

# A Sliding Mode-Multimodel Control for Torque Evolution of a Double Feed Asynchronous Generator

Ahmed RHIF, Zohra KARDOUS, Naceur BEN HADJ BRAIEK

Laboratoire des Systèmes Avancés (L.S.A)

Ecole Polytechnique de Tunisie

BP 743, 2078 La Marsa, Tunisia Email: ahmed.rhif@issatso.rnu.tn, zohra.kardous@enit.rnu.tn, naceur.benhadj@ept.rnu.tn

**Abstract - This paper proposes a robust control of double-fed induction generator of wind turbine to optimize its production: that means the energy quality and efficiency. The proposed control reposes in the sliding mode control using a multimodel approach which contributes on the minimization of the static error and the chattering phenomenon. This new approach is called sliding mode multimodel control (SMMC). Simulation results show good performances of this control.**

**Keywords** – Sliding mode control, Multimodel approach, Chattering phenomenon, Stabilization.

## 1. Introduction

The sliding mode approach is classified in the monitoring with Variable System Structure (VSS) [1]. The sliding mode is strongly requested seen its facility of establishment, its robustness against the disturbances and models uncertainties. The principle of the sliding mode control is to force the system to converge towards a selected surface and then to evolve there in spite of uncertainties and the disturbances. The surface is defined by a set of relations between the state variables of the system. The sliding surface is defined according to the control objectives and to the wished performances in closed loop, the synthesis of the discontinuous control is carried out in order to force the trajectories of the system state to reach the sliding surface, and then, to evolve in spite of uncertainties, of parametric variations,...

First of all, in this case, we will be interested in the problem of the stabilizing control existence. Then we will give an outline for the state space stabilizing partition construction. For the systems controlled with a sliding mode control (SMC), the Lyapunov function is often requested [2]. This method is based on the linearization around the balance points and on linear systems per pieces. To determine the fields of stability, many theories established the fact that the system which trajectory is attracted towards a balance point loses energy gradually in a monotonous way. Lyapunov generalizes the concept of energy by using a candidate function  $V(X)$  which depends on the state of the system [3].

In this field, the multimodel approach represents an interesting alternative. This approach constitutes a powerful tool for the identification, the control and the analysis of the complex systems. The principle of the multimodel representation makes possible to design a non linear control composed by the linear controls associated with each model. The global control can be then deduced either by a fusion or by a commutation between the different partial controls. Here, the idea is to adopt the multimodel approach to improve the performances given by a first and high order sliding mode control (SMC) using several sliding surfaces. The multimodel approach thanks to the fusion theory can reduce the control discontinuity which minimise the chattering phenomenon.

This paper is organized in four parts: first we begin by modelling the electrical process (double feed asynchronous generator). Second, we introduce the Sliding Mode Multi-Model Control (SM-MMC) which combines the tow approaches: sliding mode and multimodel control and the stabilization conditions for this new type of control. Finally, we expose the simulation results.

## 2. Process Modeling

The double feed asynchronous generator is typically modeled in the Park benchmark in a (d-q) referential "direct-quadrature transformation" giving rise to the following equations (1, 2 and 3) [4-5].

The mechanical equations are written in (1) and (2).

$$J \frac{d\omega}{dt} = p \frac{L_m}{L} (i_{qs} \phi_{dr} - i_{ds} \phi_{qr}) - C_l - f_v \omega \quad (1)$$

$$T_e = p \frac{L_m}{L} (i_{qs} \phi_{dr} - i_{ds} \phi_{qr}) \quad (2)$$

with  $\omega$  the rotor angular velocity,  $J$  the inertia,  $p$  the pole number,  $C_l$  the torque and  $f_v$  the friction coefficient.

