Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

# FUZZY SLIDING MODE CONTROLLER FOR DOUBLY FED INDUCTION MOTOR SPEED CONTROL

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Received: 17 July 2010 / Accepted: 06 December 2010 / Published online: 31 December 2010

## ABSTRACT

This paper, presents a Direct Field-Oriented Control (DFOC) of doubly fed induction motor (DFIM) with a fuzzy sliding mode controller (FSMC). Our aim is to make the speed control robust to parameter variations. The variation of motor parameters during operation degrades the performance of the controllers. The use of the nonlinear fuzzy sliding mode method provides very good performance for motor operation and robustness of the control law despite the external/internal perturbations. The chattering effects is eliminated by a particular function "sat" that presents a serious problem to applications of variable structure systems. The fuzzy sliding mode controller is designed in order to improve the control performances and to reduce the chattering phenomenon. In this technique the saturation function is replaced by a fuzzy inference system to smooth the control action. The proposed scheme gives fast dynamic response with no overshoot and zero static error. To show the validity and the effectiveness of the control method, simulation results are performed for the speed control of a doubly fed induction motor. Simulation results showed that improvement made by our approach compared to conventional sliding mode control (SMC) with the presence of variations of the parameters of the motor, in particular the face of variation of moment of inertia and disturbances of load torque. The results show that the FSMC and SMC are robust against internal and external perturbations, but the FSMC is superior to SMC in eliminating chattering phenomena and response time.

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**Key words:** Direct Field-Oriented Control, sliding mode control, fuzzy sliding mode controller, doubly fed induction motor, fuzzy logic control.

## 1. INTRODUCTION

Known since 1899 [1], [2], the doubly fed induction machine (DFIM) is an asynchronous machine with wound rotor which can be supplied even time by the stator and the rotor external source voltages. This solution is very attractive for the variable speed applications such as the electric vehicle and the electrical energy production [1], [2]. Consequently, it covers all powers ranges. Obviously, the variable speed and the performances ranges depend of the application nature. With DFIM, it can possible to modulate power flow into and out the rotor winding in order to have, at the same time, a variable speed in the characterized super-synchronous or sub-synchronous modes in motor or in generator regimes. Two modes can be associated to slip power recovery: sub–synchronous motoring and super–synchronous generating operations. In general, while the rotor is fed through a cycloconverter, the power range can attain the MW order which presents the size power often reserved to the synchronous machines [1], [2].

The DFIM has some distinct advantages compared to the conventional squirrel-cage machine. The DFIM can be fed and controlled stator or rotor by various possible combinations. Indeed, the input–commands are done by means of four precise degrees of control freedom relatively to the squirrel cage induction machine where its control appears quite simpler. The flux orientation strategy can transform the non linear and coupled DFIM-mathematical model to a linear model conducting to one attractive solution as well as under generating or motoring operations [1], [2].

Several methods of control are used to control the induction motor among which the vector control or field orientation control that allows a decoupling between the torque and the flux, in order to obtain an independent control of torque and the flux like DC motors [3].

The overall performance of field oriented controlled induction motor drive systems is directly related to the performance of current control. Therefore, decoupling the control scheme is required by compensation of the coupling effect between q-axis and d-axis current dynamics [3].

With the field orientation control (FOC) method, induction machine drives are becoming a major candidate in high-performance motion control applications, where servo quality operation is required. Fast transient response is made possible by decoupled torque and flux control [4].

Sliding mode theory, stemmed from the variable structure control family, has been used for the induction motor drive for a long time. It has for long been known for its capabilities in accounting for modeling imprecision and bounded disturbances. It achieves robust control by adding a discontinuous control signal across the sliding surface, satisfying the sliding condition. Nevertheless, this type of control has an essential drawback, which is the chattering phenomenon caused from the discontinuous control action. To alleviate the chattering phenomenon, the idea of boundary layer is used to improve it. It is called a modified controller. In this method, the control action was smoothed such that the chattering phenomenon can be decreased [5].

Fuzzy logic control is a technique of incorporating expert knowledge in designing a controller. Past research of universal approximation theorem shown that any nonlinear function over a compact set with arbitrary accuracy can be approximated by a fuzzy system [5]. Fuzzy logic has proven to be a potent tool in the sliding mode control of time-invariant linear systems as well as time-varying nonlinear systems. It provides methods for formulating linguist rules from expert knowledge and is able to approximate any real continuous system to arbitrary accuracy. Thus, it offers a simple solution dealing with the wide range of the system parameters. All kinds of control schemes, including the classical sliding mode control, have been proposed in the field of AC machine control during the past decades [5].

