A Robust Sliding Mode Control Applied To The Double Fed Induction Machine

Sid Ahmed El Mahdi ARDJOUN[1], Mohamed ABID[1], Abdel Ghani AISSAOUI[1], Ahmed TAHOUR[2]

[1]IRECOM Laboratory, Department of Electrical Engineering, Djillali Liabes University of Sidi Bel-Abbes, Algeria.
[2]Department of Technical sciences, Mascara University, Algeria.
Corresponding author e-mail: ardjoun.s.e.m@gmail.com

Abstract: *In this paper we propose to design a robust control using 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 function "sat". Simulation results show that the implementation of the DFIM sliding mode controllers leads to robustness and dynamic performance satisfaction, even when the electrical and mechanical parameters vary.*
Keywords: *Double-fed induction machine, Sliding mode, Speed control, Flux control, Robustness.*

1. 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 [1], this is due to its low cost and high reliability [2].

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 [2].

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 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 and the design of speed and flux sliding mode. Finally, we give some remarks on the proposed control.

2. 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 figure1.
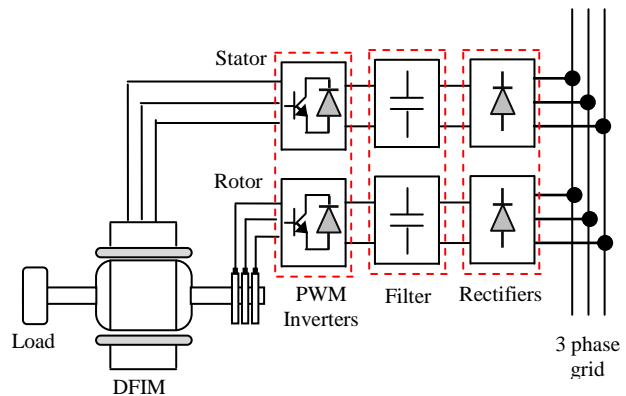

Figure 1. General scheme of DFIM drive installation

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

Figure 2 shows that the stator flux vector is oriented toward the direct axis ($\Phi_s = \Phi_{sd}$ and $\Phi_{sq} = 0$) 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 [3]. And this model can be simplified and written in (4). So, we also obtain the null direct stator voltage component ($V_{sd} = 0$).
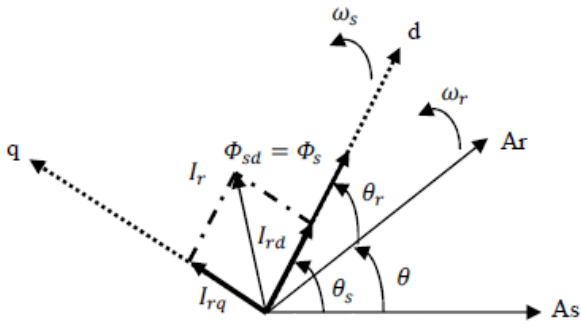

Figure 2. Stator flux vector linked to the direct axis of the (d,q) frame

General DFIM model

$$
\begin{cases}
V_{sd}(t) = R_s I_{sd} + \dfrac{d\Phi_{sd}}{dt} - \dfrac{d\theta_s}{dt}\Phi_{sq} \\[2mm]
V_{sq}(t) = R_s I_{sq} + \dfrac{d\Phi_{sq}}{dt} + \dfrac{d\theta_s}{dt}\Phi_{sd} \\[2mm]
V_{rd}(t) = R_r I_{rd} + \dfrac{d\Phi_{rd}}{dt} - \dfrac{d\theta_r}{dt}\Phi_{rq} \\[2mm]
V_{rq}(t) = R_r I_{rq} + \dfrac{d\Phi_{rq}}{dt} + \dfrac{d\theta_r}{dt}\Phi_{rd}
\end{cases}
\tag{1}
$$