Now we can write the electromagnetic equations (3).

$$\begin{cases} \frac{d\phi_{dr}}{dt} = -b\phi_{dr} + ai_{ds} - \omega p\phi_{qr} \\ \frac{d\phi_{qr}}{dt} = -b\phi_{qr} + ai_{qs} - \omega p\phi_{dr} \\ \frac{di_{ds}}{dt} = -\gamma_4 V_{ds} - \gamma_1 i_{ds} - \gamma_2 \phi_{dr} + \gamma_3 \omega \phi_{qr} \\ \frac{di_{qs}}{dt} = -\gamma_4 V_{qs} - \gamma_1 i_{qs} - \gamma_2 \phi_{qr} - \gamma_3 \omega \phi_{dr} \end{cases} \quad (3)$$

with

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}, \quad \gamma_1 = \frac{R_s}{\sigma L_s} + \frac{R_r L_m^2}{\sigma L_s L_r^2}, \quad \gamma_2 = \frac{R_r L_m}{\sigma L_s L_r^2}$$

$$\gamma_3 = \frac{L_m}{\sigma L_s L_r} p, \quad \gamma_4 = \frac{1}{\sigma L_s}, \quad a = \frac{R_r}{L_r} L_m, \quad b = \frac{R_r}{L_r}$$

where,  $\phi_{dr}$ ,  $\phi_{qr}$  the rotor flux and  $i_{ds}$ ,  $i_{qs}$  the stator current. the state function of the generator could be written as follow:

$$\begin{cases} \dot{x}_f = ax_c + A_f(\omega)x_f \\ \dot{x}_c = -\gamma_1 x_c + B_c(\omega)x_f + \gamma_4 u \end{cases} \quad (4)$$

with,

$$A_f(\omega) = \begin{pmatrix} -b & -p\omega \\ p\omega & -b \end{pmatrix}, \quad B_c(\omega) = \begin{pmatrix} -\gamma_2 & \gamma_3\omega \\ -\gamma_3\omega & \gamma_2 \end{pmatrix}$$

### 3. Process Control Design

The SMC consist on bringing back the system state on the sliding surface where it will slide along it to the desired state. However, this approach needs a high level of discontinuous control which makes harmful effects on the actuators. This problem is known as the chattering phenomenon. As solution to this inconvenient, we suggest the high order SMC which consists in the sliding variable derivative computing. This method allows the rejection of the chattering phenomenon while preserving the robustness of the approach. In the case of second order sliding mode control, the following relation (5) and (6) must be verified [6-9].

$$s(x) = \dot{s}(x) = 0 \quad (5)$$

$$\dot{V} = \frac{1}{2} \frac{\partial}{\partial t} (s^2) = ss' \leq -\eta |s| \quad (6)$$

with  $\eta > 0$  and  $V$  the Lyapunov quadratic function.

The torque reference from the maximum power point tracking (MPPT) block has two challenges: maximizing the power and the management operation of the wind area. The ratio of power extracted from the wind and the total wind

power available theoretically has a maximum defined by the Betz limit. This limit is actually never reached and each turbine is defined by its own power coefficient as a function of the relative velocity representing the ratio between the speed of the turbine blade and the wind speed. The control of the double feed asynchronous generator of the turbine must be a compromise between maintaining the optimum performance at all times and to limit the torque oscillations engendered by this maximizing. The set of reactive power will remain null in order to keep a power factor on the stator side [10-18]. Consider the general state system (7).

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (7)$$

The sliding surface chosen as follow:

$$s = C\hat{x} \quad (8)$$

$$C = (c_1 \dots c_n); \quad c_i > 0, i = 1, \dots, n$$

with  $\hat{x} = x_d - x_r$

To carry out the system on the sliding surface  $s$ , we have to select a discontinuous control which commutates between two extremes values:  $u_s = -k \text{sign}(s)$ , with  $k > 0$ . When the system reaches the surface, the process control  $u$  is equal to the equivalent control  $u_{eq}$  (9).

$$\begin{aligned} \dot{s} &= C\dot{x} = CAx + CBu_{eq} \\ \Leftrightarrow u_{eq} &= -(CB)^{-1} CAx \end{aligned} \quad (9)$$

we conclude that the global control of the system considering the two phases (reaching the sliding surface and the sliding phase to the equilibrium state) is represented in (10).

$$u = -(CB)^{-1} CAx - k \text{sign}(s) \quad (10)$$

To ensure the system stability carried out by this control, we consider the Lyapunov candidate function  $v = \frac{1}{2} s^2$ ,  $\dot{v} = ss'$ ,

then we have to prove that  $\dot{v} < 0$ .

$$\dot{s} = C\dot{x} = CAx + CBu = -CBk \text{sign}(s)$$

to ensure  $\dot{v} < 0$ , we must have  $CBk > 0$ .

