A robust fuzzy sliding mode control applied to the double fed induction machine

Sid Ahmed El Mahdi ARDJOUN, Mohamed ABID, Abdel Ghani AISSAOUI, Abedelatif NACERI

Abstract— In this paper we propose to design a robust control using fuzzy sliding mode for double-fed induction machine (DFIM), the stator and rotor are fed by two converters. The purpose is therefore to make the speed and the flux control resist to parameter variations, because the variation of parameters during motor operation degrades the performance of the controllers. The use of the nonlinear sliding mode method provides very satisfactory performance for DFIM control, and the chattering effect is also eliminated by the fuzzy mode. Simulation results show that the implementation of the DFIM fuzzy sliding mode controllers leads to robustness and dynamic performance satisfaction, even when the electrical and mechanical parameters vary.

Keywords— Double-Fed Induction Machine (DFIM), Fuzzy sliding Mode, Speed control, Flux control, Robustness.

I. Introduction

In the case of induction speed drive application which needs a constant torque under speed variation, such as railway traction system, marine propulsion system, and others..., the DFIM is an interesting alternative according to the existing solutions [13], this is due to its low cost and high reliability [7].

But the DFIM control is based on a stationary model which is submissive to many constraints, such as parameters uncertainties, (temperature, saturation .....), that might divert the system from its optimal functioning. That is why the regulation should be concerned with the control's robustness and performance [7, 8].

The purpose of this paper is to find a command structure that withstands high parametric uncertainties and allows the implementations of variable behavior with the least influence of the parameters changes. To do this, we have referred to the use of fuzzy sliding mode control. We have applied this design to control the flux and speed to achieve robustness and good performance.

In this paper, we study first the model of the DFIM and the principle of the stator flux oriented control with input-output decoupling. Then we present the theory of sliding mode, fuzzy sliding mode and the design of speed and flux fuzzy sliding mode. Finally, we give some remarks on the proposed control.

Sid Ahmed El Mahdi ARDJOUN, Mohamed ABID, Abdel Ghani AISSAOUI, Abedelatif NACERI, are with IRECOM Laboratory, Department of Electrical Engineering, Djillali Liabes University of Sidi Bel-Abbes, Algeria. (Corresponding author e-mail: ardjoun.s.e.m@gmail.com)

II. Model and Control Strategy of DFIM

The chain of energy conversion adopted for the power supply of the DFIM consists of two converters, one on the stator and the other one on the rotor. A filter is placed between the two converters, as shown in Fig.1.

The control strategy is determined from the DFIM model expressed in the (d,q) rotating reference frame.

Fig.2 shows that the stator flux vector is oriented toward the direct axis ($\Phi_s = \Phi_{sd}$ and $\Phi_s = 0$) and it also rotates at $\omega_{dq} = d\theta_{dq}/dt$ speed. The model is then expressed by (1). In steady state, $\omega_{dq} = \omega_s$ and $\theta_{dq} = \theta_s$, and by imposing $I_{sd_{ref}}$ to have a unitary power factor working [4]. And this model can be simplified and written in (4). So, we also obtain the null direct stator voltage component ($V_{sd} = 0$).

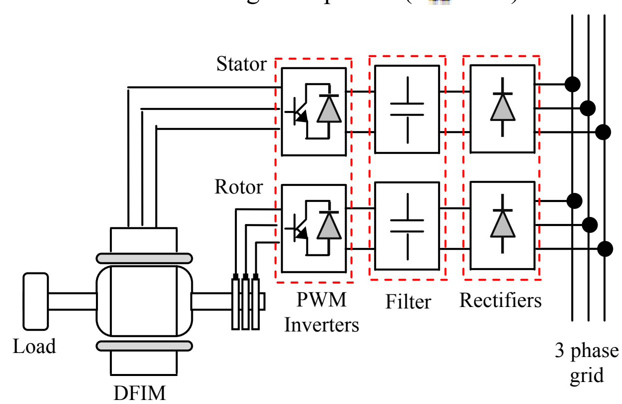

Fig.1. General scheme of DFIM drive installation.