$$
\begin{cases}
\Phi_{sd} = L_s I_{sd} + M_{sr} I_{rd} \\[1mm]
\Phi_{sq} = L_s I_{sq} + M_{sr} I_{rq} \\[1mm]
\Phi_{rd} = L_r I_{rd} + M_{sr} I_{sd} \\[1mm]
\Phi_{rq} = L_r I_{rq} + M_{sr} I_{sq}
\end{cases}
\tag{2}
$$

$$
\theta_s = \theta_r + \theta
\tag{3}
$$

With 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

$$
\begin{cases}
V_{sd} = 0 \\[1mm]
V_{sq} = R_s I_{sq} + \omega_s \Phi_{sd} \\[1mm]
V_{rd} = R_r I_{rd} - \omega_r \Phi_{rq} \\[1mm]
V_{rq} = R_r I_{rq} + \omega_r \Phi_{rd}
\end{cases}
\tag{4}
$$

The electromagnetic torque is expressed by (5)

$$
T_{em} = N_p M_{sr} I_{sq} I_{rd} = N_p \Phi_{sd} I_{sq}
\tag{5}
$$

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 [4].

This decoupling strategy is based on state space DFIM modeling as in (6):

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

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

The state space vector,

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

The input vector

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

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

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

The dynamic matrix,

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

The control matrix, $C = I_4$
The output matrix,

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

Where:

$$
a = \frac{1-\sigma}{\sigma}, a_1 = \frac{R_s}{\sigma L_s}, a_2 = \frac{R_r}{\sigma L_r}, a_3 = \frac{R_r M_{sr}}{\sigma L_s L_r}, a_4 = \frac{R_s M_{sr}}{\sigma L_s L_r}
$$

$$
a_5 = \frac{M_{sr}}{\sigma L_s}, a_6 = \frac{M_{sr}}{\sigma L_r}, b_1 = \frac{1}{\sigma L_s}, b_2 = \frac{1}{\sigma L_r}, b_3 = \frac{M_{sr}}{\sigma L_s L_r}
$$

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

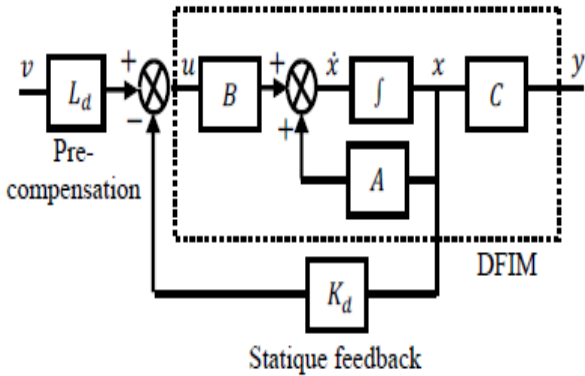Consequently, the general scheme of applied decoupling current method is presented in figure 3.

Figure 3. Decoupling current feedback for DFIM

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

To obtain the decoupling current control the new input vector v is imposed [4], and it is associated with Stator Flux Oriented Vector Control (SFOVC) strategy.

3. 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 [5]. The sliding mode control goes through three stages:

- Choice of Switching Surface

For a nonlinear system presented in the following form:

$\dot{X} = f(X,t) + g(X,t)u(X,t); \quad X \in \Re^n, u \in \Re$ (10)

Where: $f(X,t), g(X,t)$ are two continuous and uncertain non-linear functions, supposed limited.

We take the form of general equation given by J.J.Slotine to determine the sliding surface given by [6]:

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

Where

$e = X^d - X, X = \left[x, \dot{x}, ..., x^{n-1}\right]^T, X^d = \left[x^d, \dot{x}^d, \ddot{x}^d, ...\right]^T$

And e - Error on the signal to be adjusted, λ - positive coefficient, n - system order, X^d - desired signal, X - state variable of the control signal.

- Convergence Condition

The convergence condition is defined by the equation Lyapunov [7], it makes the area attractive and invariant.

$S(X)\dot{S}(X) \le 0$ (12)

- Control Calculation

The control algorithm is defined by the relation

$u = u^{eq} + u^n$ (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, $S(X,t) = 0$. 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 [6]. Then, u^n is defined by

$u^n = K\,sat(S(X)/\phi)$ (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 to the error between the reference input signal and the measured signals [8,9].