Among these different proposed designs, the sliding mode control strategy has shown robustness against motor parameter uncertainties and unmodelled dynamics, insensitivity to external load disturbance, stability and a fast dynamic response [6], [7], [8]. Hence it is found to be very effective in controlling electric drives systems. Large torque chattering at steady state may be considered as the main drawback for such a control scheme [6]. One way to improve sliding mode controller performance is to combine it with Fuzzy Logic (FL) to form a Fuzzy Sliding Mode (FSM) controller [9].

In the DFOC of DFIM, the knowledge of rotor speed and flux is necessary. In this work the flux is obtained by the measurement of stator and rotor (rotor winding) currents. The speed is measured.

In this paper, we begin with the DFIM oriented model in view of the vector-control, next the stator flux $\varphi_s$ is estimated. We, then, present the sliding mode theory and design the sliding mode and fuzzy sliding mode controllers of motor speed. Finally, conclusions are summarized in the last section.

**1.1. The DFIM model**

Its dynamic model expressed in the synchronous reference frame is given by Voltage equations [1], [2]:

$$\begin{aligned} \bar{u}_s &= R_s \bar{i}_s + \frac{d\bar{\varphi}_s}{dt} + j\omega_s \bar{\varphi}_s \\ \bar{u}_r &= R_r \bar{i}_r + \frac{d\bar{\varphi}_r}{dt} + j\omega_r \bar{\varphi}_r \end{aligned} \qquad (1)$$

Flux equations:

$$\begin{aligned} \bar{\varphi}_s &= L_s \bar{i}_s + M \bar{i}_r \\ \bar{\varphi}_r &= L_r \bar{i}_r + M \bar{i}_s \end{aligned} \qquad (2)$$

From (1) and (2), the state-all-flux model is written like:

$$\begin{aligned} \bar{u}_s &= \frac{1}{\sigma T_s}\bar{\varphi}_s - \frac{M}{\sigma T_s L_r}\bar{\varphi}_r + \frac{d\bar{\varphi}_s}{dt} + j\omega_s \bar{\varphi}_s \\ \bar{u}_r &= -\frac{M}{\sigma T_r L_s}\bar{\varphi}_s + \frac{1}{\sigma T_r}\bar{\varphi}_r + \frac{d\bar{\varphi}_r}{dt} + j\omega_r \bar{\varphi}_r \end{aligned} \qquad (3)$$

The electromagnetic torque is done as:

$$C_e = \frac{PM}{\sigma L_s L_r}\Im m\left[\bar{\varphi}_s \bar{\varphi}_r\right] \qquad (4)$$

and its associated motion equation is:

$$C_e - C_r = J\frac{d\Omega}{dt} \qquad (5)$$

**1.2. Direct Field-Oriented Control of DFIM**

In this section, the DFIM model can be described by the following state equations in the synchronous reference frame whose axis *d* is aligned with the stator flux vector, ($\varphi_{sd} = \varphi_s$ and $\varphi_{sq} = 0$ ), [10], [11]:

$$i_{rd} = \frac{\varphi_s^*}{M} \tag{6}$$

$$i_{rq} = -\frac{L_s}{P.M\,\varphi_s^*} Ce^* \tag{7}$$

$$\frac{d\theta_s}{dt} = \omega_s = \left( \frac{R_s.M}{L_s} i_{rq} + V_{sq} \right) / \varphi_s^* \tag{8}$$

$$\dot{i}_{rd} = -\frac{1}{\sigma}\left( \frac{1}{T_r} + \frac{M^2}{L_S.T_s.L_r} \right) i_{rd} - \frac{M}{\sigma.L_r.L_s} V_{sd} + \frac{M}{\sigma.L_r.L_S.T_s}\varphi_{sd} + (\omega_s - \omega) i_{rq} + \frac{1}{\sigma L_r} V_{rd} \tag{9}$$

$$\dot{i}_{rq} = -\frac{1}{\sigma}\left( \frac{1}{T_r} + \frac{M^2}{L_S.T_s.L_r} \right) i_{rq} - \frac{M}{\sigma.L_r.L_s} V_{sq} + \frac{M}{\sigma.L_r.L_S}\omega\varphi_{sd} - (\omega_s - \omega) i_{rd} + \frac{1}{\sigma L_r} V_{rq} \tag{10}$$

$$\dot{\varphi}_{sd} = V_{sd} + \frac{M}{T_s} i_{rd} - \frac{1}{T_s}\varphi_{sd} \tag{11}$$

$$\dot{\varphi}_{sq} = V_{sq} + \frac{M}{T_s} i_{rq} - \omega_s \varphi_{sd} \tag{12}$$

$$\dot{\Omega} = -\frac{P.M}{J.Ls}(i_{rq}.\varphi_{sd}) - \frac{C_r}{J} - \frac{f}{J}\Omega \tag{13}$$

