# Fractional Second Order Sliding Mode Controller for The Control of Wind Generator Based on a DFIG

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***Abstract:*** In order to reduce the chattering phenomena in the conventional sliding mode controller, which appears mostly in the rotor currents of doubly fed indication generator (DFIG), a new Fractional Second Order Sliding Mode Controller is proposed. In this controller, the sliding surfaces are chosen so that they will be compatible with the errors in the rotor currents. The simulation results, show the robustness of the proposed control model, the minimization of the chattering and they improve the total harmonics distortion of the rotor currents.

***Keywords***: Doubly fed induction generator, Wind turbine, Rotor side converter, Fractional Second Order Sliding Mode controller, Total harmonics distortion,

## 1. Introduction

In today's human survival and development, energy and environment are the pressing problems to be solved. Wind power, as one source of inexhaustible, clean and pollution-free power, it is prospective of large-scale development and utilization, and is to an effective form by harnessing the wind. At present, the main power generation system of wind driven generator is VSCF (Variable Speed Constant Frequency) wind power generation system for grid.

For the wind energy conversion systems (WECSs) connected to the grid, the doubly fed induction generators received an important consideration compared to other generators types [1-2], due especially to the static converter size, and the wide speed range. Due to several functionalities, the DFIG active and reactive stator powers control is required [1 - 7]. In order to deliver a constant frequency in the DFIG stator, under changing the mechanical speed or wind speed conditions, the rotor of this generator must feeding with variable frequency, where, the control algorithm law of the rotor side converter (RSC) can be applied as shown in Figure 1.

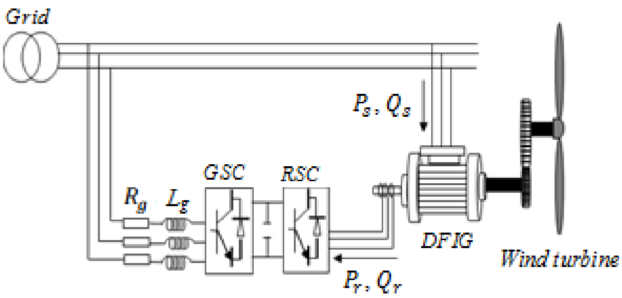


Figure 1: The general structure of a double fed wind generator.

The sliding mode control has received much attention in the field of electrical drives control [8 - 10]. In this method, the response of control system depends only on the sliding surface.

Despite the robustness of this control, the sliding mode control faces the main problem of the chattering phenomenon resulting by the discontinuous control. Various approaches, such as in [11 – 20], have been proposed recently to avoid chattering in the currents, powers and the electromagnetic torque of the electric generators. In this paper, we propose a novel control strategy of the rotor side converter based on the Fractional Second Order Sliding Mode Controller, where, we present another solution to reduce the chattering phenomenon in the conventional sliding mode.

The maximization of the power with speed control, using the proportional integral (PI) regulator, is applied to determinate the optimal values of the reference of the active power used in the stator power control loop.

## 2. Basic definitions of fractional order calculus:

The two most used definitions for the general fractional differentiation and integration are the Grunwald-Letnikov(GL) the Riemann-Liouville (RL) definition.

The Grunwald-Letnikov is given by:

$$\alpha D_t^{\alpha} f(t) = \lim_{h\to 0} \frac{1}{h^{\alpha}} \sum_{j=0}^{\left[\frac{t-a}{h}\right]} (-1)^j \binom{\alpha}{j} f(t-jh) \qquad (1)$$

where h is increment

[.] means the integer part and

The Riemann-Liouville (RL) is given by:

$$\alpha D_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\lambda)} \frac{d^n}{dt^n} \int_{\alpha}^{t} \frac{f(\tau)}{(t-\tau)^{(\lambda-n+1)}} d\tau \qquad (2)$$

where n-1< $\lambda$< n and $\Gamma(.)$ is the Gamma function .

the Laplace transformation of RL definition for a fractional order λ is given by

$$L\{\alpha D_t^{\alpha} f(t)\} = s^{\lambda} F(s) \qquad (3)$$

where the *F(s)* is the Laplace transformation of *f(t).*

## 3. Wind Turbine Modeling:

The mechanical power obtained from the wind is given by the following expression [20 – 21]:

$$V_{dr} = R_r.i_{dr} + s.L_r.\sigma.i_{dr} - g.\omega_s.L_r.i_{qr}.\sigma$$

$$V_{qr} = R_r.i_{qr} + s.L_r.\sigma.i_{qr} + g.\omega_s L_r.i_{dr}.\sigma + \frac{g.M.v_s}{L_s}$$

$$P_a = C_P.P_{vent} = C_P(\lambda,\beta).\frac{\rho.\pi.R^2.{V_{vent}}^3}{2} \qquad (4)$$

$$C_P = 0.5 - 0.167.(\beta-2).\sin\left[\frac{\pi.(\lambda+0.1)}{(18.5-0.3.\beta)}\right] - 0.00184.(\lambda-3).(\beta-2) \qquad (5)$$

