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A NEW APPROACH CONTROLLERS SYNTHESIS FOR THREE PHASE INDUCTION MOTOR DRIVES BASED ON THE ARTIFICIAL INTELLIGENCE TECHNIQUES

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Abstract: *In this work, we introduced a new method toward the design of hybrid control with sliding-mode (SMC) plus fuzzy logic control (FLC) for induction motors. As the variations of both control system parameters and operating conditions occur, the conventional control methods may not be satisfied further. Sliding mode control is robust with respect to both induction motor parameter variations and external disturbances. By combination of a fuzzy logic control and the sliding mode control, the chattering (torque-ripple) problem with varying parameters, which are the main disadvantage in sliding-mode control, can be suppressed, Simulation results of the proposed control theme present good dynamic and steady-state performances as compared to the classical SMC from aspects for torque-ripple minimization, the quick dynamic torque response and robustness to disturbance and variation of parameters.*
Keywords: *Induction Motor (IM), Sliding Mode Control (SMC), Fuzzy Logic Control (FLC), Fuzzy Logic Sliding Mode Control (FLSMC), Torque Ripple*

INTRODUCTION

Induction Motors (IM) are applied today to a wider range of applications requiring variable speed. Generally, variable-speed drives for induction motors require both wide operating range of speed and fast torque response, regardless of load variations. However, induction motor has disadvantages, such as complex, nonlinear, and multivariable of mathematical model, and the induction motor is not inherently capable of providing variable speed operation.

Field oriented control method is used for advanced control of induction motor drives. By providing decoupling of torque and flux control demands, the vector control can govern an induction motor drive similar to a separate excited direct current motor without sacrificing the quality of the dynamic performance.

However, the field oriented control of induction motor drives presents two main problems that have been providing quite a bit research interest in the last decade. The first one relies on the uncertainties in the machine models and load torque, and the second one is the precise computation of the motor speed without using speed sensors.

The decoupling characteristics of the vector control are sensitive to machine parameters variations. Moreover, the machine parameters and load characteristics are not exactly known, and may vary during motor operations. Thus the dynamic characteristics of such systems are very complex and nonlinear. Therefore, many studies have been made on the motor drives in order to preserve the performance under these parameter variations and external load disturbances, such as nonlinear control, optimal control, variable structure system control, adaptive control and neural control [5], [6],[8], [11] and [12].

Sliding mode control (SMC), based on the theory of variable structure systems (VSS), has been applied to robust control of nonlinear systems [9]. Sliding mode control performs well in trajectory tracking of some nonlinear systems. It employs a discontinuous control law to drive the state trajectory toward specified sliding surface and maintain its motion along the sliding surface in the state space. It is a common opinion that the major drawback of sliding mode control is the so-called chattering phenomenon. Such a phenomenon consists of the oscillation of the control signal, tied to the discontinuous nature of the control strategy, at a frequency and with an amplitude capable of disrupting, damaging or, at least, wearing the controlled physical system (e.g., in mechanical systems with backlash).

Several methods of chattering reduction have been reported. One approach [3], [13] places a boundary layer around the switching surface such that the relay control is replaced by a saturation function. Another method [3], [14] replaces a max–min-type control by a unit vector function. These approaches, however, provide no guarantee of convergence to the sliding mode and involve a tradeoff between chattering and robustness.

Reduced chattering may be achieved without sacrificing robust performance by combining the attractive features of fuzzy control with SMC [2], [7], [10] and [15]. Fuzzy logic, first proposed by Zadeh [16], has proven to be a potent tool for controlling ill-defined or parameter-variant plants. By encapsulating heuristic engineering rules a fuzzy logic controller can cope well with severe uncertainties, although a heavy computational burden may arise withsome implementations. Fuzzy schemes with explicit expressions for tuning can avoid this problem [4].

In this paper, we presented a new hybrid nonlinear control method which is based on sliding mode control and fuzzy logic method, sliding mode control approach is employed to design the induction motor speed and flux controllers. The dynamic decouple control has been accomplished under the condition that the parameter of stator resistance variants and theload torque is time variant. In order to reduce the undesired chattering phenomenon of signum function, the fuzzy control method is used, which can be used to design a new fuzzy switching function to replace the traditional sliding mode signum function, Finally, simulations and a comparison are presented to demonstrate the contribution of this approach.