With:

$$T_r = \frac{L_r}{R_r} \;;\; T_s = \frac{L_s}{R_s} \;;\; \sigma = 1 - \frac{M^2}{L_s.L_r}$$

Where:

$i_{rd}$ , $i_{rq}$ are rotor current components, $\varphi_{sd}$ , $\varphi_{sq}$ are stator flux components, $V_{sd}$ , $V_{sq}$ are stator voltage components, $V_{rd}$ , $V_{rq}$ rotor voltage components. $R_s$ and $R_r$ are stator and rotor resistances, $L_s$ and $L_s$ are stator and rotor inductances, $M$ is mutual inductance, $\sigma$ is leakage factor and $P$ is number of pole pairs. $C_e$ is the electromagnetic torque, $C_r$ is the load torque, $J$ is the moment of inertia of the DIFIM, $\Omega$ is mechanical speed, $\omega_s$ is the stator pulsation, $\omega$ is the rotor pulsation, $f$ is the friction coefficient, $T_s$ and $T_r$ are statoric and rotoric time-constant.

### 1.3. Stator flux estimator

For the direct stator flux orientation control (DSFOC) of DFIM, accurate knowledge of the magnitude and position of the stator flux vector is necessary. In a DFIM motor mode, as stator and rotor current are measurable, the stator flux can be estimated (calculate). The flux estimator can be obtained by the following equations:

$$¤_{sd} = L_s i_{sd} + M i_{rd} \tag{14}$$

$$¤_{sq} = L_s i_{sq} + M i_{rq} \tag{15}$$

The position stator flux is calculated by the following equations:

$$\overline{\ }_r = \overline{\ }_s - \overline{\ } \tag{16}$$

In which:

$$\overline{\ }_s = \int µ_s dt \ , \ \overline{\ } = \int µ \, dt \ , \ \ µ = P\Omega \, .$$

### 1.4. Sliding Mode Control

A Sliding Mode Controller (SMC) is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control surface, whereas switching among different functions is determined by plant state represented by a switching function [12].

The design of the control system will be demonstrated for a following nonlinear system [13]:

$$\dot{x} = f(x,t) + B(x,t).u(x,t) \tag{17}$$

Where $x \in {}^n$ is the state vector, $u \in {}^m$ is the control vector, $f(x,t) \in {}^n$, $B(x,t) \in {}^{n\times m}$.

From the system (17), it possible to define a set $S$ of the state trajectories x such as:

$$S = \{x(t) \mid ±(x,t) = 0\} \tag{18}$$

Where:

$$±(x,t) = [±_1(x,t), ±_2(x,t), ..., ±_m(x,t)]^T \tag{19}$$

and $[.]^T$ denotes the transposed vector, $S$ is called the sliding surface.

To bring the state variable to the sliding surfaces, the following two conditions have to be satisfied:

$$±(x,t) = 0 \ , \quad \dot{±}(x,t) = 0 \tag{20}$$

The control law satisfies the precedent conditions is presented in the following form:

$$\begin{aligned} u &= u^{eq} + u^n \\ u^n &= -k_f \, sgn(±(x,t)) \end{aligned} \tag{21}$$

Where $u$ is the control vector, $u^{eq}$ is the equivalent control vector, $u^{n}$ is the switching part of the control (the correction factor), $k_f$ is the controller gain. $u^{eq}$ can be obtained by considering the condition for the sliding regimen, $\pm(x,t)=0$. The equivalent control keeps the state variable on sliding surface, once they reach it.

