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A comparative performance analysis based on artificial intelligence techniques applied to three-phase induction motor drives

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SUMMARY

In this work, we introduced a new robust hybrid control to an induction motor (IM), based on the theory of fuzzy logic and variable structure with sliding-mode control (SMC). As the variations of both control system parameters and operating conditions occur, the conventional control methods may not be satisfied further. Fuzzy tuning schemes are employed to improve control performance and to reduce chattering in the sliding mode. The combination of these two theories has given high performance and fast dynamic response with no overshoot. As it is very robust, it is insensitive to process parameters variation and external disturbances.

KEY WORDS: *induction motor (IM), sliding mode control (SMC), fuzzy logic control (FLC), fuzzy logic sliding mode control (FLSMC).*

1. INTRODUCTION

Nowadays, induction motors (IM) are used in a wide range of applications requiring variable speed. Generally, variable-speed drives for induction motors require both a wide operating range of speed and fast torque response, regardless of load variations. However, an induction motor has disadvantages, such as complex, nonlinear, and multivariable mathematical model, and an inherent incapability of providing variable speed operation.

Field-oriented control method is used for an 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, a 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 the variations of machine parametres. 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 variations and external load disturbances such as: nonlinear control, optimal control, variable structure system control, adaptive control and neural control [1-5].

Sliding mode control (SMC), based on the theory of variable structure systems (VSS), has been applied to robust control of nonlinear systems [6]. Sliding mode control performs well in trajectory tracking of some nonlinear systems. It employs a discontinuous control law to drive the state trajectory toward a 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 [7,8] places a boundary layer around the switching surface such that the relay control is replaced by a saturation function. Another method [7,9] assumes replacing 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 attractive features of fuzzy control with SMC [10-13]. Fuzzy logic, first proposed by Zadeh [14], 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 with some implementations. Fuzzy schemes with explicit expressions for tuning can avoid this problem [15].

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 condition that the parameter of stator resistance variants and the load 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 a 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:

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

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

$$
\begin{aligned}
\varphi_{s\alpha} &= L_s I_{s\alpha} + M_{sr} I_{r\alpha} \\
\varphi_{s\beta} &= L_s I_{s\beta} + M_{sr} I_{r\beta} \\
\varphi_{r\alpha} &= L_r I_{r\alpha} + M_{sr} I_{s\alpha} \\
\varphi_{r\beta} &= L_r I_{r\beta} + M_{sr} I_{s\beta}
\end{aligned} \tag{2}
$$

The electromechanical torque is given by:

$$
T_e = p\frac{M_{sr}}{L_r}\cdot\left[\bar{\varphi}_r \wedge \bar{I}_s\right] = p\frac{M_{sr}}{L_r}\cdot\left[\varphi_{r\alpha}\cdot i_{s\beta} - \varphi_{r\beta}\cdot i_{s\alpha}\right] \tag{3}
$$

The mechanical equation is given by:

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

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

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

With:

$$
\dot{X} = \begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \\ \dot{X}_5 \end{bmatrix} = \begin{bmatrix} \dot{I}_{s\alpha} \\ \dot{I}_{s\beta} \\ \dot{\varphi}_{r\alpha} \\ \dot{\varphi}_{r\beta} \\ \dot{\omega} \end{bmatrix},\quad F\ (X,t)\ = \begin{bmatrix} -a_1\cdot I_{s\alpha} + b_1\cdot\varphi_{r\alpha} + c_1\cdot\omega\cdot\varphi_{r\beta} \\ -a_1\cdot I_{s\beta} - b_1\cdot\omega\cdot\varphi_{r\alpha} + c_1\cdot\varphi_{r\beta} \\ a_3\cdot I_{s\alpha} - b_3\cdot\varphi_{r\alpha} - \omega\cdot\varphi_{r\beta} \\ a_3\cdot I_{s\beta} + \omega\cdot\varphi_{r\alpha} - b_3\cdot\varphi_{r\beta} \\ b_5\cdot\left[\varphi_{r\alpha}\cdot I_{s\beta} - \varphi_{r\beta}\cdot I_{s\alpha}\right] - c_5\cdot T_L - a_5\cdot\omega \end{bmatrix},
$$

$$
B(X,t) = \begin{bmatrix} d_1 & 0 \\ 0 & d_1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},\quad U\ (t) = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix},
$$

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

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

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 [16]:

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 ensures that the sliding mode is reached and subsequently maintained [16].