2. MODELLING OF INDUCTION MOTOR

The induction motor model can be developed from its fundamental electrical and mechanical equations. In stationary reference frame the voltage equations are given by:

$$\begin{aligned} V_{s\alpha} &= R_s I_{s\alpha} + \frac{d\phi_{s\alpha}}{dt} \\ V_{s\beta} &= R_s I_{s\beta} + \frac{d\phi_{s\beta}}{dt} \\ V_{r\alpha} &= 0 = R_r I_{r\alpha} + \frac{d\phi_{r\alpha}}{dt} + \omega\phi_{r\beta} \\ V_{r\beta} &= 0 = R_r I_{r\beta} + \frac{d\phi_{r\beta}}{dt} - \omega\phi_{r\alpha} \end{aligned} \quad (1)$$

The stator and rotor flux linkages are defined using respective self-leakage inductances and mutualinductance as given bellow:

$$\begin{aligned} \phi_{s\alpha} &= L_s I_{s\alpha} + M_{sr} I_{r\alpha} \\ \phi_{s\beta} &= L_s I_{s\beta} + M_{sr} I_{r\beta} \\ \phi_{r\alpha} &= L_r I_{r\alpha} + M_{sr} I_{s\alpha} \\ \phi_{r\beta} &= L_r I_{r\beta} + M_{sr} I_{s\beta} \end{aligned} \quad (2)$$

The electromechanical torque is given by:

$$T_e = p\frac{M_{sr}}{L_r}\cdot\left[\bar{\phi}_r \wedge \bar{I}_s\right] = p\frac{M_{sr}}{L_r}\cdot\left[\phi_{r\alpha}\cdot i_{s\beta} - \phi_{r\beta}\cdot i_{s\alpha}\right] \quad (3)$$

The mechanical equation is given by:

$$J\cdot\frac{d\Omega}{dt} = T_e - T_L - f_r\cdot\Omega \quad (4)$$

The state model of the induction motor is a nonlinear system multivariable taking the following form:

$$\dot{X}(t) = F(X,t) + B(X,t)\cdot U(t) \quad (5)$$

With:

$$\dot{X} = \begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \\ \dot{X}_5 \end{bmatrix} = \begin{bmatrix} \dot{i}_{s\alpha} \\ \dot{i}_{s\beta} \\ \dot{\phi}_{r\alpha} \\ \dot{\phi}_{r\beta} \\ \dot{\omega} \end{bmatrix}, \quad B(X,t) = \begin{bmatrix} d_1 & 0 \\ 0 & d_1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$F(X,t) = \begin{bmatrix} -a_1\cdot I_{s\alpha} + b_1\cdot\phi_{r\alpha} + c_1\cdot\omega\cdot\phi_{r\beta} \\ -a_1\cdot I_{s\beta} - b_1\cdot\omega\cdot\phi_{r\alpha} + c_1\cdot\phi_{r\beta} \\ a_3\cdot I_{s\alpha} - b_3\cdot\phi_{r\alpha} - \omega\cdot\phi_{r\beta} \\ a_3\cdot I_{s\beta} + \omega\cdot\phi_{r\alpha} - b_3\cdot\phi_{r\beta} \\ b_5\cdot\left[\phi_{r\alpha}\cdot I_{s\beta} - \phi_{r\beta}\cdot I_{s\alpha}\right] - c_5\cdot T_L - a_5\cdot\omega \end{bmatrix},$$

$$U(t) = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix},$$

$$a_1 = \frac{1}{\sigma\cdot\tau_s} + \frac{1-\sigma}{\sigma\cdot\tau_r},\quad b_1 = \frac{(1-\sigma)}{\sigma\cdot M_{sr}\cdot\tau_r},\quad c_1 = \frac{(1-\sigma)}{\sigma\cdot M_{sr}},\quad d_1 = \frac{1}{\sigma\cdot L_s},$$

$$a_3 = \frac{M_{sr}}{\tau_r},\quad b_3 = \frac{1}{\tau_r},\quad a_5 = \frac{f_r}{p\cdot J},\quad b_5 = \frac{p^2\cdot M_{sr}}{J\cdot L_r},\quad c_5 = \frac{p}{J}$$

with: $\tau_s = \frac{L_s}{R_s}$, $\tau_r = \frac{L_r}{R_r}$ and $\sigma = 1 - \frac{M_{sr}^2}{L_s L_r}$.

3. BASIC CONCEPTS OF THE CONTROL MANIFOLD

The design procedure for a state based sliding mode controller can be divided into two parts [1]:

Step 1: Finding the switching function S defined by:

$$S(X) = \left(\frac{\partial}{\partial t} + \lambda\right)^{r-1}\cdot e(X) \quad (6)$$

Such as the internal dynamics in sliding mode are stable.

$S(X)$ is the sliding surface or switching surface . It is a surface in $\Re^n$ that divides the state space into two disjoint parts: $S(X) > 0$ and $S(X) < 0$

Step 2: Designing a controller U, which insures that the sliding mode is reached and subsequently maintained [1].

$$U = \begin{cases} U^{eq} + U^n & \text{if } S(X) > 0 \\ U^{eq} - U^n & \text{if } S(X) < 0 \end{cases} \quad (7)$$

When the system is in sliding mode, the trajectory will remain on the switching surface. This can be expressed by:

$$S(X) = 0 \text{ and } \dot{S}(X) = 0 \quad (8)$$

This condition is called invariance condition of the sliding surface.