In fact, the control approach in which we interest to expose in this paper consists in carrying out a fusion on the sliding mode discontinuous control instead of commutations, as shown in Figure 1, in order to eliminate or minimize the chattering phenomenon.

To adapt the controlling process to each sub model, we think about using several sliding surfaces, each state of a sub model  $M_i$  is considered to reach one of these sliding surfaces  $s_i$

(Fig.1). To ensure the SMC existence, we use several switching control  $u_{si}$  (11) relative to each sliding surface  $s_i$ . After that the process will converge to the sum of those surfaces weighted by the correspondent validities  $v_i$  (12) and the global control will be obtained by adding the partials controls  $u_i$  (13) weighted by adapted validities computed on line (14).

$$u_{si} = \begin{cases} u_{si \min} & si \quad sign(s) < 0 \\ u_{si \max} & si \quad sign(s) > 0 \end{cases} \quad (11)$$

$$S = \sum_i v_i s_i \quad (12)$$

$$u_i = u_{ei} + u_{si} \quad (13)$$

$$u_g = \sum_{i=1}^N v_i u_i \quad (14)$$

with  $u_{ei}$  the equivalent control relative to each sliding surface.

The multimodel approach consists in representing a complex system with a number of simple linear model  $M_i$  ( $i=1, \dots, n$ ). Consider system (15).

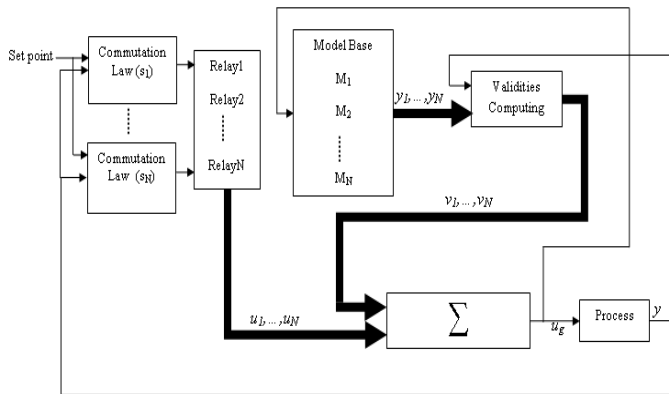
$$M_i = \begin{cases} \dot{x} = A_i x + B_i u \\ y = C_i x \end{cases} \quad (15)$$

The multimodel control in which we are interested consists in the fusion of partial controls. Hence, we have to compute the validities of each partial model and associate the sub controls weighted by the correspondent coefficients. The obtained result will control the global process (16). Then the system is represented by (17).

$$u(t) = \sum_{i=1}^N v_i(t) u_i(t) \quad (16)$$

$$\begin{cases} \dot{x} = \sum_{i=1}^n v_i (A_i x + B_i u) \\ y = \sum_{i=1}^n v_i C_i x \end{cases} \quad (17)$$

with  $v_i$  and  $v_i$ ,  $i=1, \dots, n$ , the correspondent validities.



**Fig.1** Sliding mode multimodel control structure

To reduce the chattering phenomenon, we will use the saturation function which gives:

$$u_i = \lambda \text{sat} \left( \frac{s_i}{\Omega} \right) \quad (18)$$

where,

$$u_i = \begin{cases} \lambda \text{sign}(s_i) & \text{if } |s_i| \geq \Omega \\ \lambda \left( \frac{s_i}{\Omega} \right) & \text{if } |s_i| \leq \Omega \end{cases} \quad (19)$$

with  $\lambda$  and  $\Omega > 0$ ,  $\Omega$  defines the boundary layer thickness.