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

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

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

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} is the equivalent control.

U^n is 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 Eqs. (5) and (9) in Eq. (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 $\left(\dot{S}(X) = 0 \;\; and \;\; U^n = 0 \right)$. 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 to take a finite value, it must:

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

By replacing the equivalent control by expression in Eq. (14), a new expression for the derivative of the surface is yielded:

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

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

The basic form of the attractive control U^n is a relay. In this case the discontinuous control is given by [16]:

$$U^{n}=-k\cdot sign\ \left(S(X)\right) \tag{17}$$

Where k is a strictly positive constant.

4. DESIGN OF FUZZY LOGIC SLIDING MODE (FLSMC)

The conventional 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 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).

$$U_{FLSMC}=U^{eq}+U^{Fuzzy} \tag{18}$$

Where:

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

4.1 SYNTHESIS OF SLIDING MODE CONTROLLERS SMC

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

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

$$S_2(e_2)=\lambda_2\cdot e_2+\dot{e}_2\quad with\quad e_2=\varphi_{rref}^2-\varphi_r^2 \tag{20}$$

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: $\varphi_r^2=\varphi_{r\alpha}^2+\varphi_{r\beta}^2$

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

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

$$S_2(e_2)=\lambda_2\cdot\left(\varphi_{rref}^2-\varphi_r^2\right)+\left(\dot{\varphi}_{rref}^2-\dot{\varphi}_r^2\right) \quad (22)$$

The development of calculated derivatives of the surfaces gives:

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

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

With:

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

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

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

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

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

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

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

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:

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

4.2 DESIGN OF FUZZY LOGIC CONTROLLERS FLC FOR INDUCTION MOTOR DRIVE

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

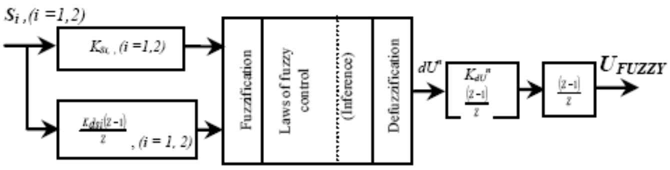
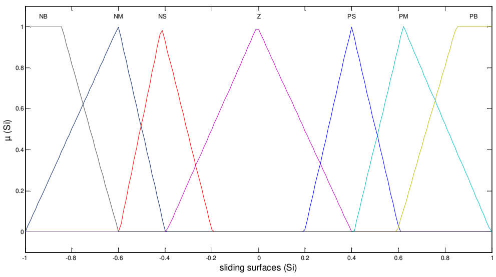


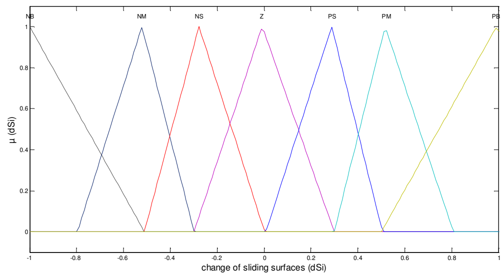
Fig. 1 *Diagram of the fuzzy logic sliding mode controllers*

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 a sliding surface dS_i, $(i=1,2)$. The output variable is the change of controllers dU_i, $(i=1,2)$.

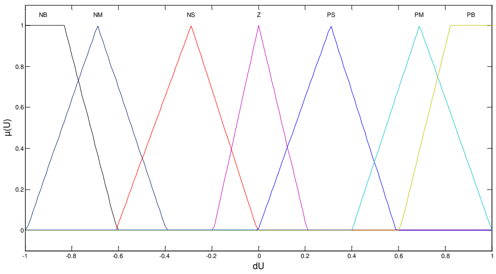
The membership functions for input and output variables are shown in Figure 2.