3.1. Speed Control

The speed error is defined by:

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

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

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

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

With the mechanical equation:

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

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

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

We take:

$$I_{rq}^{ref} = I_{rq}^{eq} + I_{rq}^{n} \tag{20}$$

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:

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

Therefore, the correction factor is given by:

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

$K_{I_{rq}}$: positive constant.

3.2. Stator Flux Control

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

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

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

With the flux equation

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

Substituting the expression of Φ_{sd} in equation (24), we obtain:

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

The control current I_{rd} is defined by:

$$I_{rd}^{ref} = I_{rd}^{eq} + I_{rd}^{n} \tag{27}$$

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:

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

Where, the correction factor is given by

$$I_{rd}^{n} = K_{I_{rd}} sat(S(\Phi_{sd})) \tag{29}$$

$K_{I_{rd}}$: positive constant.

4. 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. Figure 4 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

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.

Figure 5 shows the response of the system without parametric uncertainties and figure 6 shows the response with parametric uncertainties.

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.

5. Conclusion

This paper suggests a 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 sliding mode. 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.

Simulation results have then shown robustness and good performances when the DFIM is confronted to internal and external perturbations. Furthermore, this regulation presents a simple robust control algorithm that has the advantage to be easily implantable in calculator.

6. Annex

Table 1. Nomenclature and numeric values

|		
Pn	1.5 kW	Nominal power
Usn	380 V	Stator nominal voltage
Urn	225 V	Rotor nominal voltage
Isn	4.3 A	Stator nominal current
Irn	4.5 A	Rotor nominal current
Np	2	Pair poles
Rs	1.75 Ω	Stator resistance
Rr	1.68 Ω	Rotor resistance
Ls	0.295 H	Stator inductance
Lr	0.104 H	Rotor inductance
Msr	0.165 H	Mutual inductance
Jt	0.0426 kg.m^2	Inertia
ft	0.00.27 kg.m^2.s^{-1}	Friction
Ωn	1420 rpm	Nominal rotation speed
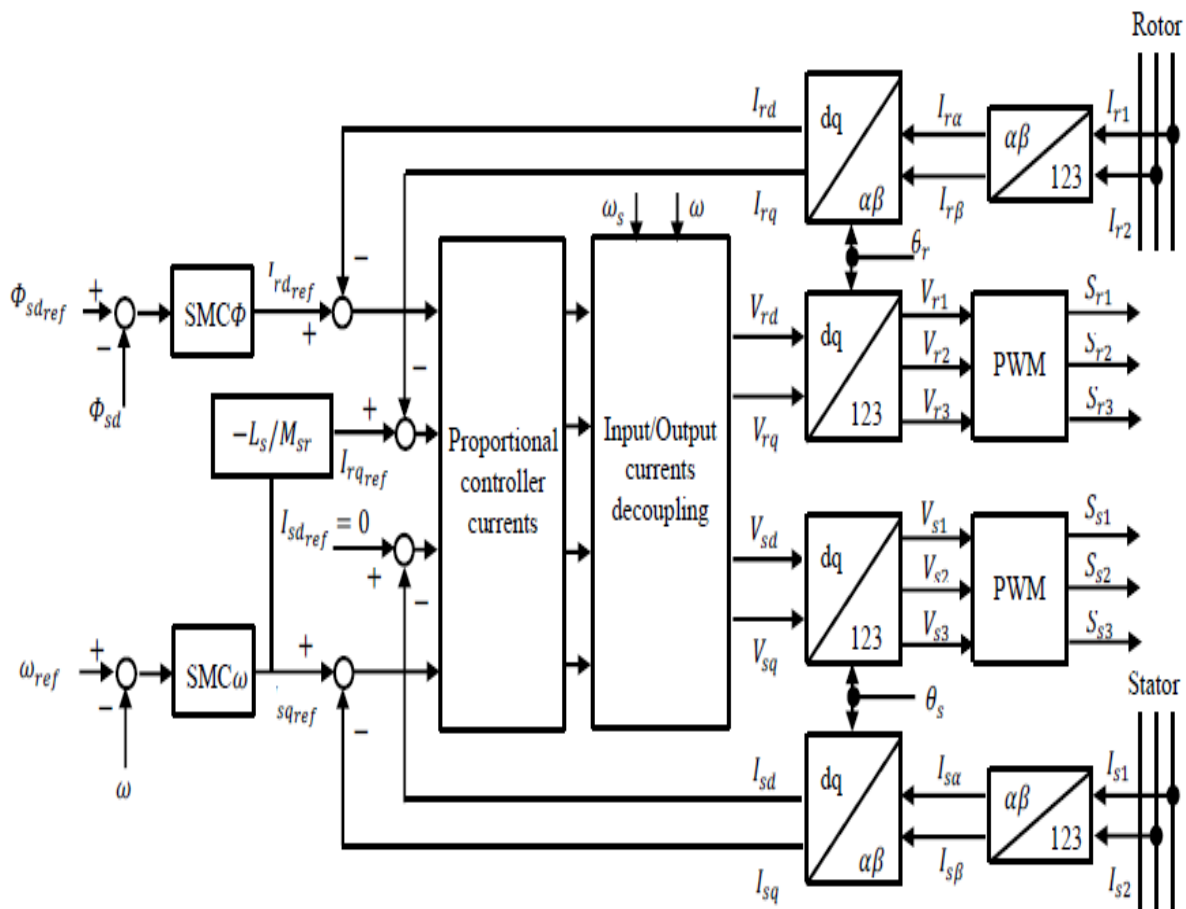
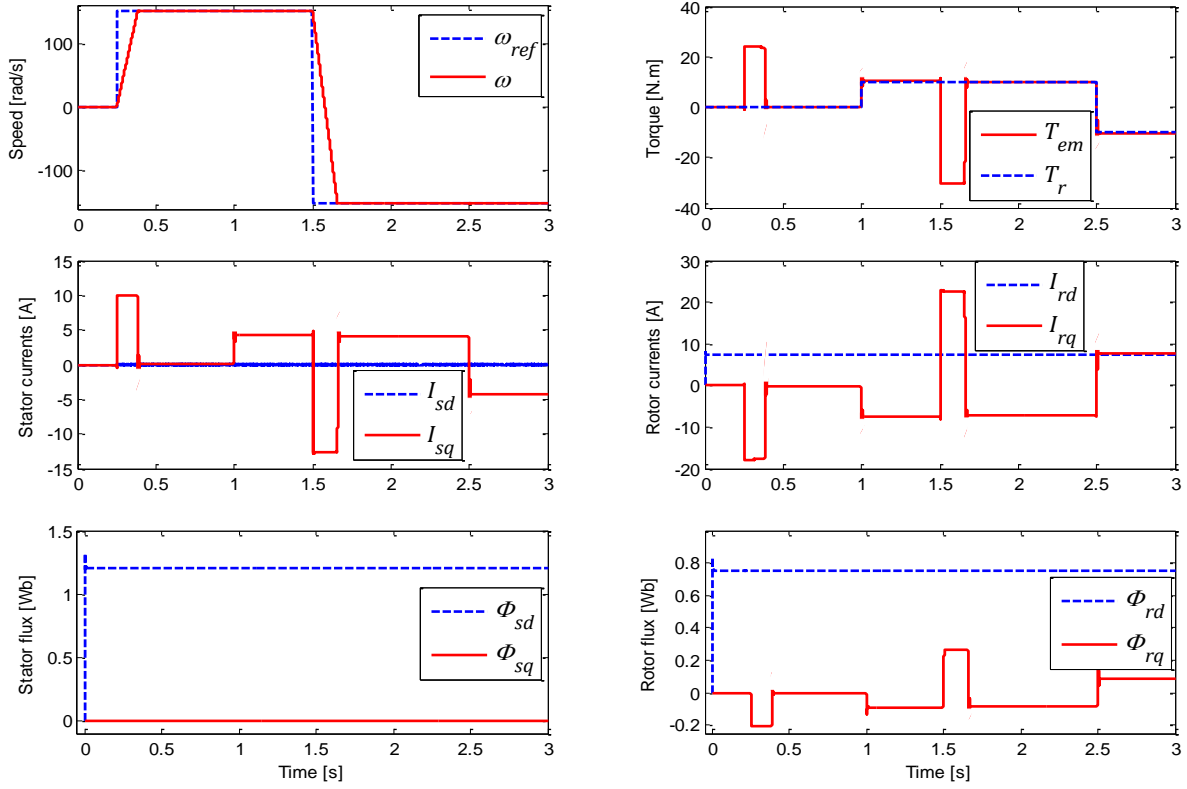**Figure 4.** DFIM developed control