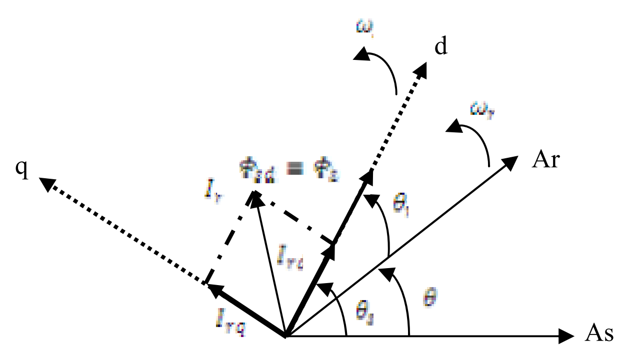

Fig.2. Stator flux vector linked to the direct axis of the (d,q) frame.

General DFIM model

$$\begin{cases} V_{sd}(t) = R_s\, I_{sd} + \frac{d\Phi_{sd}}{dt} - \frac{d\theta_s}{dt}\Phi_{sq} \\ V_{sq}(t) = R_s\, I_{sq} + \frac{d\Phi_{sq}}{dt} + \frac{d\theta_s}{dt}\Phi_{sd} \\ V_{rd}(t) = R_r\, I_{rd} + \frac{d\Phi_{rd}}{dt} - \frac{d\theta_r}{dt}\Phi_{rq} \\ V_{rq}(t) = R_r\, I_{rq} + \frac{d\Phi_{rq}}{dt} + \frac{d\theta_r}{dt}\Phi_{rd} \end{cases} \quad (1)$$

$$\begin{cases} \Phi_{sd} = L_s\, I_{sd} + M_{sr}\, I_{rd} \\ \Phi_{sq} = L_s\, I_{sq} + M_{sr}\, I_{rq} \\ \Phi_{rd} = L_r\, I_{rd} + M_{sr}\, I_{sd} \\ \Phi_{rq} = L_r\, I_{rq} + M_{sr}\, I_{sq} \end{cases} \quad (2)$$

With $\theta_s = \theta_r + \theta$ (3)

θ: angle between the stator and rotor winding, θ_s: angle between the stator winding and the axis d, θ_r: angle between the rotor winding and the axis d.

Steady state DFIM model

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = R_s\, I_{sq} + \omega_s\, \Phi_{sd} \\ V_{rd} = R_r\, I_{rd} - \omega_r\, \Phi_{rq} \\ V_{rq} = R_r\, I_{rq} + \omega_r\, \Phi_{rd} \end{cases} \quad (4)$$

The electromagnetic torque is expressed by (5)

$$T_{em} = N_p M_{sr} I_{sq} I_{rd} = N_p\, \Phi_{sd}\, I_{sq} \quad (5)$$

The control of the DFIM vector is designed with an input/output current decoupling strategy which permits an independent control of the four current components, I_{sd}, I_{sq}, I_{rd} and I_{rq}. Concerning the details of this method, they are presented in [10]. This decoupling strategy is based on state space DFIM modeling as in (6):

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (6)$$

$$x = [I_{sd}\ \ I_{sq}\ \ I_{rd}\ \ I_{rq}]^T \in \mathcal{R}^n$$

The state space vector,

$$u = [V_{sd}\ \ V_{sq}\ \ V_{rd}\ \ V_{rq}]^T \in \mathcal{R}^m$$

The input vector

$$y = [I_{sd}\ \ I_{sq}\ \ I_{rd}\ \ I_{rq}]^T \in \mathcal{R}^p$$

With n: state variables number, m: inputs number, p: outputs number. So, the different matrices of the state space equation are as below:

$$A = \begin{bmatrix} -a_1 I_2 - j(a\omega + \omega_s) & a_3 I_2 - j\, a_5\, \omega \\ a_4 I_2 + j\, a_6\, \omega & -a_2 I_2 - j(\omega_s - \frac{\omega}{\sigma}) \end{bmatrix} \quad (7)$$

The dynamic matrix,

$$B = \begin{bmatrix} b_1 I_2 & -b_3 I_2 \\ -b_3 I_2 & b_2 I_2 \end{bmatrix} \quad (8)$$

The control matrix,

$$C = I_4$$

The output matrix,

With $I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $j = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$, $I_4 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Where:

$$a = \frac{1-\sigma}{\sigma},\ a_1 = \frac{R_s}{\sigma\, R_s},\ a_2 = \frac{R_r}{\sigma\, R_r},\ a_3 = \frac{R_r\, M_{sr}}{\sigma\, L_s\, L_r}$$

$$a_4 = \frac{R_s\, M_{sr}}{\sigma\, L_s\, L_r},\ a_5 = \frac{M_{sr}}{\sigma\, L_s},\ a_6 = \frac{M_{sr}}{\sigma\, L_r},\ b_1 = \frac{1}{\sigma\, L_s}$$

$$b_2 = \frac{1}{\sigma\, L_r},\ b_3 = \frac{M_{sr}}{\sigma\, L_s\, L_r}$$

And $\sigma = (1 - \frac{M_{sr}^2}{L_s\, L_r})$

Consequently, the general scheme of applied decoupling current method is presented in Fig.3.