## 4. Maximum Power Point Tracking

The ($C_P = 0.5$ ) is reached at tip speed ratio (λ = 9) and at β constant and equal to two degrees (β = 2°), the mechanical speed is controlled by the proportional integral controller. Where, the reference rotor speed is given by the following formula:

$$\Omega^* = \frac{\boldsymbol{\lambda(C_{P\,max}).W_{speed}}}{\mathbf{R}} \qquad (6)$$

## 5. The Doubly Fed Induction Generator:

The generator dynamics model is given by the following equations system:

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\emptyset_{ds}}{dt} - \omega_s \emptyset_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\emptyset_{qs}}{dt} + \omega_s \emptyset_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d\emptyset_{dr}}{dt} - (\omega_s - \omega)\emptyset_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\emptyset_{qr}}{dt} + (\omega_s - \omega)\emptyset_{dr} \end{cases} \qquad (7)$$

Where

$$\begin{cases} \emptyset_{ds} = L_S.i_{ds} + M.i_{dr} \\ \emptyset_{qs} = L_S.i_{qs} + Mi_{qr} \\ \emptyset_{dr} = L_r.i_{dr} + M.i_{ds} \\ \emptyset_{qr} = L_r.i_{qr} + M.i_{qs} \end{cases} \qquad (8)$$

And the mechanical model of the doubly fed indication generator will be given by the following expression:

$$C_e - C_r = J\frac{d\Omega}{dt} + f\Omega \qquad (9)$$

## 6. A Fractional Second Order Sliding Mode Controller Design:

The fractional order sliding surfaces are:

$$S(i_{dr}) = e_1 + c_d.D^{-1}.e_1 \qquad (10)$$

$$S(i_{qr}) = e_2 + c_q.D^{-1}.e_2 \qquad (11)$$

$$S = \left[ S(i_{dr}) \quad S(i_{qr}) \right]$$

We define the rotor currents errors, respectively, as follow:e$_1$ = ($i_{dr}^*$–$i_{dr}$) and e$_2$ = ($i_{qr}^* - i_{qr}$), where the $i_{dr}^*$ and $i_{qr}^*$ are, respectively.

where the rotor volage can be written as follow:

The nonlineare state space model is given under the form:

$$\dot{x} = f(x) + gV_r \qquad (12)$$

where

$$V_r = \left[V_{dr} \quad V_{qr}\right]^T$$

$$x = \left[\, i_{dr} \quad i_{qr}\right]^{\mathrm{T}}$$

where α represents order of fractional operator, cd, cq are positive tuning parameters.

The main condition in the sliding mode is achieving the following equality:

$$\frac{dS(i_{dr})}{dt} = \frac{dS(i_{qr})}{dt} = 0$$

So:

$$\dot{S} = \begin{bmatrix} S(\dot{i}_{dr}) \\ S(\dot{i}_{qr}) \end{bmatrix} = \begin{bmatrix} \dot{e}_1 + c_d.D^{1-\alpha}.e_1 \\ \dot{e}_2 + c_q.D^{1-\alpha}.e_2 \end{bmatrix} \qquad (13)$$

And the rotor controlled voltage may be derived according to the control law:

$$V_{dr} = V_{dr\,ST} + V_{dr\,eq} \qquad (14)$$

$$V_{qr} = V_{qr\,ST} + V_{qr\,eq} \qquad (15)$$

$$V_{eq}{}^{d,q} = g^{-1}\left[-f(x) + x^{*} - k.sgn - \begin{bmatrix} c_d.D^{1-\alpha}.e_1 \\ c_q.D^{1-\alpha}.e_2 \end{bmatrix}\right]$$

where

$k = [k_1 \quad k_2]^T$ are the positive control gains.

- ✓ **The super- twisting algorithm:**

The super-twisting algorithm (STA), has been adopted given by:

$$\begin{cases} STA(e_1) = \delta_q |e_1|^{(1/2)} sgn(e_1) - w_q \int sgn\,(e_1)dt \\ \\ STA(e_2) = \delta_d |e_2|^{(1/2)} sgn(e_2) - w_d \int sgn\,(e_2)dt \end{cases}$$

(16)

where $\delta_d$, $\delta_q$, $w_d$ and $w_q$ are the positive control gains, The function *sgn*, equations(14) and (15),will be will be substituted by a STA,

## 7. Simulation Studies

Results of simulation studies, performed using MATLAB software, in response to the change of wind speed as shown in Figure 2, are described in this Section.

The DFIG - wind turbine system parameters are given Table 1.