(a)



(b)



(c)

Fig. 2 *Input and output variables*
(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 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 an induction motor. All fuzzy rules used in the proposed system are summarized in Table 1:

Table 1 *Inference table (rules)*

dU_i (i=1, 2)		Change of surfaces (dS_i) 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 centrr of the defuzzifier area.

5. SIMULATION RESULTS AND DISCUSSION

The behaviour of the overall system is tested by simulation for the three-phase induction machine represented in Figure 3.

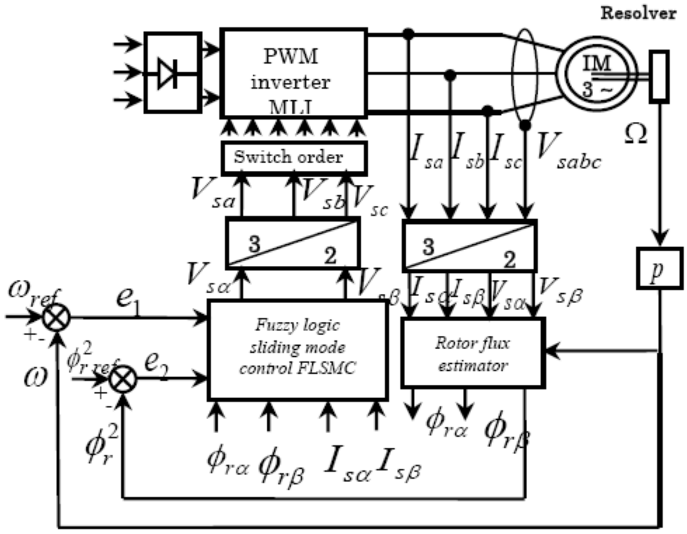


Fig. 3 *Principe scheme of the proposed FLSMC of IM*

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

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

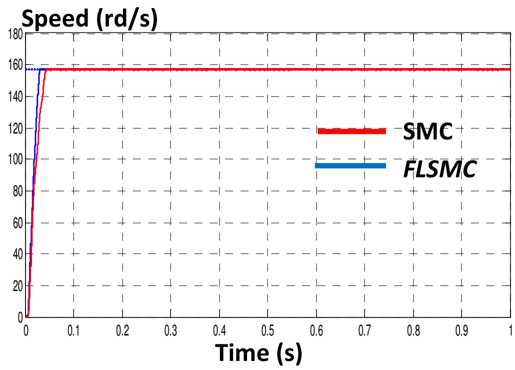


Fig. 4 *Speed response comparison at no load T_L=0*

In Figure 5, A comparison test using SMC and FLSMC controller have been performed starting-up towards 1500 rpm at no load *TL=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.