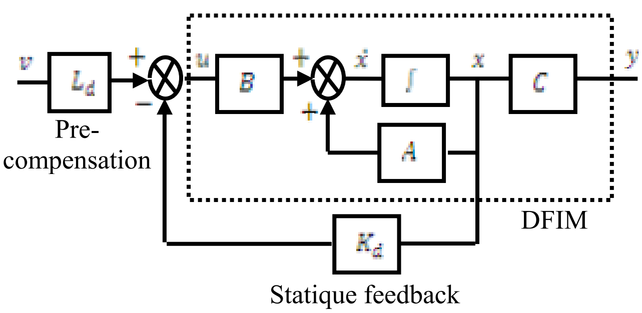

Fig.3. Decoupling current feedback for DFIM.

With

$$\begin{cases} L_d = B^{-1} \\ K_d = B^{-1}\, A \end{cases} \quad (9)$$

To obtain the decoupling current control the new input vector v is imposed [10], and it is associated with Stator Flux Oriented Vector Control (SFOVC) strategy.

III. SLIDING MODE CONTROL

The sliding mode control has been very successful in recent years. This is due to the simplicity of implementation and robustness against system uncertainties and external disturbances affecting the process.

The basic idea of sliding mode control is first to draw the states of the system in an area properly selected, then design a law command that will always keep the system in this region [14]. The sliding mode control goes through three stages:

- *Choice of switching surface*

For a nonlinear system presented in the following form :

$$\dot{X} = f(X,t) + G(X,t)U(X,t) \quad (10)$$

Where $X \in \mathcal{R}^n$ is the state vector, $U \in \mathcal{R}^m$ is the control vector, $f(X,t) \in \mathcal{R}^n$, $(X,t) \in \mathcal{R}^{n \cdot m}$.

We take the form of general equation given by J.J.Slotine to determine the sliding surface given by [17]:

$$S(X) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \quad (11)$$

Where $X = [X, \dot{X}, \ldots, X^{n-1}]^T$ is the state vector, $X^d = [X^d, \dot{X}^d, X^d]^T$ is the desired state vector, $e = X^d - X = [e, \dot{e}, \ldots, e^{n-1}]^T$ is the error vector, and λ is a vector of slopes of the *S*.

- *Convergence condition*

The convergence condition is defined by the equation Lyapunov [12], it makes the area attractive and invariant.

$$S(X)\dot{S}(X) \leq 0 \quad (12)$$

- *Control calculation*

The control algorithm is defined by the relation

$$U = U^{eq} + U^n \quad (13)$$

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)

U^{eq} can be obtained by considering the condition for the sliding regime, $\dot{S}(X,t) = 0$. The equivalent control keeps the state variable on sliding surface, once they reach it.

U^n is needed to assure the convergence of the system states to sliding surfaces in finite time.

In order to alleviate the undesirable chattering phenomenon, J. J. Slotine proposed an approach to reduce it, by introducing a boundary layer of width ϕ on either side of the switching surface [17]. Then, U^n is defined by

$$U^n = K\ sat(S(X)/\phi) \quad (14)$$

Where $sat(S(X)/\phi)$ is the proposed saturation function, ϕ is the boundary layer width, K is the controller gain designed from the Lyapunov stability

Commonly, in DFIM control using sliding mode theory, the surfaces are chosen according of the error between the reference input signal and the measured signals [20].

A. Speed control

The speed error is defined by:

$$e = \Omega_{ref} - \Omega \quad (15)$$

For n =1, the speed control manifold equation can be obtained from equation (11) as follow:

$$S(\Omega) = e = \Omega_{ref} - \Omega \quad (16)$$

$$\dot{S}(\Omega) = \dot{\Omega}_{ref} - \dot{\Omega} \quad (17)$$

With the mechanical equation:

$$\dot{\Omega} = -\frac{N_p M_{sr}}{J_t L_s}\left(I_{rq}\Phi_{sd}^{ref}\right) - \frac{C_r}{J_t} - \frac{f_t}{J_t}\Omega \quad (18)$$