Table I: The DFIG - wind turbine system parameters.

| Parameters | **Units** | **Value** |
|---|---|---|
| The nominal power | [MW] | 1.5 |
| The stator voltage | [V] | 690 |
| The stator frequency | [Hz] | 50 |
| The number of poles pairs | [ ] | 2 |
| The stator resistance | [Ω] | 0.012 |
| The rotor resistance | [Ω] | 0.021 |
| The stator inductance | [H] | 0.0137 |
| The rotor inductance | [H] | 0.0136 |
| The mutual inductance | [H] | 0.0135 |
| The inertia | [Kg.m²] | 1000 |
| The friction coefficient | [N.m.s/rad] | 0.0024 |
| The tip speed ratio max | [ ] | 9 |
| The power coefficient $C_{P\,max}$ | [ ] | 0.5 |
| The radius of the wind | [m] | 35.25 |
| The gain multiplier | [ ] | 90 |
| The air density | [kg/m3] | 1.225 |

The DFIG- wind turbine system tracks the maximum power point as the wind speed changes. It is confirmed from Figure 3 where the power coefficient follows its optimal reference and is equal to 0.5. Similarly, the BDFIG control system ensures that the optimal constant tip speed ratio value, equal to 9, is maintained as shown in Figure 4. It is evident from Figure 5 that the mechanical speed tracks its optimal reference almost perfectly.

Response of the DFIG, Figures 6 and 7, shows that the active and reactive powers reach their optimally values. Neglecting the starting transients in the first 0.5 s, a good dynamic performance is clearly achieved as there is minimum overshoot in the powers around their desired values in the transitory regime and the response time is practically negligible. It is observed from Figures 8 and 9 that the two components of the rotor currents reach their reference values in a negligible response time and a low overshoot. It is also seen from Figure 9 that the quadrature components of current keep track of the wind speed profile, while it is clearly in the same figure that the optimal values of the quadrature component of the rotor currents is obtained through the controlling of the DFIG- wind turbine system under the maximizing the power in the system.

Total harmonic distortion of the rotor currents with Fractional Second Order Sliding Mode Controller is proposed is illustrated in Figure 11. THD is equal to 1.4% indicating that the harmonic content of the rotor currents is very small. It is also seen from the rotor currents that there is no chattering phenomenon. The DFIG electromagnetic torque, depicted in Figure 12, is the image of the wind profile.

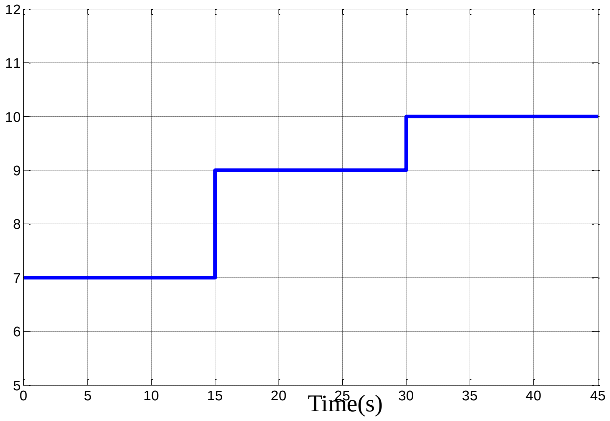


*Figure. 2 :* The wind speed applied to wind turbine.

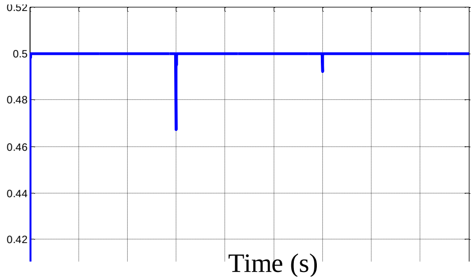


*Figure .3 :* The power coefficient $C_P$.

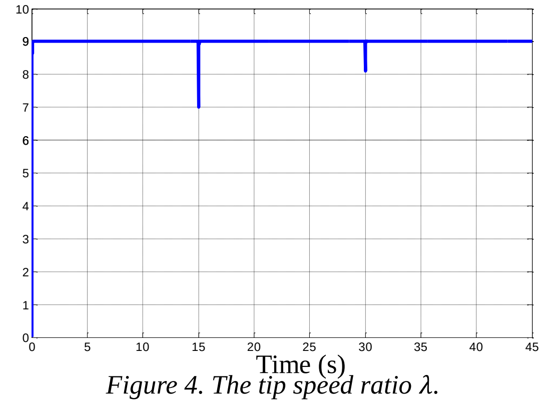


*Figure 4. The tip speed ratio λ.*

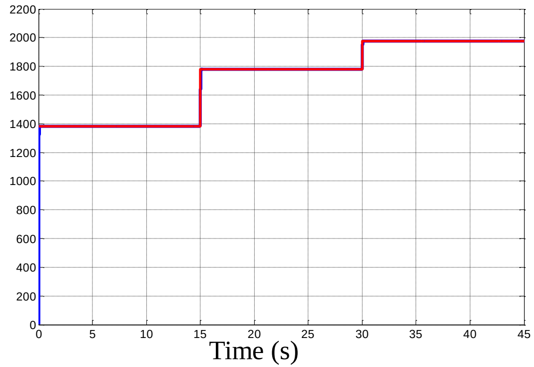


*Figure.5* The mechanical speed and its reference (rpn/min).