For a defined function ¨ [14], [15]:

$$sgn(¨)=\begin{cases} 1, & if\ ¨>0 \\ 0, & if\ ¨=0 \\ -1, & if\ ¨>0 \end{cases} \tag{22}$$

The controller described by the equation (21) presents high robustness, insensitive to parameter fluctuations and disturbances, but it will have high-frequency switching (chattering phenomena) near the sliding surface due to $sgn$ function involved. These drastic changes of input can be avoided by introducing a boundary layer with width £ [16]. Thus replacing $sgn(\pm(t))$ by $sat(\pm(t)/£)$ (saturation function), in (21), we have

$$u = u^{eq} - k_f\ sat(\pm(x,t)) \tag{23}$$

Where $£ > 0$

$$sat(¨)=\begin{cases} sgn(¨), & if\ |¨|\geq 1 \\ ¨, & if\ |¨|<1 \end{cases} \tag{24}$$

Consider a Lyapunov function [14]:

$$V = \frac{1}{2}\pm^{2} \tag{25}$$

From Lyapunov theorem we know that if $\dot{V}$ is negative definite, the system trajectory will be driven and attracted toward the sliding surface and remain sliding on it until the origin is reached asymptotically [16]:

$$\dot{V} = \frac{1}{2}\frac{d}{dt}\pm^{2} = \pm\,\dot{\pm} \leq -¦\,|\pm| \tag{26}$$

Where ¦ is a strictly positive constant.

In this paper, we use the sliding surface proposed par J.J. Slotine,

$$\pm(x,t)=\left(\frac{d}{dt}+a\right)^{n-1} e \tag{27}$$

Where

$x = [x, \dot{x}, ..., x^{n-1}]^T$ is the state vector, $x^d = [x^d, \dot{x}^d, ..., x^d]^T$ is the desired state vector, $e = x^d - x = \left[e, \dot{e}, ..., e^{n-1}\right]$ is the error vector, and ª is a positive coefficient, and $n$ is the system order.

Commonly, in DFIM control using sliding mode theory, the surfaces are chosen as functions of the error between the reference input signal and the measured signals [13].

### 1.5. Speed Control with SMC

The speed error is defined by:

$$e = \Omega_{ref} - \Omega \tag{28}$$

For $n = 1$, the speed control manifold equation can be obtained from equation (27) as follow:

$$\pm(\Omega) = e = \Omega_{ref} - \Omega \tag{29}$$

$$\dot{\pm}(\Omega) = \dot{\Omega}_{ref} - \dot{\Omega} \tag{30}$$

Substituting the expression of $\dot{\Omega}$ equation (13) in equation (30), we obtain:

$$\dot{\pm}(\Omega) = \dot{\Omega}_{ref} - \left( -\frac{P.M}{J.Ls}(i_{rq}.¤_{sd}) - \frac{C_r}{J} - \frac{f}{J}\Omega \right) \tag{31}$$

We take:

$$i_{rq} = i_{rq}^{eq} + i_{rq}^{n} \tag{32}$$

During the sliding mode and in permanent regime, we have:

$$\pm(\Omega) = 0,\ \dot{\pm}(\Omega) = 0,\ i_{rq}^{n} = 0$$

Where the equivalent control is:

$$i_{rq}^{eq} = -\frac{J.L_s}{P.M.¤_{sd}}\left( \dot{\Omega}_{ref} + \frac{C_r}{J} + \frac{f}{J}\Omega \right) \tag{33}$$

Therefore, the correction factor is given by:

$$i_{rq}^{n} = k_{i_{rq}} sat(\pm(\Omega)) \tag{34}$$

$k_{i_{rq}}$ : negative constant.

### 1.6. Speed Control with fuzzy Sliding Mode Control

The disadvantage of sliding mode controllers is that the discontinuous control signal produces chattering dynamics; chatter is aggravated by small time delays in the system. In order to eliminate the chattering phenomenon, different schemes have been proposed in the literature [9]. Another approach to reduce the chattering phenomenon is to combine (Fuzzy Logic) FL with a Sliding Mode control (SMC) [15]. Hence, a new Fuzzy Sliding Mode (FSM) controller is formed with the robustness of SMC and the smoothness of FL. The fuzzy sliding mode control combines the advantages of the two techniques [17] (SMC and FL). The control by fuzzy logic is introduced here in order to improve the dynamic performances of the system and makes it possible to reduce the residual vibrations in high frequencies [17] (chattering phenomenon). The switching functions of sliding mode and FSM schemes are shown in figure 1. In this technique, the saturation function is replaced by a fuzzy inference system to smooth the control action. The block diagram of the hybrid fuzzy sliding mode controller is shown in figure 2.