The total control is given by:

$$U = U^{eq} + U^n \quad (9)$$

where: U^{eq} : The equivalent control.

U^n : The attractive control

The derivative of the surface S(X) is:

$$\dot{S}(X) = \frac{\partial S}{\partial t} = \frac{\partial S}{\partial X}\cdot\frac{\partial X}{\partial t} = \frac{\partial S}{\partial X}\cdot\dot{X} \quad (10)$$

By introducing (5) and (9) in (10), we obtain:

$$\dot{S}(X) = \frac{\partial S}{\partial X}\cdot\left[F(X,t) + B(X,t)\cdot U^{eq}\right] + \frac{\partial S}{\partial X}\cdot\left[B(X,t)\cdot U^n\right] \quad (11)$$

During the sliding mode and the permanent state, the surface is zero $(S(X) = 0)$ and therefore, its derivative and the discontinuous part are also zero ($\dot{S}(X) = 0$ and $U^n = 0$). Hence, we deduce the expression of the equivalent control:

$$\frac{\partial S}{\partial X}\cdot\left[F(X,t) + B(X,t)\cdot U^{eq}\right] = 0 \quad (12)$$

$$U^{eq} = -\left[\frac{\partial S}{\partial X}\cdot B(X,t)\right]^{-1}\cdot\left[\frac{\partial S}{\partial X}\cdot F(X,t)\right] \quad (13)$$

For the equivalent command can take a finite value, it must:

$$\frac{\partial S}{\partial X}\cdot B(X,t) \neq 0 \quad (14)$$

By replacing the equivalent control by expression in (14) yields the new expression for the derivative of the surface:

$$\dot{S}(X)=\frac{\partial S}{\partial X}\cdot\left[B(X,t)\cdot U^{n}\right] \qquad (15)$$

$$S(X)\cdot\dot{S}(X)=S(X)\frac{\partial S}{\partial X}\cdot\left[B(X,t)\cdot U^{n}\right]<0 \qquad (16)$$

The basic form of the attractive control U^{n} is a relay. In this case the discontinuous control is given by [1]:

$$U^{n}=-k\cdot \text{sign}\ (S(X)) \qquad (17)$$

where kis a strictly positive constant.

4. DESIGN OF FUZZY LOGIC SLIDING MODE FLSMC

Theconventional sliding mode control is based on the discontinuous function of state variables in the system that is used to create a "sliding surface". When this surface is reached, the discontinuous function keeps the trajectory on the surface of such so that the desired system dynamics is obtained.

In this paper, the controllers of speed and rotor flux are substituted by a fuzzy sliding mode control to obtain a robust performance. By keeping one part of the equivalent control (SMC) and adding the fuzzy logic control (FLC) we obtain the new method control (FSMC).

$$U_{FLSMC}=U^{eq}+U^{Fuzzy} \qquad (18)$$

Where: U^{Fuzzy} : is FLC witch replacing the attractive control.

4.1. Synthesis of sliding mode controllers SMC

The first step of sliding mode control design is to select a sliding surface that models the desired closed-loop performance in state variable space. Then design the control such that the system state trajectories are forced toward the sliding surface and stay on it. Now, suppose that a sliding surface is given as:

$$S_1(e_1)=\lambda_1\cdot e_1+\dot{e}_1 \qquad (19)$$
$$\text{with: } e_1=\omega_{ref}-\omega$$

$$S_2(e_2)=\lambda_2\cdot e_2+\dot{e}_2 \qquad (20)$$
$$\text{with: } e_2=\phi_{rref}^2-\phi_r^2$$

Where λ_1 and λ_2 are non-zero positive gains.

Our objective is to control rotor speed ω and rotor magnitude flux given by: $\phi_r^2=\phi_{r\alpha}^2+\phi_{r\beta}^2$

Here ϕ_{rref} and ω_{ref} are the desired flux and the desired speed respectively.

$$S_1(e_1)=\lambda_1\cdot(\omega_{ref}-\omega)+(\dot{\omega}_{ref}-\dot{\omega}) \qquad (21)$$

$$S_2(e_2)=\lambda_2\cdot(\phi_{rref}^2-\phi_r^2)+(\dot{\phi}_{rref}^2-\dot{\phi}_r^2) \qquad (22)$$