By replacing the mechanical equation in the equation of the switching surface, the derivative of the surface becomes:

$$\dot{S}(\Omega) = \dot{\Omega}_{ref} - \left(-\frac{N_p M_{sr}}{J_t L_s}\left(I_{rq}\Phi_{sd}^{ref}\right) - \frac{C_r}{J_t} - \frac{f_t}{J_t}\Omega\right) \quad (19)$$

We take:

$$I_{rq}^{ref} = I_{rq}^{eq} + I_{rq}^{n} \quad (20)$$

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

$$S(\Omega) = 0\ , \dot{S}(\Omega) = 0\ ,\ I_{rq}^{n} = 0$$

Where the equivalent control is:

$$I_{rq}^{eq} = -\frac{J_t L_s}{N_p M_{sr}\Phi_{sd}^{ref}}\left(\dot{\Omega}_{ref} + \frac{C_r}{J_t} + \frac{f_t}{J_t}\Omega\right) \quad (21)$$

Therefore, the correction factor is given by:

$$I_{rq}^{n} = K_{Irq} \cdot sat(S(\Omega)) \quad (22)$$

K_{Irq}: positive constant.

B. Stator flux control

In the proposed control, the manifold equation can be obtained by:

$$S(\Phi_{sd}) = \Phi_{sd}^{ref} - \Phi_{sd} \quad (23)$$

$$\dot{S}(\Phi_{sd}) = \dot{\Phi}_{sd}^{ref} - \Phi_{sd}' \quad (24)$$

With the flux equation

$$\dot{\Phi}_{sd} = V_{sd} + \frac{M_{sr}}{T_s} I_{rd} - \frac{1}{T_s}\Phi_{sd} \qquad (25)$$

Substituting the expression of $\dot{\Phi}_{sd}$ in equation (24), we obtain:

$$S(\Phi_{sd}) = \dot{\Phi}_{sd}^{ref} - (V_{sd} + \frac{M_{sr}}{T_s} I_{rd} - \frac{1}{T_s}\Phi_{sd} \qquad (26)$$

The control current I_{rd} is defined by:

$$I_{rd}^{ref} = I_{rd}^{eq} + I_{rd}^{n} \qquad (27)$$

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

$S(\Phi_{sd}) = 0 \,, \dot{S}(\Phi_{sd}) = 0 \,, \; I_{rd}^{n} = 0$

The equivalent control is:

$$I_{rd}^{eq} = \left(\dot{\Phi}_{sd}^{ref} - V_{sd} + \frac{1}{T_s}\Phi_{sd}\right)\frac{T_s}{M_{sr}} \qquad (28)$$

Where, the correction factor is given by

$$I_{rd}^{n} = K_{Ird}.sat(S(\Omega)) \qquad (29)$$

K_{Ird}: positive constant.

IV. Fuzzy Sliding Mode Control

The disadvantage of sliding mode controllers is that the discontinuous control signal produces chattering. In order to eliminate the chattering phenomenon, we propose to use the fuzzy sliding mode control.

The fuzzy sliding mode controller (FSMC) is a modification of the sliding mode controller (eqn. (13)), where the switching controller term $K\ sat(S(X)/\phi)$, has been replaced by a fuzzy control input as given below [1, 15].

$$U = U^{eq} + U^{fuzz} \qquad (30)$$

The proposed fuzzy sliding mode control, which is designed to control the speed, is shown in Fig. 5.

The simplest three rules, selected three input-output linguistic variables, which are: NB-for negative big, ZM-for zero medium, PS-for positive small. N, Z, and P are linguistic terms of fuzzy sets and their corresponding membership functions are depicted in fig. 6. The rules base can be written as shown in the Table 1.

Fuzzy input $S(\Omega)$	NB	ZM	PS
Fuzzy output I_{rq}^{ref}	BIG	SMALL	MEDIUM

Table 1. The rules base of the PFSM

For this purpose, it is used a Mamdani-type fuzzy logic system. The membership function of the result aggregation is by maximum method. The control output is accomplished by using the Mean Maximum operator.The defuzzification is centroid method.

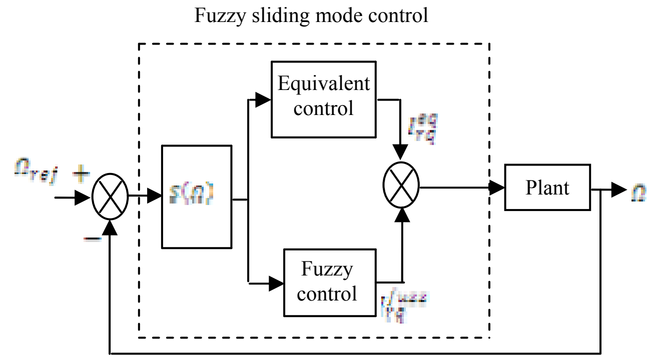

Fig. 5. Block diagram of the speed fuzzy sliding mode control.