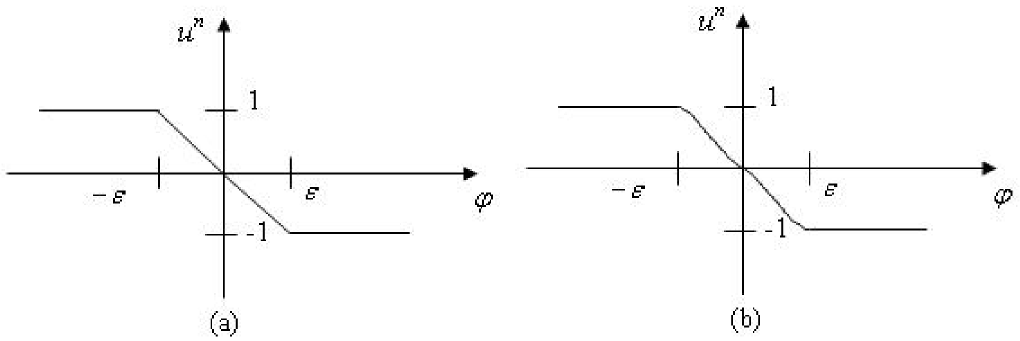



**Fig.1.** Switching functions (a) Sliding mode (b) Fuzzy sliding mode

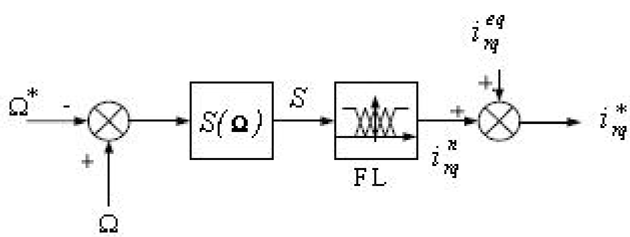



**Fig.2.** Fuzzy sliding mode speed controller

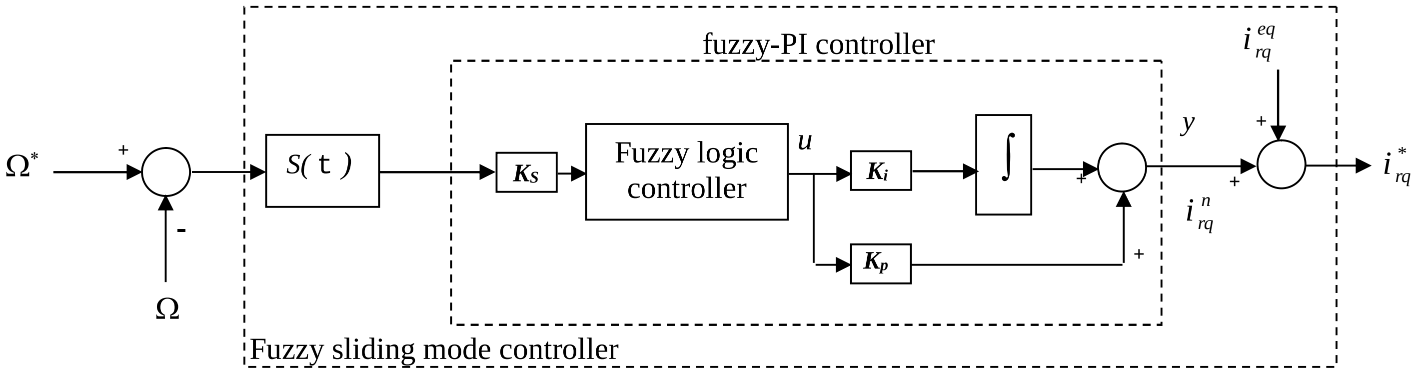



**Fig.3.** Block diagram of speed fuzzy sliding mode controller

### 1.7. Synthesis of the regulator fuzzy-PI:

With this intention, we take again the internal diagram of the fuzzy regulator, figure3.

We have :

$$u = K_S . S \tag{35}$$

or:

$$S = k_{i_{rq}} .sat(S(\Omega)) \tag{36}$$

Substituting the equation (35) in equation (36), we obtain:

$$u = K_S . k_{i_{rq}} .sat(S(\Omega)) \tag{37}$$

The fuzzy-PI output is:

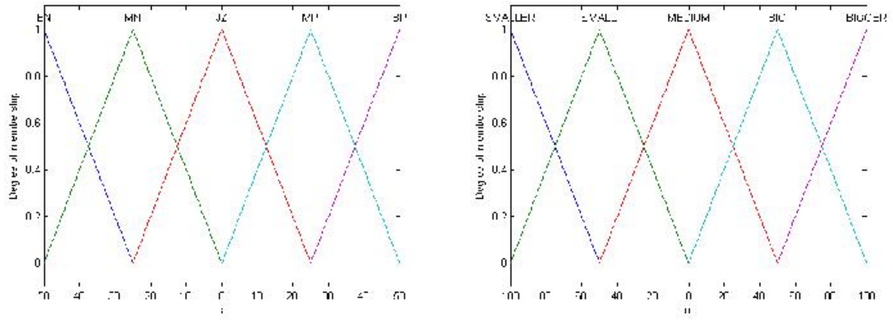
$$y = k_p . u + \int k_i . u \tag{38}$$

Substituting the equation (37) in equation (38), we obtain:

$$y = K_p . \left( K_S . k_{i_{rq}} .sat(S(\Omega)) \right) + \int K_i . \left( K_S . k_{i_{rq}} .sat(S(\Omega)) \right) \tag{39}$$