The development of calculated derivatives of the surfaces gives:

$$\begin{aligned}\dot{S}_1(e_1)&=\lambda_1(\dot{\omega}_{ref}-\dot{\omega})+(\ddot{\omega}_{ref}-\ddot{\omega})\\ &=\lambda_1\cdot\dot{\omega}_{ref}+\ddot{\omega}_{ref}-(\lambda_1-a_5)\cdot\dot{X}_5\\ &\quad+b_5\left[a_1(X_2\cdot X_3-X_1\cdot X_4)+c_1\cdot\phi_r^2\cdot X_5+X_1\cdot X_4-X_2\cdot X_3\right]+\\ &\quad+c_5\cdot\dot{T}_L+b_5\cdot d_1\cdot X_4\cdot U_1-b_5\cdot d_1\cdot X_3\cdot U_2\end{aligned} \qquad (23)$$

$$\begin{aligned}\dot{S}_2(e_2)&=\lambda_2(\dot{\phi}_{rref}^2-\dot{\phi}_r^2)+(\ddot{\phi}_{rref}^2-\ddot{\phi}_r^2)\\ &=\lambda_2\cdot\dot{\phi}_{rref}^2+\ddot{\phi}_{rref}^2-(\lambda_2-2\cdot b_3)\cdot\dot{\phi}_r^2\\ &\quad-2\cdot a_3\left[X_1\cdot\dot{X}_3+X_2\cdot\dot{X}_4-a_1(X_1\cdot X_3+X_2\cdot X_4)+b_1\cdot I_s^2\right]\\ &\quad-2\cdot a_3\cdot d_1\cdot X_3\cdot U_1-2\cdot a_3\cdot d_1\cdot X_4\cdot U_2\end{aligned} \qquad (24)$$

with:

$$I_s^2=I_{s\alpha}^2+I_{s\beta}^2 \qquad (25)$$

The surfaces derivatives can be written in the following condensed form:

$$\dot{S}=\left[\dot{S}_1(e_1)\quad \dot{S}_2(e_2)\right]^T=G(X)+Q(X)\cdot U \qquad (26)$$

$$G(X)=\left[G_1(X)\quad G_2(X)\right]^T \qquad (27)$$

$$\begin{aligned}G_1(X)&=\lambda_1\cdot\dot{\omega}_{ref}+\ddot{\omega}_{ref}-(\lambda_1-a_5)\cdot\dot{X}_5+\\ &\quad+b_5\left[a_1(X_2\cdot X_3-X_1\cdot X_4)+c_1\cdot\phi_r^2\cdot X_5+X_1\cdot X_4-X_2\cdot X_3\right]\\ &\quad+c_5\cdot\dot{T}_L\end{aligned} \qquad (28)$$

$$\begin{aligned}G_2(X)&=\lambda_2\cdot\dot{\phi}_{rref}^2+\ddot{\phi}_{rref}^2-(\lambda_2-2\cdot b_3)\cdot\dot{\phi}_r^2-\\ &\quad-2\cdot a_3\left[X_1\cdot\dot{X}_3+X_2\cdot\dot{X}_4-a_1(X_1\cdot X_3+X_2\cdot X_4)+b_1\cdot I_s^2\right]\end{aligned} \qquad (29)$$

$$Q(X)=\begin{bmatrix}b_5\cdot d_1\cdot X_4 & -b_5\cdot d_1\cdot X_3\\ -2\cdot a_3\cdot d_1\cdot X_3 & -2\cdot a_3\cdot d_1\cdot X_4\end{bmatrix} \qquad (30)$$

The necessary condition for the states system follows the trajectory defined by the sliding surfaces is: $S_i(e_i)=0,(i=1,2)$, the equivalent part U^{eq} is the control to providing $\dot{S}_i(e_i)=0$.

For the nominal system $\dot{S}_i(e_i)=0$ give:

$$\begin{aligned}&\dot{S}=0\Rightarrow\left[\dot{S}_1(e_1)\quad \dot{S}_2(e_2)\right]^T=0\\ &\quad\Rightarrow G(X)+Q(X)\cdot U=0\\ &\quad\Rightarrow\quad U=-Q^{-1}(X)\cdot G(X)=U^{eq}=\left[V_{s\alpha}\quad V_{s\beta}\right]^T\end{aligned} \qquad (31)$$

4.2. Design of fuzzy logic controllers FLC for induction motor drive

The proposed fuzzy controller is presented in Fig. 1. The FLSMC is introduced to replace the sign function in SMC controller.

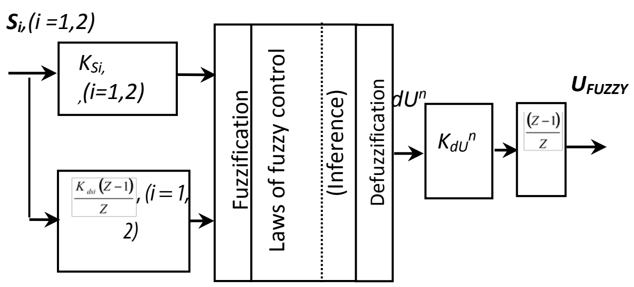
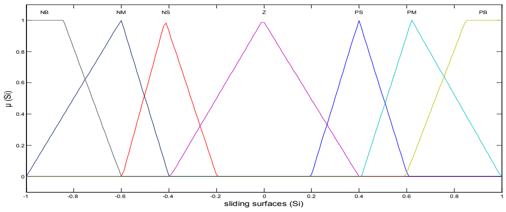