N.B: The some procedure can be used for the flux

V. Simulation Results

To validate the robustness and good performance of speed and flux regulator in the sliding mode, we vary the speed and load torque with and without parameters uncertainties. Fig.7 shows a block diagram of the studied system

The reference speed and torque are defined as follows:

- $t = 0\,s$: Flux installation, speed at zero
- $t = 0.25\,s$: Motor start up with a speed reference of 157 rd/s
- $t = 1\,s$: Application of nominal constant torque.
- $t = 1.5\,s$: Changing direction of rotation
- $t = 2.5\,s$: Reversal of the torque
- $t = 3\,s$: Transition to a low speed of 2.5% base speed
- $t = 3.5\,s$: Reversal of the torque

In the case of parametric uncertainties, we limit our simulations for the worst case, that is to say, where the resistance is increasing by 50%, 30% of the inductances, inertia of 200% and friction of 500%.

The simulations were performed using the Matlab-Simulink software. The engine parameters are indicated in Annex.

Fig. 8 shows the response of the system without parametric uncertainties and Fig. 9 shows the response with parametric uncertainties.

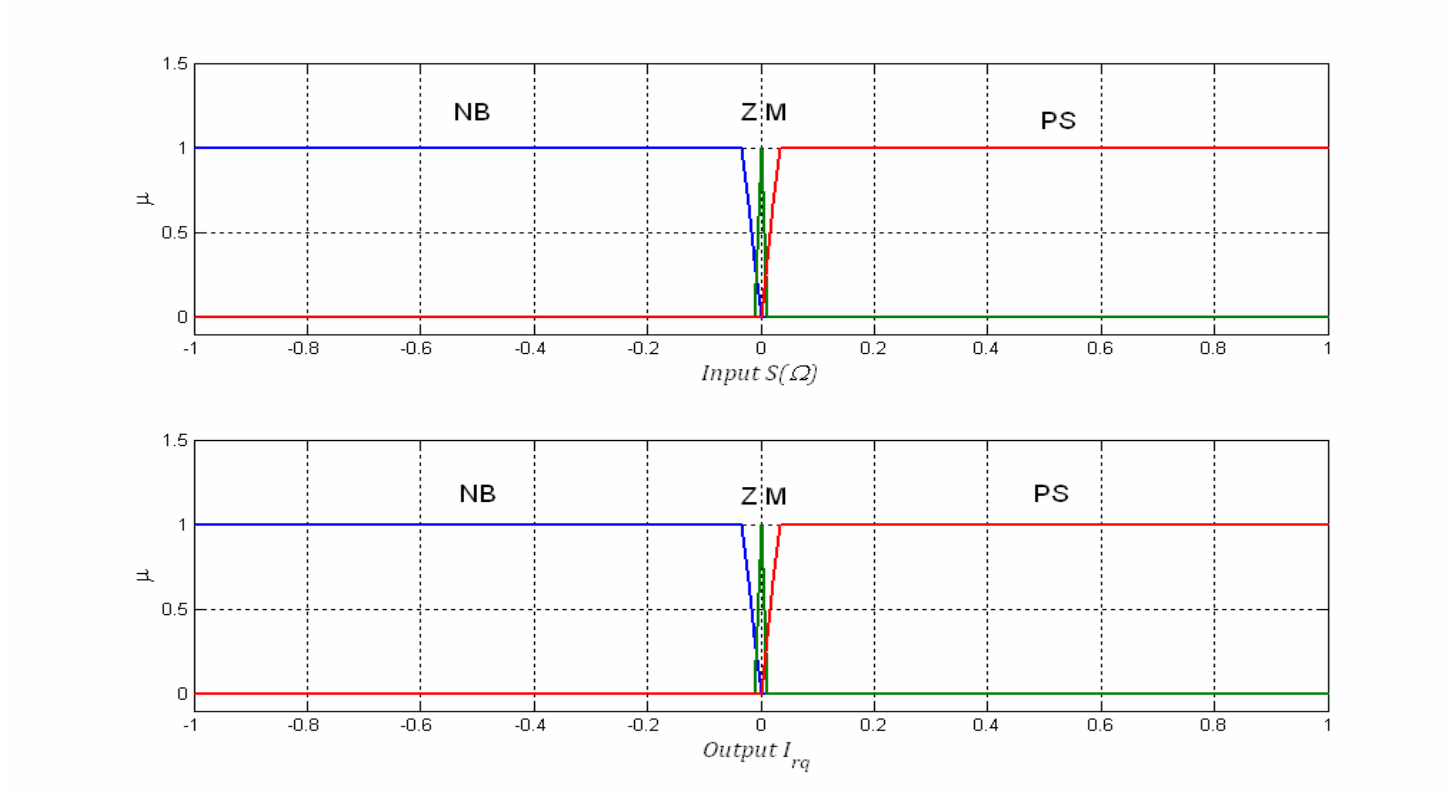

Fig. 6. The membership functions sets for the PFSMC

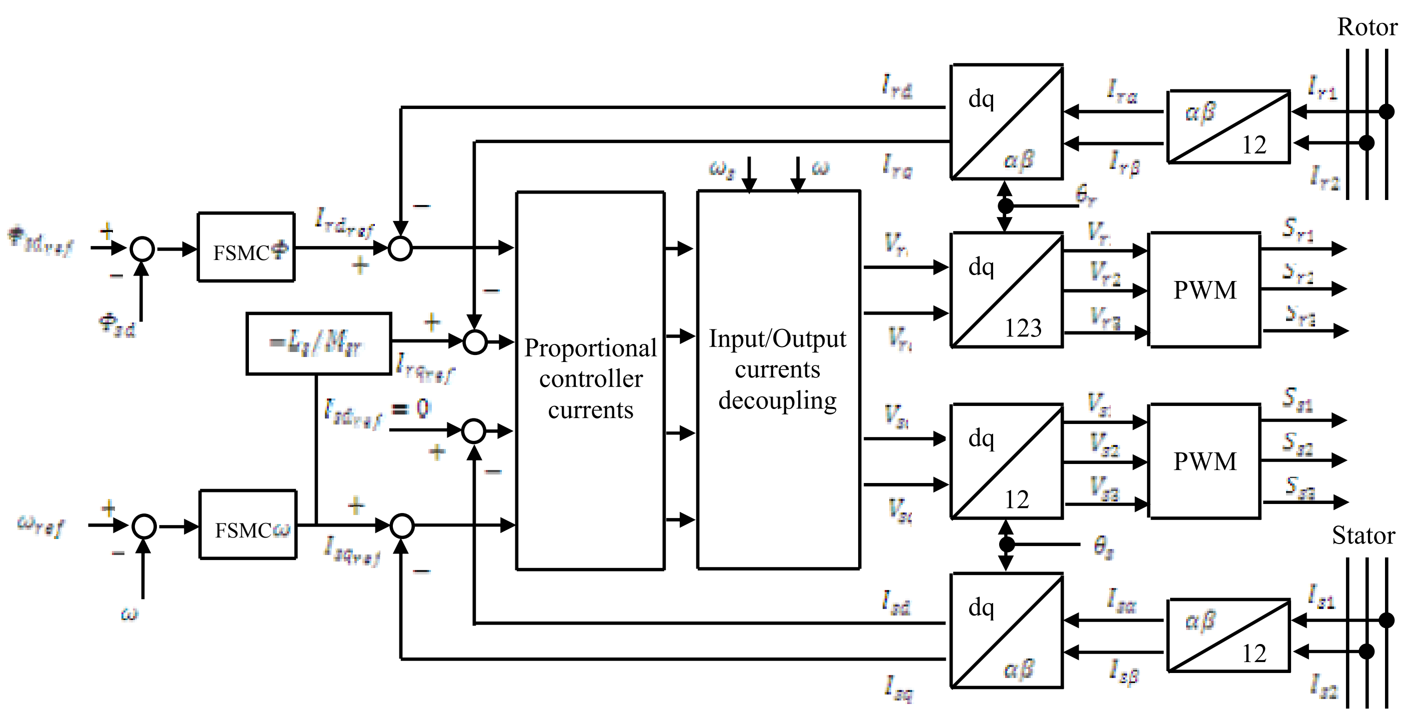

Fig. 7. DFIM developed control.