Where: $K_S$ is the gain of the speed surface, $K_p$ is the proportional factor; $K_i$ is the integral factor, $k_{i_{rq}}$ : negative constant, $u$ is the fuzzy output, $S(\Omega))$ is the speed surface.

The membership functions for the input and output of the FL controller are obtained by trial error to ensure optimal performance and are shown in figure 4.



(a) (b)

**Fig.4.** Fuzzy logic membership functions (a) input (b) output

The If-Then rules of the fuzzy logic controller can be written as [9]:

If $s$ is BN then $u^n$ is BIGGER

If $s$ is MN then $u^n$ is BIG

If $s$ is JZ then $u^n$ is MEDIUM

If $s$ is MP then $u^n$ is SMALL

If $s$ is BP then $u^n$ is SMALLER

In this paper, the triangular membership function, the max-min reasoning method, and the center of gravity defuzzification method are used, as those methods are most frequently used in many literatures [18].

### 1.8. Law of control

The structure of a fuzzy sliding mode controller as a sliding mode controller comprises two parts: the first relates to the equivalent control $(u^{eq})$ and the second is the correction factor $(u^n)$, but into the case of a fuzzy sliding mode controller we introduce the fuzzy logic control into this last part $(u^n)$.

We have the equation (33) :

$$i_{rq}^{eq} = -\frac{J.L_s}{P.M.\Phi_{sd}}\left(\dot{\Omega}_{ref} + \frac{C_r}{J} + \frac{f}{J}\Omega\right) \tag{40}$$

and we have of figure 3:

$$i_{rq}^{n} = y \tag{41}$$

Substituting the equation (39) in equation (41), we obtain:

$$i_{rq}^{n} = K_p.\left(K_S.k_{i_{rq}}.sat(S(\Omega))\right) + \int K_i.\left(K_S.k_{i_{rq}}.sat(S(\Omega))\right) \tag{42}$$

## 2. RESULTS AND DISCUSSION

The FSMC controller in a vector-control of DFIM is used as presented in figure 5. The DFIM used in this work is a 0.8 kW, whose nominal parameters are reported in appendix.

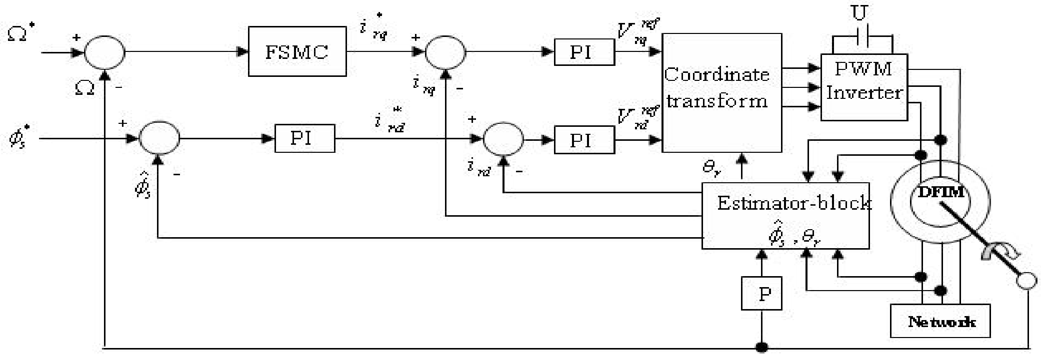



**Fig.5.** Block diagram of vector-control of DFIM using FSMC controller

The motor is operated at 157 rad/s under no load and a load disturbance torque (5 N.m) is suddenly applied at t=0.5s and eliminated at t=0.8s, followed by a consign inversion (-157 rad/s) at t=1s, also a load disturbance torque (-5 N.m) is suddenly applied at t=1.5s and eliminated at t=1.8s.

In these tests, the SMC (figure 6) rejects the load disturbance instantaneous with no overshoot and without static error.