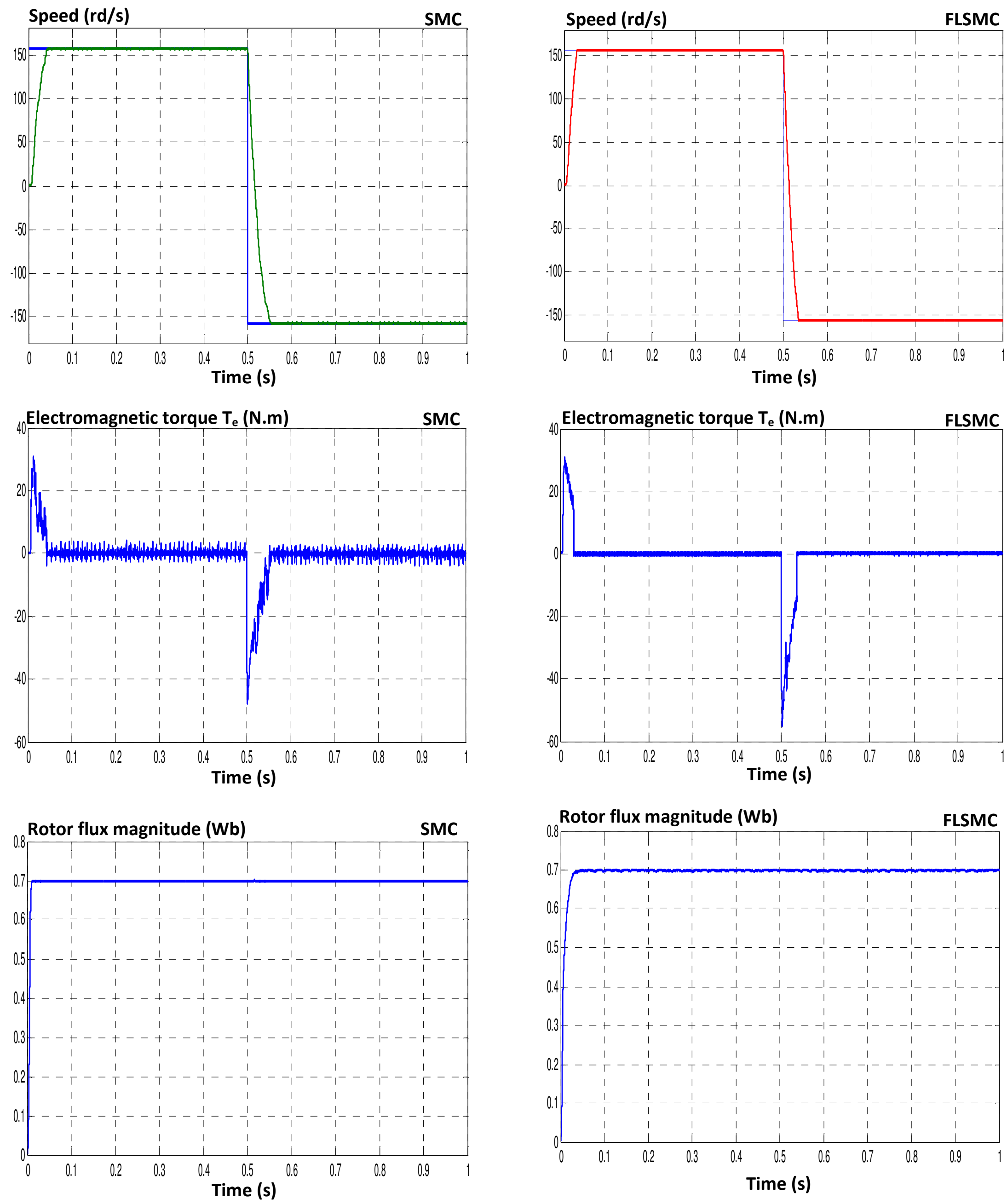


Fig. 5 *Comparison results between the SMC and FLSMC at no load $T_L = 0$ N.m*

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.