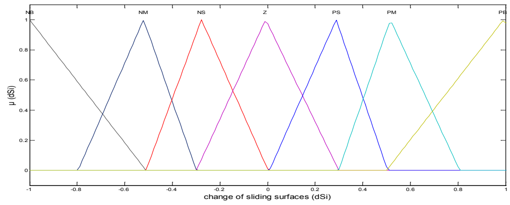
Figure 1. *Diagram of the fuzzy logic sliding mode controllers.*

FLSMC in this system uses Mamdani fuzzy inference system to relate two input variables to one output variable. The first input variable is the sliding surface $(S_i(e_i)=0,(i=1,2))$, while the other input is the change of sliding surface $(dS_i,(i=1,2))$. The output variable is the change of controllers $(dU_i,(i=1,2))$.

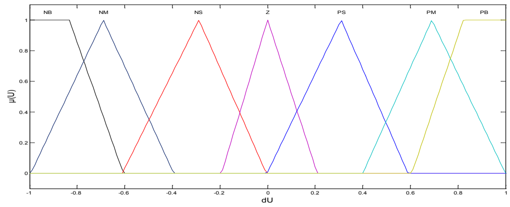
The membership functions for input and output variables are shown in Figure 2.



(a) Input variable (S_i)



(b) Input variable (dS_i)



(c) Output variable (dU_i)

Figure 2. Membership functions

(a) Membership function for input variable(S_i). (b) Membership function for input variable (dS_i). (c) Membership function for output variable dU_i).

All input and output variables were normalized to be fit the range of $(-1\ to\ 1)$. The output variable (**dU**$_i$) is used to calculate the needed change of controllers which will be used to control the speed and rotor flux of induction motor. All fuzzy rules used in the proposed system are summarized in Table 1.

Table 1. Inference table (rules).

dU_i		Change of surfaces (dS_i)						
	(i=1,2)	NB	NM	NS	Z	PS	PM	PB
Surfaces (S_i)	NB	NB	NB	NB	NM	NS	NS	Z
	NM	NB	NM	NM	NM	NS	Z	PS
	NS	NB	NM	NS	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PS	PM	PB
	PM	NS	Z	PS	PM	PM	PM	PB
	PB	Z	PS	PS	PM	PB	PB	PB

For the defuzzifier of the crisp value of output (**dU**$_i$), we use the center of area defuzzifier.

5. SIMULATION RESULTS AND DISCUSSION

The behavior of the overall system is tested by simulation for three phase induction machine represented at Figure 3.

A series of simulation tests were carried out on induction motor drive using both the sliding mode controller SMC and fuzzy logic sliding mode controller FLSMC based intelligent controller for various operating conditions.

Figure 4 shows speed response with both the SMC and FLSMC based controller. The FLSMC controller performed better performance with respect to rise time and steady state error. The speed response is well damped within a rise time of 0.025s.

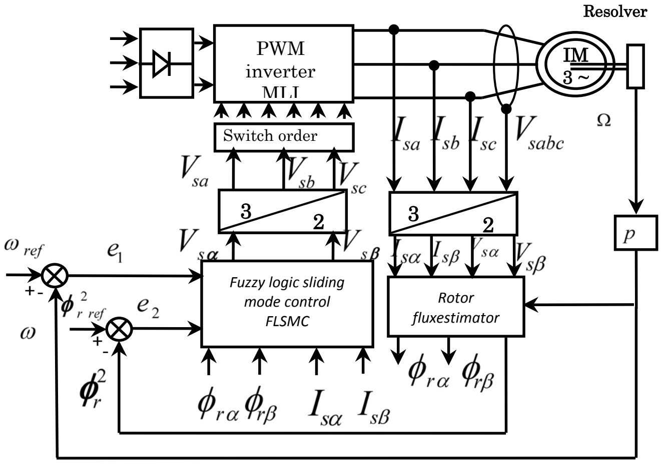


Figure 3. Principe scheme of the proposed FLSMC of IM.

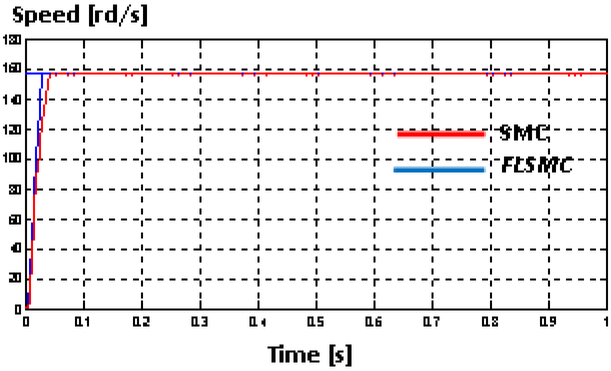


Figure 4. Speed response comparison at no load (T_L =0).