Figure 5. The response of the system without parametric uncertainties
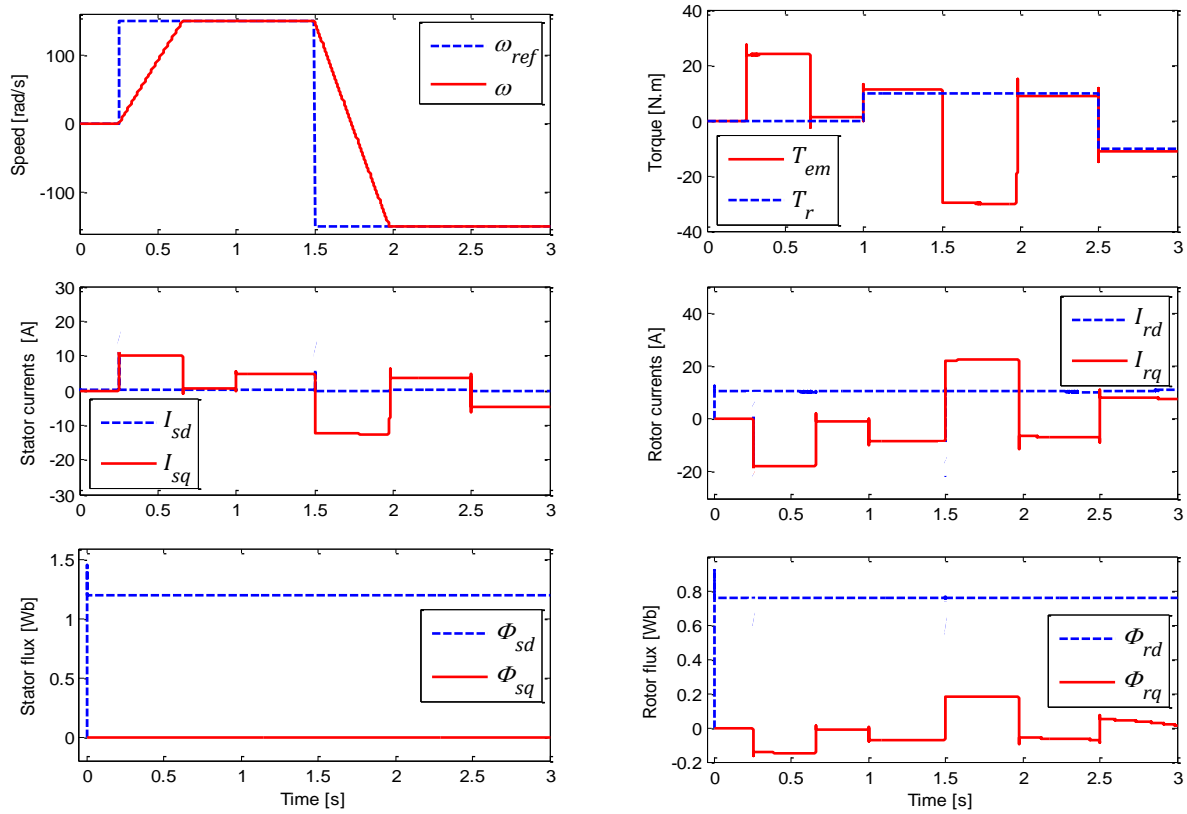

Figure 6. The response of the system with parametric uncertainties (R+50%, L+30%, *Jt*+200%, and *ft* +500%)

7. References

[1] P-E. Vidal, and M. Pietrzak-david, "Flux Sliding Mode Control of a Doubly Fed Induction Machine", *European Conference on Power Electronics and Applications*, 2005.