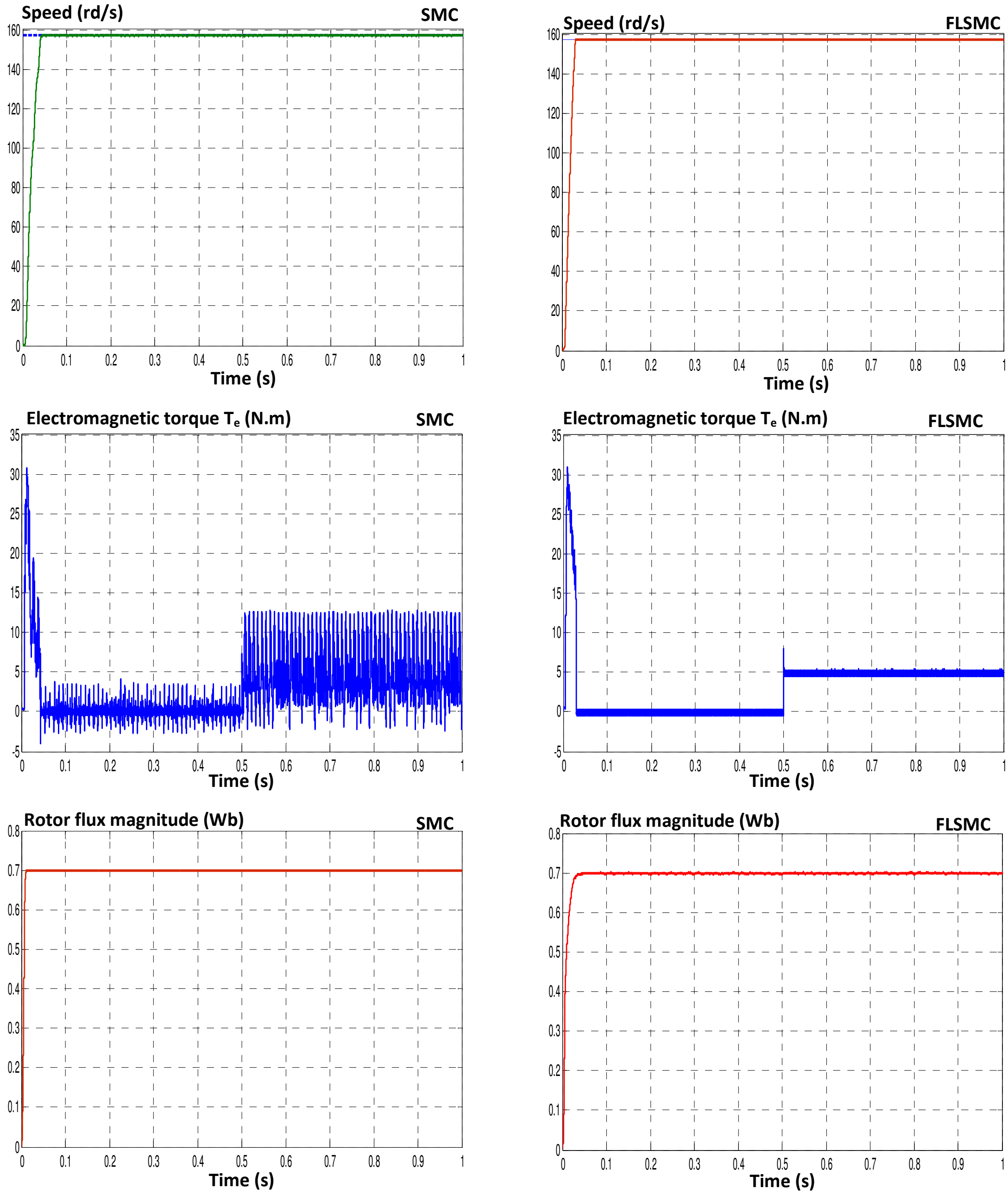


Fig. 6 *Comparison results between the SMC and FLSMC when load T_L = 5 N.m*

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

Figure 7 shows the test of robustness obtained with the sliding mode controller - SMC - and FSMC for different values of the rotor resistance.