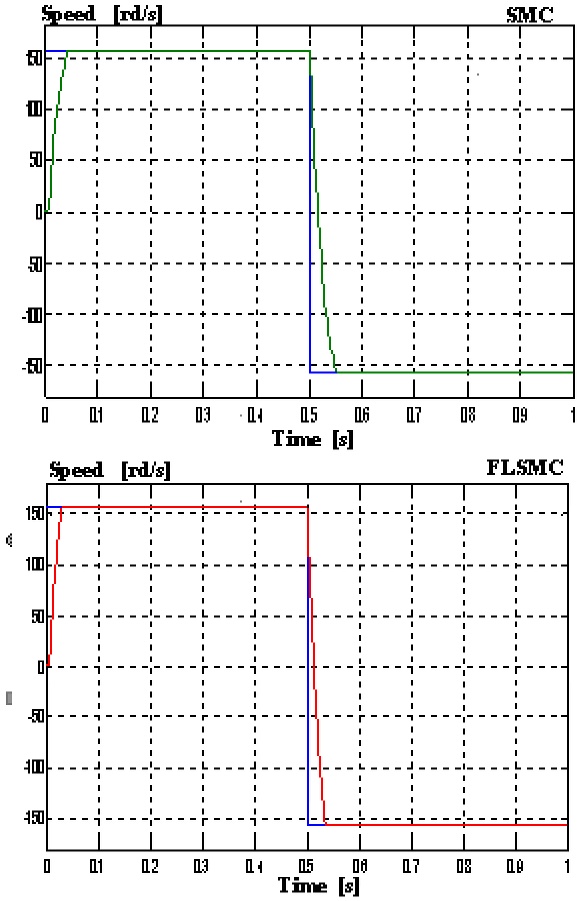


Figure 5.a. Comparison results between the SMC and FLSMC at no load (T_L = 0 N.m). a) speed

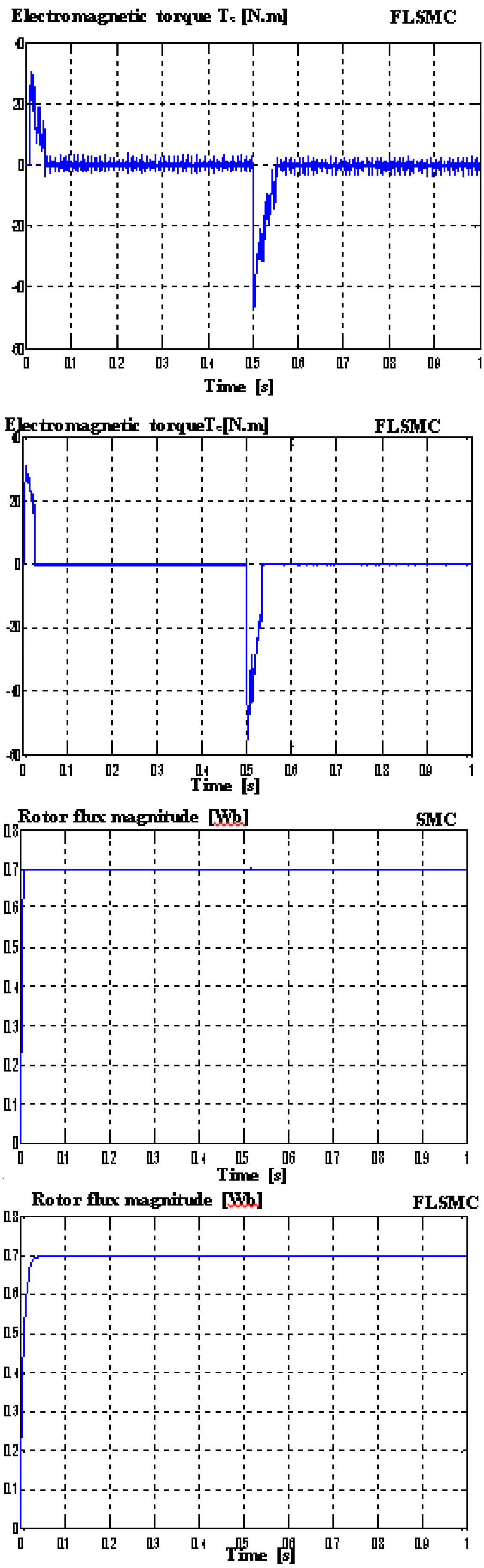


Figure 5.b-c. *Comparison results between the SMC and FLSMC at no load ($T_L = 0$ N.m). b) electromagnetic torque; c) rotor flux magnitude*