#### 4. Sufficient conditions of stabilization for the SMMMC

When we adopt the fusion approach, the different sliding surfaces and the sub controls will be weighted by the correspondent validities and then added (20). To satisfy this condition, we choose a non quadratic function operating in  $S$  (21) and we have to verify that  $\dot{V}(s) < 0$ .

$$S = \sum_i \mu_i s_i \quad (20)$$

$$V(s) = \sum_{i=1}^m P_i s_i^2(x) \quad (21)$$

Noted that we use the fusion approach, the global process will be represented by (22).

$$\begin{cases} \dot{x} = \sum_{i=1}^n v_i (A_i x + B_i u + \varphi(x, u)) \\ y = \sum_{i=1}^n v_i C_i x \end{cases} \quad (22)$$

with

$$A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times m}, C = (c_1 \dots c_n); \quad c_i > 0, i=1, \dots, n$$

and  $\varphi(x, u)$  the nonlinear part (23).

$$\varphi(x, u) = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ \varphi_n \end{pmatrix}; \quad \|\varphi(x, u)\| < Mx \quad (23)$$

**Theorem:** The SM-MMC stabilizes the system (22) if it fulfils the two conditions:

i)

$$\begin{cases} k_i > (B\alpha_i)^{-1} (A_i + MI) \\ u = -\sum_i \left( (v_i B\alpha_i)^{-1} (A_i + MI) x \right) - \varepsilon \end{cases} \quad (24)$$

with  $0 < \mu_i, v_i < 1$ ,  $\alpha_i$  a linear vector and  $\varepsilon > 0$ .

$$ii) \begin{cases} P_{n-1} > 0 \\ (A_{n-1}^i - B_{n-1}^i L_{n-1}^i)^T P_{n-1} + P_{n-1} (A_{n-1}^i - B_{n-1}^i L_{n-1}^i) < 0 \end{cases} \quad (25)$$

*Proof-Theorem:*

i) In the convergence phase we have to verify the condition  $S\dot{S} < 0$  using a switching control  $u_s = -KS$  with

$$K = \sum_i \mu_i k_i.$$

$$\text{Equation (21) gives } \dot{V}(s) = \sum_{i=1}^m 2P_i s_i \dot{s}_i$$

Consider that  $s_i(x) = \alpha_i x$

$\dot{s}_i(x) = \alpha_i \dot{x}$  we will have:

$$\dot{s}_i(x) = \alpha_i A_i x + \alpha_i B_i u_i + \alpha_i \varphi(x, u)$$

$$s_i \dot{s}_i = x^T \alpha_i^T \alpha_i A_i x + x^T \alpha_i^T \alpha_i B_i u + x^T \alpha_i^T \alpha_i \varphi(x, u)$$

we use the fact that :

$$\varphi(x, u) < Mx \text{ and } u_{s_i} = -k_i |s_i| \text{sign}(s_i) = -k_i s_i$$

$$\Rightarrow s_i \dot{s}_i < x^T (\alpha_i^T \alpha_i A_i - \alpha_i^T \alpha_i B_i k_i \alpha_i + \alpha_i^T \alpha_i M I) x$$

$$s_i \dot{s}_i < 0 \Rightarrow A_i - B_i k_i \alpha_i + M I < 0 \Rightarrow k_i > (B_i \alpha_i)^{-1} (A_i + M I)$$

after fusion:

$$K > \sum_i \mu_i \left( (B_i \alpha_i)^{-1} (A_i + M I) \right)$$

The explicit form of the control that make the system reach the sliding surface  $S$  is given by the following equation (26).

$$u_i = -(\mu_i B_i \alpha_i)^{-1} (A_i + M I) x - \varepsilon \quad (26)$$

Consider the non quadratic function operating in  $s$  (22):

$$V(s) = \sum_{i=1}^m P_i s_i^2(x) \Rightarrow \dot{V}(s) = \sum_i 2P_i s_i \dot{s}_i$$

$$\dot{V}(s) = \sum_i 2P_i (x^T \alpha_i^T \alpha_i A_i x + x^T \alpha_i^T \alpha_i B_i u + x^T \alpha_i^T \alpha_i \varphi(x, u))$$

$$\dot{V}(s) < \sum_i 2P_i x^T \alpha_i^T \alpha_i (A_i x + B_i \mu_i u_i + Mx)$$

then,

$$\dot{V}(s) < 0 \Rightarrow A_i x + B_i \mu_i \alpha_i u_i + Mx < 0$$

$$\Leftrightarrow u_i < -(\mu_i B_i \alpha_i)^{-1} (A_i + M I) x$$

$$\Leftrightarrow u_i = -(\nu_i B_i \alpha_i)^{-1} (A_i + M I) x - \varepsilon$$

In this way, the global control is written as follow:

$$u = -\sum_i \left( (\nu_i B_i \alpha_i)^{-1} (A_i + M I) x \right) - \varepsilon$$

ii) In the reaching phase, we choose a non quadratic Lyapunov function :

$$V(x_{n-1}) = \sum_i x_{n-1}^T P_{n-1} x_{n-1}$$

$$\dot{V}(x_{n-1}) = \sum_i \left( \dot{x}_{n-1}^T P_{n-1} x_{n-1} + x_{n-1}^T P_{n-1} \dot{x}_{n-1} \right)$$

