) from starting and the moments of change of the rotational speed for both techniques. But the time to rethink the SMC technique is faster then they catch the torque required by the load on the motor shaft.

VII. CONCLUSION

This paper presents a comparison of Sliding Mode Control (SMC) and Indirect Field Oriented Control (IFOC), to analyze dynamical performances and sensitivity to motor parameter changes of induction motor.

The simulation results, obtained by Matlab showed that the Sliding Mode Control (SMC) technique is more robust and guarantee a better insensitivity to parameter variations of the machine than the Indirect Field Oriented Control (IFOC) technique. In addition, it has the advantage of being simple to implement in practice.

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