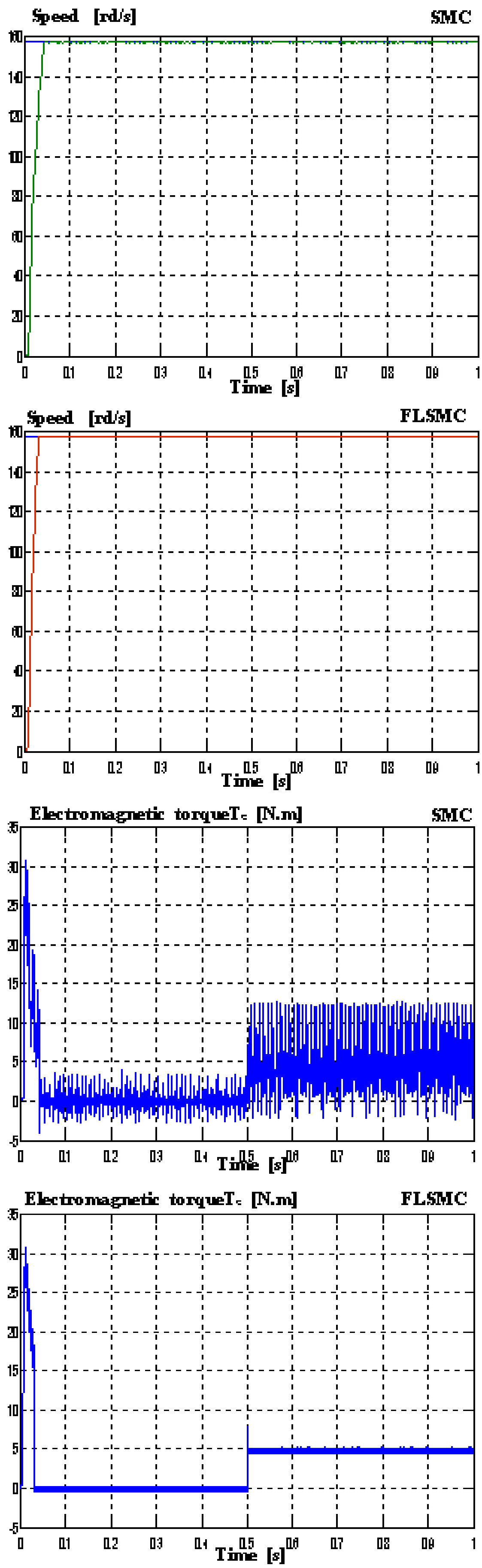


Figure 6.a-b. *Comparison results between the SMC and FLSMC when load ($T_L = 5$ N.m). a) speed; b) electromagnetic torque;*

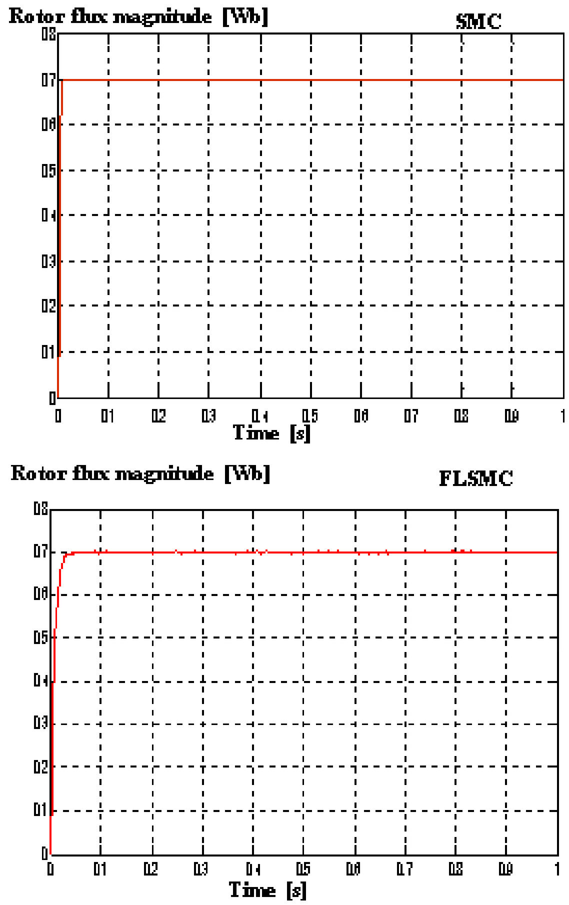


Figure 6.c. *Comparison results between the SMC and FLSMC when load ($T_L = 5$ N.m). c) rotor flux magnitude*