[2] G. Salloum, R. Mbayed, and M. Pietrzak-david, "Mixed Sensitivity H_∞ Control of Doubly Fed Induction Motor", *IEEE International Symposium on Industrial Electronics*, pp: 1300 - 1304, 2007.

[3] M. Abdellatif, M. Pietrzak-David and I. Slama-Belkhodja, "Sensitivity of the Currents Input-Output Decoupling Vector Control of the DFIM versus Current Sensors Fault", *13th International Power Electronics and Motion Control Conference, EPE-PEMC*, pp 938-944, 2008.

[4] G. Salloum, "Contribution à la commande robuste de la machine asynchrone à double Alimentation", Thèse de Doctorat en Génie Électrique, Institut National Polytechnique deToulouse, France, 2007.

[5] P-E. Vidal, "Commande non-linéaire d'une machine asynchrone à double alimentation", Thèse de doctorat en Génie Electrique, Institut National Polytechnique de Toulouse, France, 2004.

[6] J.J.E. Slotine, W. Li, "Applied nonlinear control", Prence Hall, USA, 1998.

[7] P. Lopez and A. S. Nouri, "Théorie Elémentaire Et Pratique de La Commande Par Les Régimes Glissants", Springer, 2006.

[8] V. I. Utkin, "Sliding mode control design principles and applications to electric drives", *IEEE Trans. Ind. electronic*, vol. 40, pp.23-36, Feb.1993.

[9] V.I. Utkin, "Variable structure systems with sliding modes", *IEEE Trans. Automat. Contr.,* vol. AC-22, no. 2. pp. 212-222, Apr.1977.

Biographies

Sid ahmed El Mahdi ARDJOUN was born in 1985 in Sidi Bel Abbes, Algeria. He received his BS and MS degree in electrical engineering from the Electrical Engineering Institute of The University of Sidi Bel Abbes in 2008 and 2010 respectively. Currently he is working on his PhD thesis. His main areas of research interests are control of electric drives (robust and intelligent control) in renewable energy domain.

Mohamed ABID was born on 11.02.1963. In 1997 he graduated (MSc) with distinction at the department of electrical engineering of the faculty of science engineering at Djillali Liabes University in Sidi Bel Abbes, Algeria. He defended his PhD in the field of electrical engineering in 2005; his thesis title was "The optimized control adaptation to the field-oriented induction machine fed by a PWM converter". Since 2000 he is teaching at the department of electrical engineering at Djillali Liabes University in Sidi Bel Abbes, Algeria. His scientific research is focusing on Modeling and Simulation of electric machines, Sliding mode in continuous systems, Control of electric drives.

Abdelghani AISSAOUI was born on 07.10.1967. In 1997 he graduated (MSc) with distinction at the department of electrical engineering of the faculty of science engineering at Djillali Liabes University in Sidi Bel Abbes, Algeria. He defended his PhD in the field of electrical engineering in 2007; his thesis title was "Neural network and fuzzy logic used to control a synchronous machine". Since 2001 he is teaching at the department of electrical engineering at the University of Bechar, Algeria. His scientific research is focusing on Power electronics and Control of electrical machines.

Ahmed Tahour was born in 1972 in ouled mimoun, Tlemcen, Algeria. He received his BS degree in electrical engineering from the Electrical Engineering Institute of The University of Sidi Bel Abbes in 1996, and the MS degree from the Electrical Engineering Institute of The University of Sidi Bel Abbes in 1999 and The PhD from the Electrical Engineering Institute of the University of Sidi Bel Abbes in 2007. He is currently Professor of electrical engineering at University of Bechar (Algeria). His current research interest includes power electronics and control of electrical machines.