So  $\dot{x}_{n-1}^T P_{n-1} x_{n-1} + x_{n-1}^T P_{n-1} \dot{x}_{n-1} < 0$  when  $\dot{V}(x_{n-1}) < 0$ .

## 5. Simulation Results and Discussion

Simulations results are illustrated in figures 2 to 8. In this simulation, we consider that the process is controlled only with the discontinuous control  $u = u_s$ . Simulation is accomplished thanks to the software MATLAB V6.5.

Figure 2 shows that, with a first order sliding mode control (SMC1) we cannot reach the torque desired value and the control level ( $u = \pm 3$ ) and its switching frequency are high (Figure 3). In addition, we notice that the reaching phase presents commutations known as chattering phenomenon. However, the second order sliding mode control (SMC2) reduces considerably the chattering phenomenon (Figure 4) but the level of the control is always high ( $u = \pm 3$ ) and its commutation frequency is even higher (Figure 5). As a solution to this problem, we apply the SMMC which sliding surface defined in (20). To reach the sliding surface and to converge to zeros, we choose  $\phi = 2$  and  $\lambda = 1$ . The simulation results of this approach are given in Figure 6 to 8. We notice that the system error converges to zero (Figure 6) and that we have reduced considerably the chattering effect relatively to the two last approaches simulated in this paper. Other ways, we notice that the control level (Figure 7) has little commutation in the beginning of the system evolution then it stabilizes in ( $u = 0.2$ ) after a period of time ( $\sim 50s$ ).