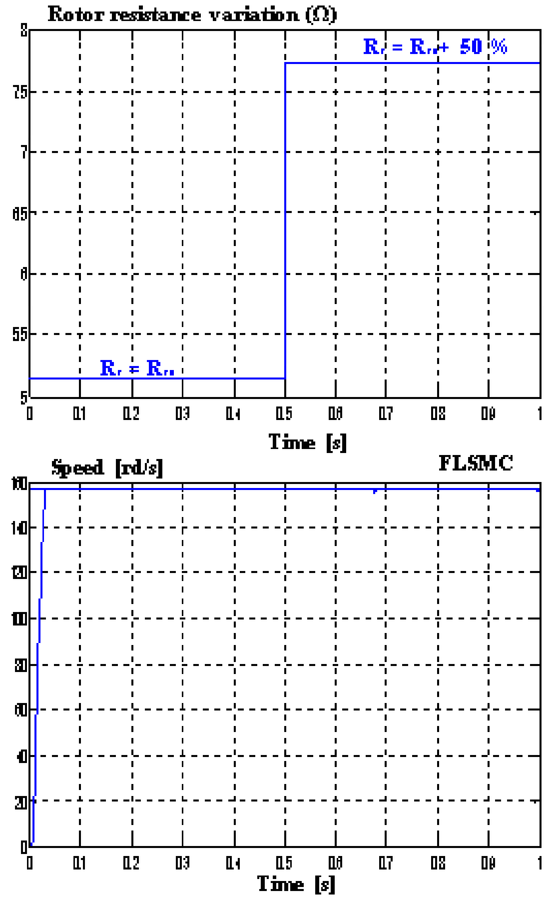


Figure 7. *Simulation results under rotor resistance variation*

In Figure 5, A comparison test using SMC and FLSMC controller have been performed starting-up towards 1500 rpm at no load ($T_L = 0$ N.m).

In this test, the simulation results show that the FLSMC gives good performances in minimization of the torque ripple with higher tracking precision.

The simulation test reported in Figure 6 shows the load disturbance rejection capabilities of each controller when using a step load from 0 to 5 N.m at 0.5 seconds.

A test of robustness has been also performed by tuning the rotor resistance parameter with the over-estimation.

Figure 7 shows the test of robustness realized with the sliding mode controller SMC and FSMC for different value of the rotor resistance.

Figure 8 shows the test of robustness realized with the sliding mode controller SMC and FSMC for different value of the moment of inertia.

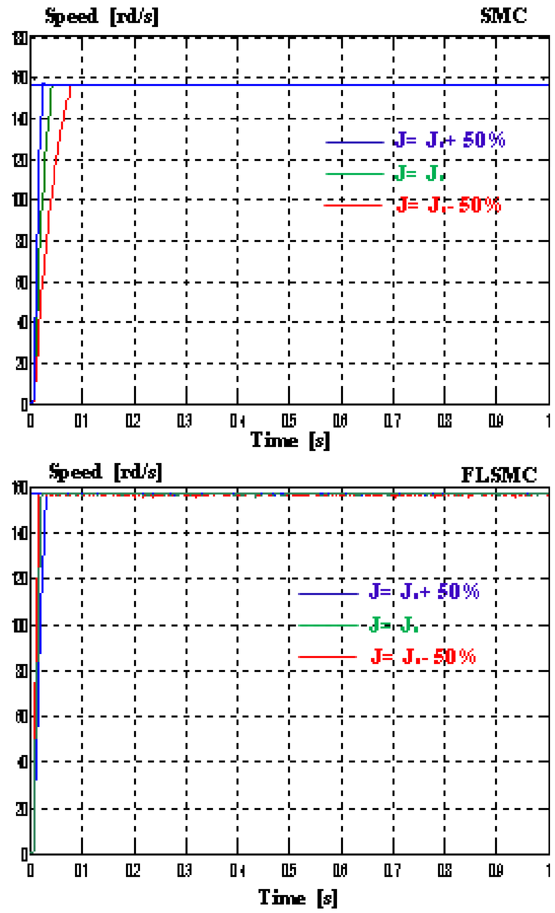


Figure 8. *Simulation results under variations of the moment of inertia.*

The variation of the moment of inertia has no significant influence on performances of the FLSMC proposed control.

6. CONCLUSION

A new hybrid technique control system to indirect vector controlled induction motor combining the features of SMC and fuzzy control has been presented in this paper. Fuzzy tuning schemes are employed to reduce chattering and accelerate the reaching phase. The FLSMC has the advantage in handling the torque ripple phenomenon and reducing the number of the fuzzy rules and the rules themselves were simplified. The drive system was simulated with fuzzy logic controller and SMC controller and their performance was compared. Here simulation results shows *that the designed FLSMC controller realizes a good dynamic behavior of the motor with a rapid settling time, no overshoot and has better performance than SMC controller. FLSMC control has more robust with regard to parameter variations and external disturbance.*

Appendix:

s ,r: Stator and rotor index.
ref : Reference value.
α, β: Rotor reference frame.
V: Voltage, [V].
I : Current, [A].
Ω: Mechanical speed, [rad/s].
ϕ: Flux, [Wb].
T_e: Electromechanical torque, [N.m].
ω: Rotor angular frequency, [rad/s].
f_r: Viscose friction coefficient, [N.m.s/rad].
J: Moment of inertia, [Kg.m^2].
p: Pole pair number.
σ: Total leakage coefficient.
R_s , R_r: Stator, rotor resistance, [Ω].
L_s, L_r, M_{sr}: Stator, rotor and mutual inductance, [H].
$\tau_s \tau_r$: Stator and Rotor time constant,[s].

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