The same tests applied for SMC are applied with the FSMC. Figure 7 shows the performances of the fuzzy sliding mode controller (FSMC).

The control presents the best performances, to achieve tracking of the desired trajectory. The fuzzy sliding mode controller also rejects the load disturbance instantaneous with no overshoot and without static error.

The simulation results show that the proposed controller is superior to SMC in eliminating chattering phenomena that appears torque oscillation (figure 6 and figure 7). The FSMC rejects the load disturbance instantaneous with no overshoot, with a minimum response time more than the SMC, which is shown clearly in figure 8.

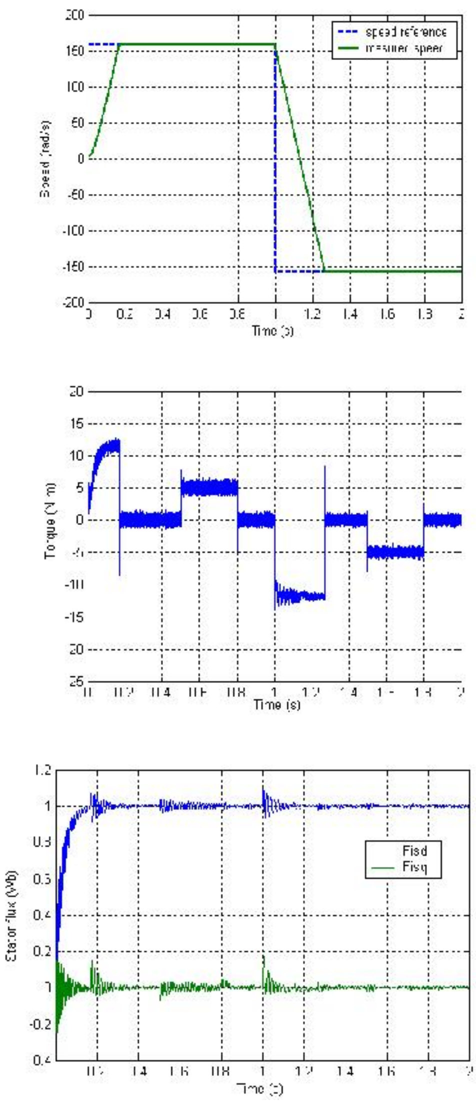



**Fig.6.** Results of speed control using SMC controller

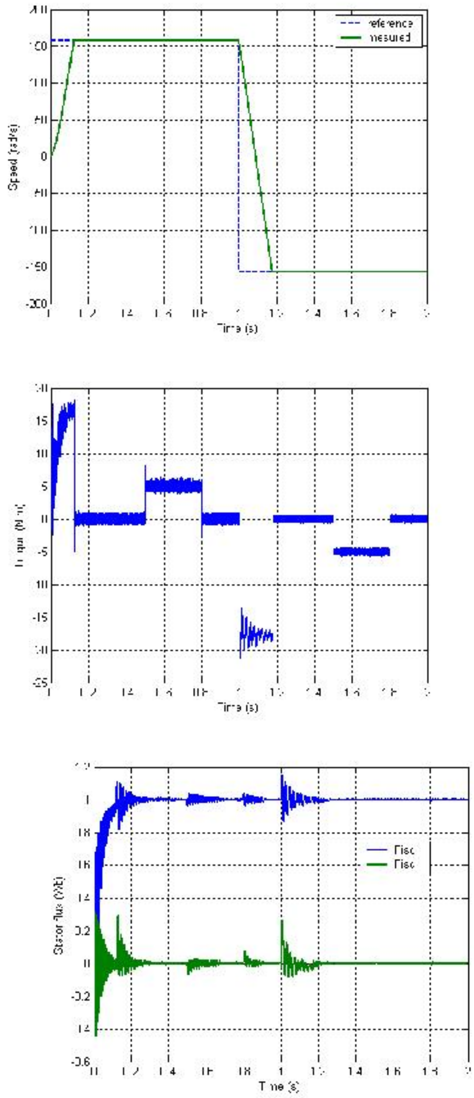


**Fig.7.** Results of speed control using FSMC controller

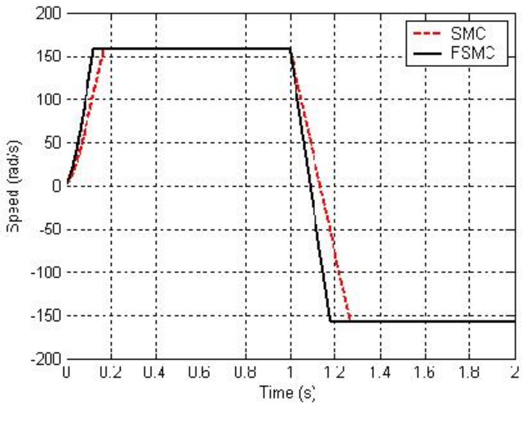



**Fig.8.** Simulated results of the comparison between the SMC and FSMC of DFIM

### 2.1. Robust control for different values of the moment of inertia

In order to test the robustness of the used method (FSMC) we have studied the effect of the parameters uncertainties on the performances of the speed control.