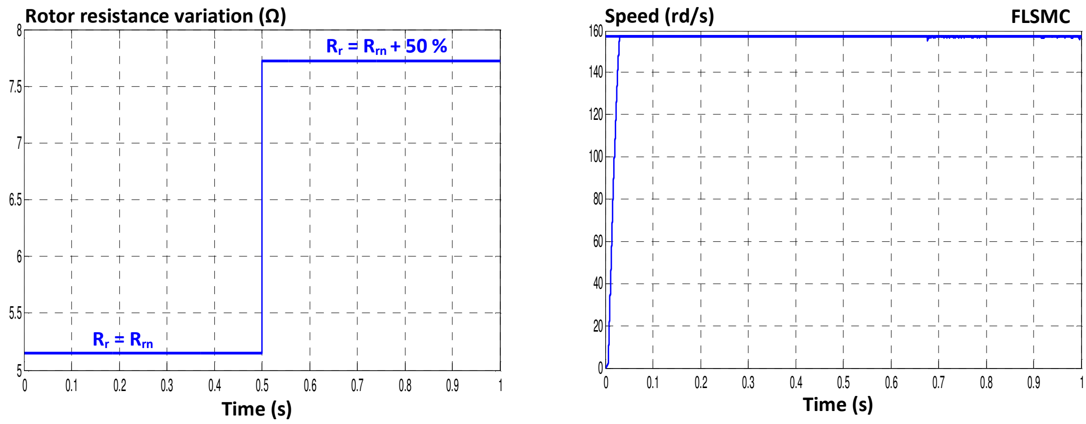


Fig. 7 *Simulation results under rotor resistance variation*

Figure 8 shows the test of robustness obtained with the sliding mode controller – SMC - and FSMC for different values of the moment of inertia.

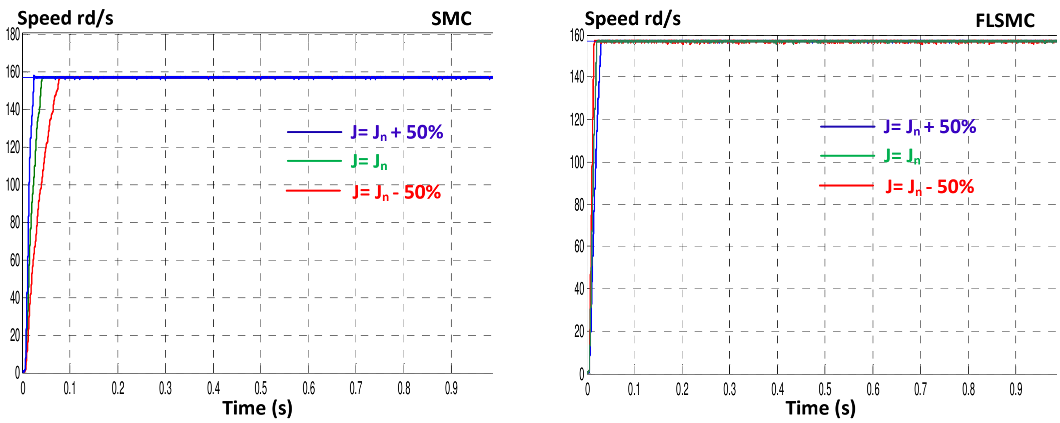


Fig. 8 *Simulation results under variations of the moment of inertia*

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

6. CONCLUSION

A new, hybrid, technique for system control of 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 an advantage in handling the torque ripple phenomenon and both in reduction and simplification of the fuzzy rules. The drive system was simulated with a fuzzy logic controller and an SMC controller, and their performance was compared. The simulation results show that the designed FLSMC controller attains good dynamic behaviour of the motor with a rapid settling time, no overshoot and has a better performance than the SMC controller. The FLSMC control has more robustness with regard to parameter variations and external disturbance.

7. 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].

τ_s, τ_r - Stator and Rotor time constant, [s].

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KOMPARATIVNA ANALIZA PERFORMANSI TEMELJENA NA METODAMA UMJETNE INTELIGENCIJE S PRIMJENOM NA MOTORE S FAZNOM INDUKCIJOM

U radu se uvodi novi tip robusne hibridne regulacije indukcijskog motora temeljene na teoriji neizrazite logike i varijabilne strukture uz kontrolu klizajućeg moda. Uz pojavu istovremene varijacije parametara kontrole sustava i radnih uvjeta, konvencionalne metode regulacije više nisu efikasne. Sheme 'neizrazitog ugađanja' se koriste za poboljšanje performansi i za redukciju trešnji u klizajućem modu. Kombinacijom ovih dvaju teorija ostvaruju se jako dobre performanse i brz dinamički odgovor bez ikakvog prebacivanja. Zbog svoje robusnosti, predloženi tip hibridne kontrole nije osjetljiv na promjenu parametara procesa i vanjske poremećaje.

KLJUČNE RIJEČI: *indukcijski motor, kontrola klizajućeg moda, teorija neizrazite logike, kontrola klizajućeg moda temeljena na teoriji neizrazite logike.*