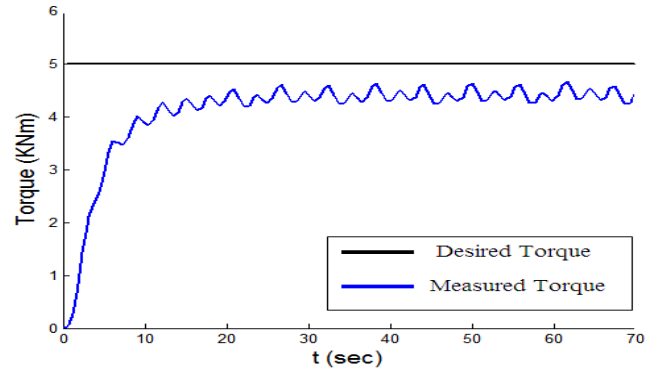


Fig.2 Torque evolutions by SMC1

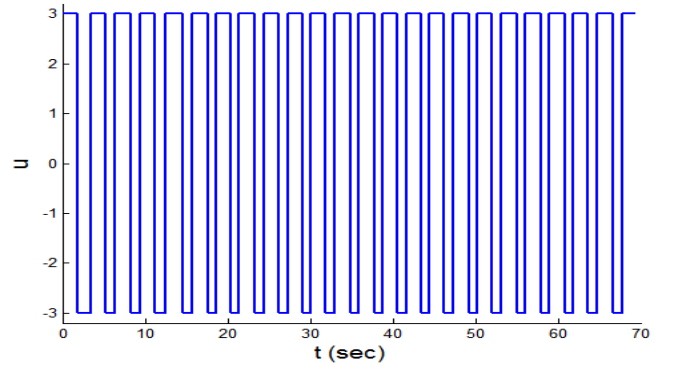


Fig.3 Control evolutions by SMC1

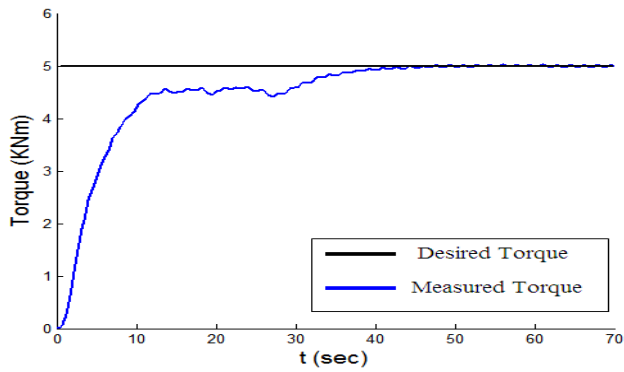


Fig.5 Torque evolutions by SMC2

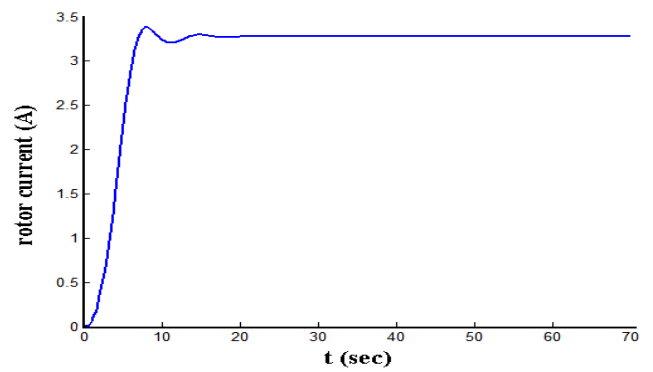


Fig.8 Current evolutions by SMMC

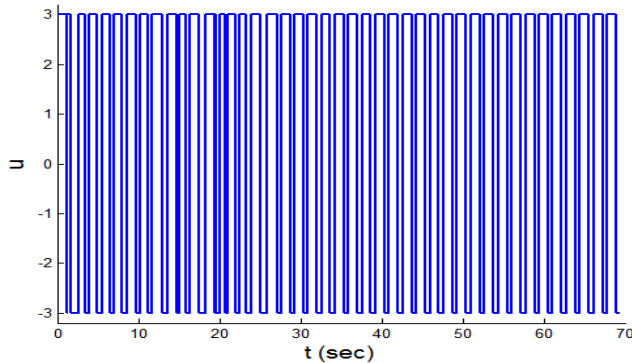


Fig.5 Control evolutions by SMC2

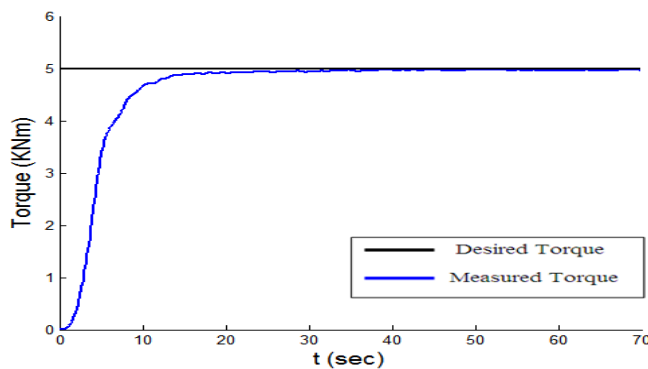


Fig.6 Torque evolutions by SMMC

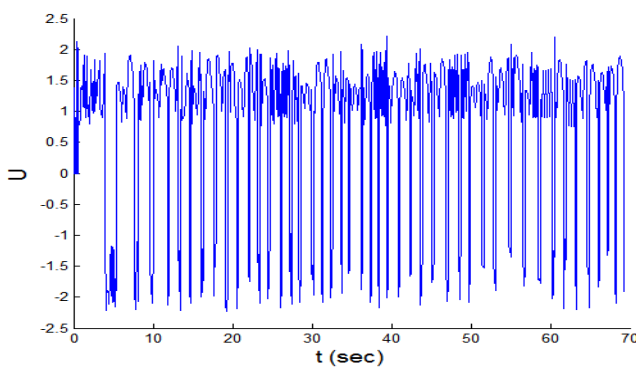


Fig.7 Control evolutions by SMMC

## 6. Conclusion

In this work, a new type of controller have been presented, detailed and justified by simulation results. We approached the synthesis method of a control law by sliding mode using a nonlinear sliding surface. In the first time, we presented the class and the properties of this sliding surface adopted. Then, a sliding mode control using the sliding surface developed together with stability studies were elaborated. After that, to reduce the static error, a sliding mode multimodel control has been developed and simulated. This last approach show very effective qualities of control and robustness especially in term of the control level reduction and the sliding mode discontinuous control minimization.