To show the effect of the parameters uncertainties, we have simulated the system with different values of the parameter considered and compared to nominal value (real value).

We consider:

-The moment of inertia (+50%).

For the robustness of control, an increase of the moment of inertia J gives best performances, but it presents a slow dynamic response (figure 9). The proposed control gives to our controller a great place towards the control of the system with unknown parameters.

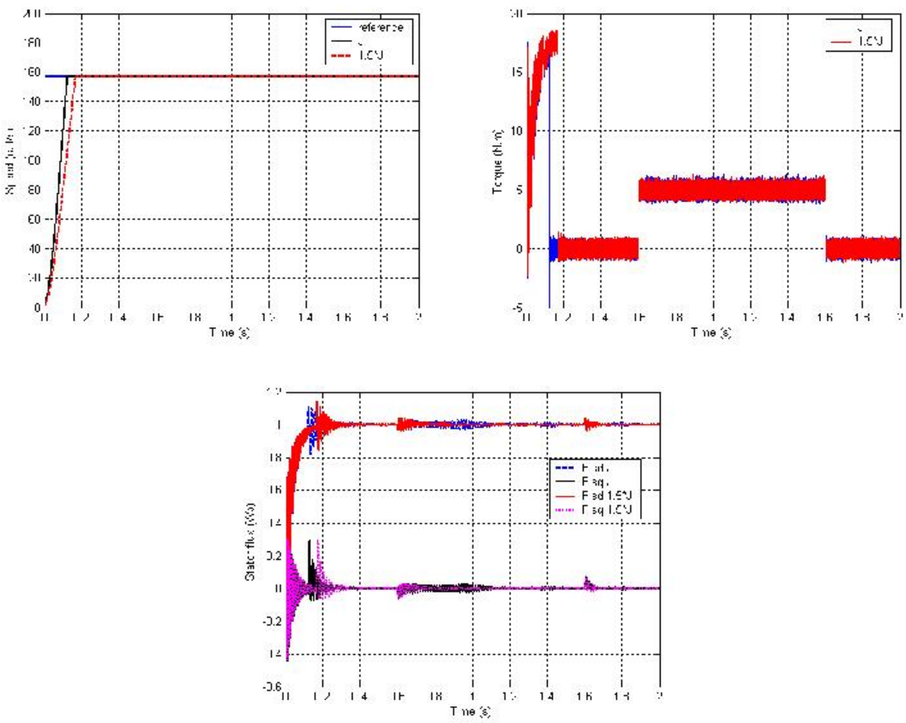


**Fig.9.** Test of robustness for two values of moment of inertia: nominal case and +50%

## 3. CONCLUSION

In this paper, a direct Field-Oriented Control of doubly fed induction motor by fuzzy sliding mode regulator has been presented. Simulation results show good performance obtained with proposed control. Also, compared to the conventional sliding mode control. The different simulation results obtained show the high robustness of the controller in presence of the parameters variation as the moment of inertia or the load. The control of speed gives fast dynamic response. The decoupling, stability and convergence to equilibrium point are verified. Simulations results reveal some very interesting features and show that the proposed fuzzy sliding mode control could be used as an alternative to the conventional sliding mode control of induction motors.

**Appendix**

Rated Data of the simulated doubly fed induction motor:

Rated values: 0.8 KW; 220/380 V-50 Hz; 3.8/2.2 A, 1420 rpm.

Rated parameters:

$R_s$ = 11.98 Ω

$R_r$ = 0.904 Ω

$L_s$ = 0.414 H

$L_r$ = 0.0556 H

$M$ = 0.126 H

$P$ = 2.0

Mechanical constants:

$J$ = 0.01 Kg.m$^2$

$f$ = 0.00 I.S.

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**How to cite this article**
Bekakra Y, Ben Attous D. Fuzzy sliding mode controller for doubly fed induction motor speed control. J Fundam Appl Sci. 2010, 2(2), 272-287.