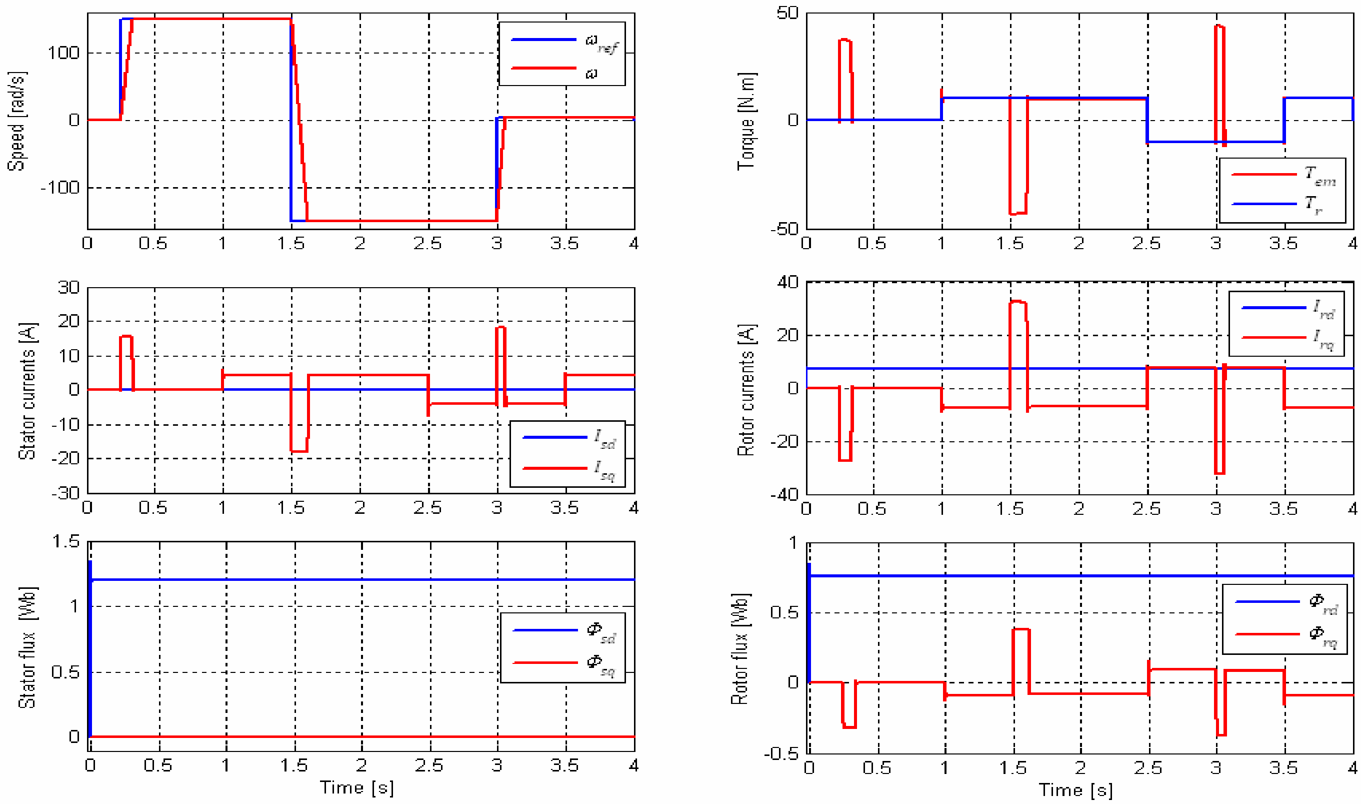

Fig.8. The response of the system without parametric uncertainties

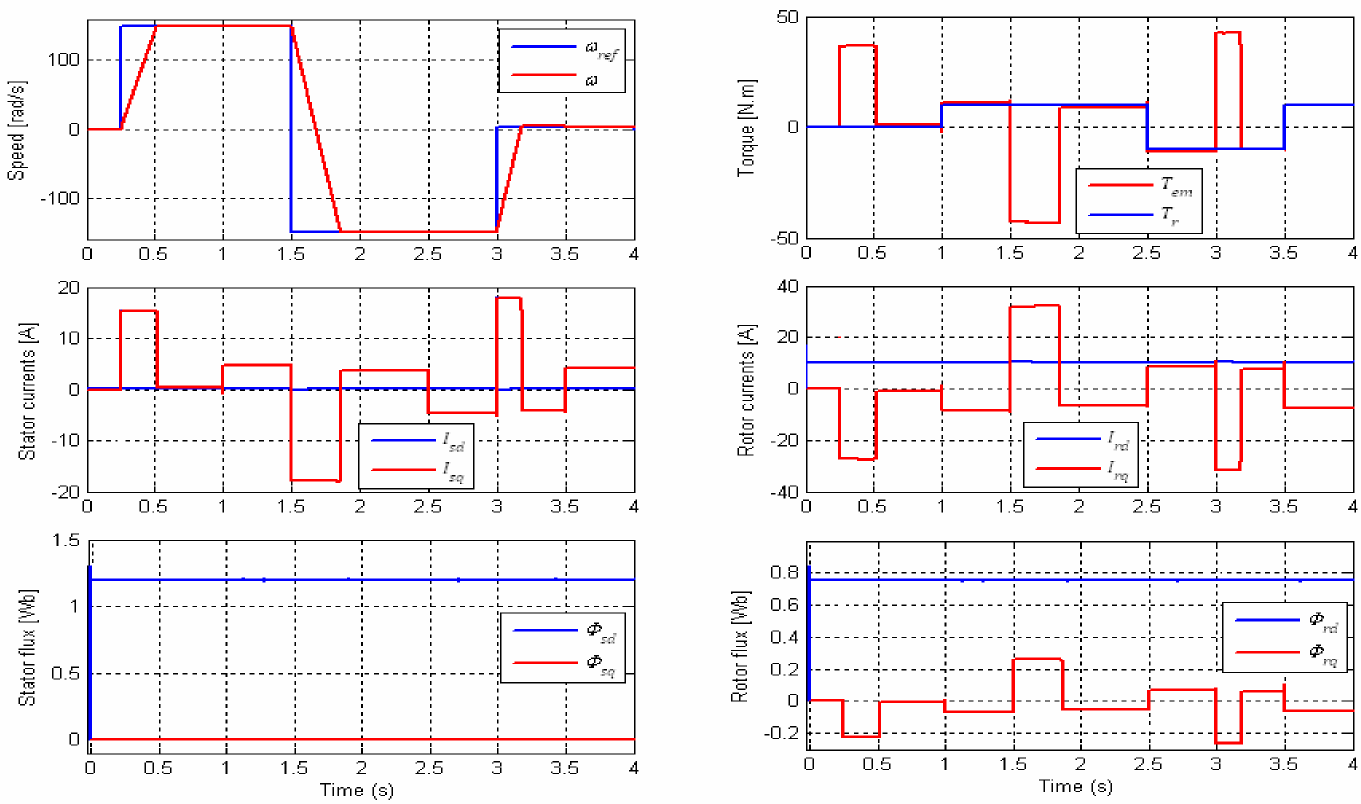

Fig.9. The response of the system with parametric uncertainties
(R+50%, L+30%, J_t+200%, and f_t+500%)

The simulation results clearly show that:

The decoupling between the electromagnetic torque and stator flux is very satisfactory.

In the transitory regime the current mark spikes without reaching the saturation, with increasing settling time in the case of parametric uncertainties, and in the steady state they remain at their nominal values.

The speed response follows exactly the model applied with increasing response time in the case of parametric uncertainties and the impacts of load torque does not affect it.

VI. Conclusion

This paper suggests a fuzzy sliding mode control method that is used for the speed and flux control of a double fed induction machine using stator flux vector oriented control with input-output decoupling.

After modeling the system we have developed two controllers (one for the speed and the other one for the flux) using the fuzzy sliding mode. In order to eliminate the chattering effect we have used the fuzzy mode.

Simulation results have shown robustness and good performances according to parametric variations.

With the appropriate choice of the parameters control and the smoothing of the discontinuity control, the chattering effects are reduced, and the torque fluctuations are decreased too.

Furthermore, this regulation presents a simple robust control algorithm that has the advantage to be easily implantable in calculator.

Annex

P_n	1.5 kW	Nominal power
U_{sn}	380 V	Stator nominal voltage
U_{rn}	225 V	Rotor nominal voltage
I_{sn}	4.3 A	Stator nominal current
I_{rn}	4.5 A	Rotor nominal current
N_p	2	Pair poles
R_s	1.75 Ω	Stator resistance
R_r	1.68 Ω	Rotor resistance
L_s	0.295 H	Stator inductance
L_r	0.104 H	Rotor inductance
M_{sr}	0.165 H	Mutual inductance
J_t	0.0426 kg.m^2	Inertia
f_t	0.00.27 kg.m^2.s^{-1}	Friction
Ω_n	1420 rpm	Nominal rotation speed

Table.2 Nomenclature and numeric values

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