## 7. References

- [1] S. Singaravelu , S. Velusami, «Capacitive VAR requirements for wind driven self-excited induction generators », *Energy conversion and management*, pp. 1-16, 2006.
- [2] Vedrana Spudic, Mate Jelavic, Mato Baotic, " Wind Turbine Power References in Coordinated Control of Wind Farms", *AUTOMATIKA*, vol. 52, pp.82-94, 2011.
- [3] Badrul H. Chowdhury , Srinivas Chellapilla, "Double-fed induction generator control for variable speed wind power generation », *Energy conversion and management*, pp. 786-800, 2005.
- [4] Jamal A. Baroudi, Venkata Dinavahi , Andrew M. Knight, "A review of power converter topologies for wind generators", *Renewable Energy*, pp. 2369–2385, 2007.
- [5] B. Boukhezzara, L. Lupua, H. Siguerdidjanea, M. Hand, "Multivariable control strategy for variable speed, variable pitch wind turbines", *Renewable Energy*, pp. 1273–1287, 2007.
- [6] A.Rhif, " Position Control Review for a Photovoltaic System: Dual Axis Sun Tracker", *IETE Technical Review*, Vol. 28, pp. 479-485, 2011.

- [7] A.Rhif, Z.Kardous, N.Ben Hadj Braiek, "A high order sliding mode-multimodel control of non linear system simulation on a submarine mobile", *International Multi-Conference on Systems, Signals & Devices, Sousse, Tunisia, March 2011*.
- [8] A.Rhif," A Review Note for Position Control of an Autonomous Underwater Vehicle", ", *IETE Technical Review*, Vol. 28, pp. 486-493, 2011.
- [9] Z.Kardous, N.Ben Hadj Braiek, P.Borne, A.El Kamel, "On the multimodel stabilizing control of uncertain systems. Multimodel control and validity analysis," *International journal problems of non linear analysis of non linear system*, Vol 26, 2006.
- [10] A.Rhif & Y.Saoudi, K.Bouallegue, "A PID-Sliding Mode Control Synthesis: Application on an Hydraulic Plant", *International Conference on Modeling, Simulation and Applied Optimization*, Hammamet, 2013.
- [11] N.Petrellis, N.Konofaos, G.Ph.Alexiou, "Estimation of a target position based on infrared pattern reception quality", *IETE Technical Review*, pp. 36-45, Vol. 27, 2010.
- [12] C .Hua, C.Shen, "Comparative Study of Peak Power Tracking Techniques for Solar Storage System", *IEEE Applied Power Electronics Conference and Exposition*, USA, Feb. 15-19, 1998.
- [13] Igor Erceg, Gorislav Erceg, Damir Sumina, "Development and Implementation of Control Algorithms for Synchronous Generator", *AUTOMATIKA*, vol. 52, pp.95-106, 2011.
- [14] A.Rhif, Z.Kardous, N.Ben Hadj Braiek, "A High Order Sliding Mode Observer: Torpedo Guidance Application," *Journal of Engineering & Technology*, vol. 2, pp.13-18, 2012.
- [15] F. Boudjema and J.L. Abatut, "Sliding-Mode : A new way to control series resonant converters," *IEEE Conf. Ind. Electron. Society*, pp. 938-943, 1990.
- [16] A.Rhif, Z.Kardous, N.Ben Hadj Braiek, "A sliding mode multimodel control for a sensorless photovoltaic system", *Journal of Scientific and Industrial Research*, Vol.71, pp.418-424, 2012.
- [17] M.Wöllmer , M.Al-Hames, F.Eyben, B.Schuller, G.Rigoll "A multidimensional dynamic time warping algorithm for efficient multimodel fusion of asynchronous data streams," *Neurocomputing, Elsevier*, Vol. 73, pp. 366-380, May 2009.
- [18] A.Rhif & Y.Saoudi, K.Bouallegue, "A Sliding Mode Observer for a Sensorless Pumping System", *International Conference on Modeling, Simulation and Applied Optimization*, Hammamet, 2013.