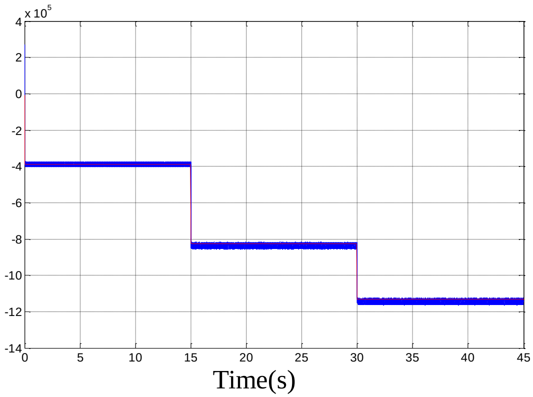


*Figure.6 The stator active power[W]*

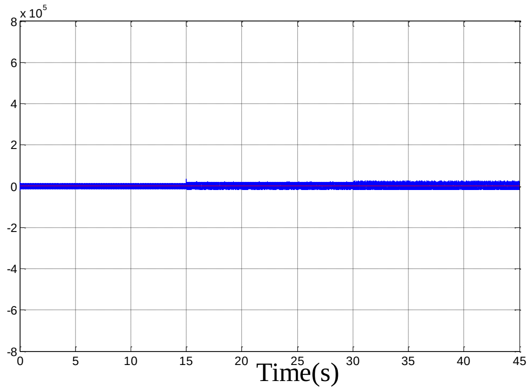


*Figure.7 The stator active power[VAR].*

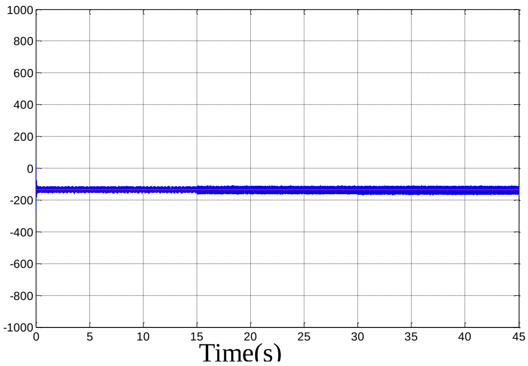


*Figure.8. The direct component of the rotor currents[A].*

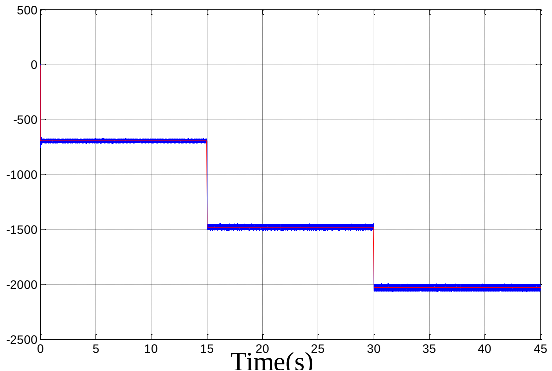


*Figure.9. The quadrature component of the rotor currents[A].*

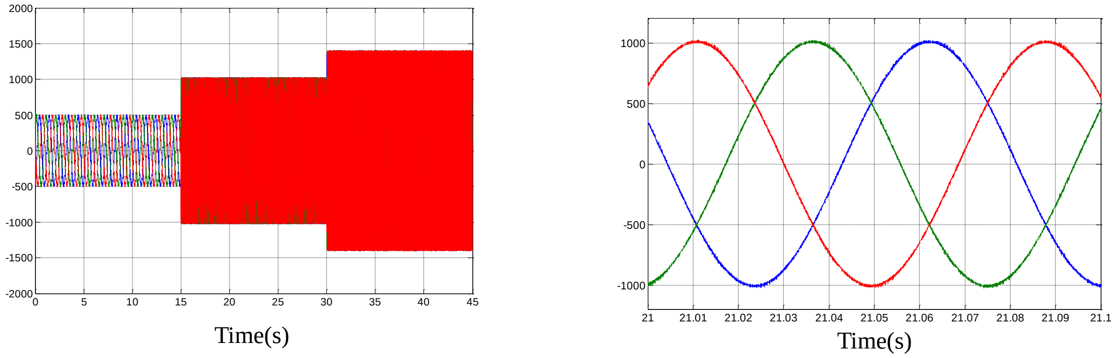
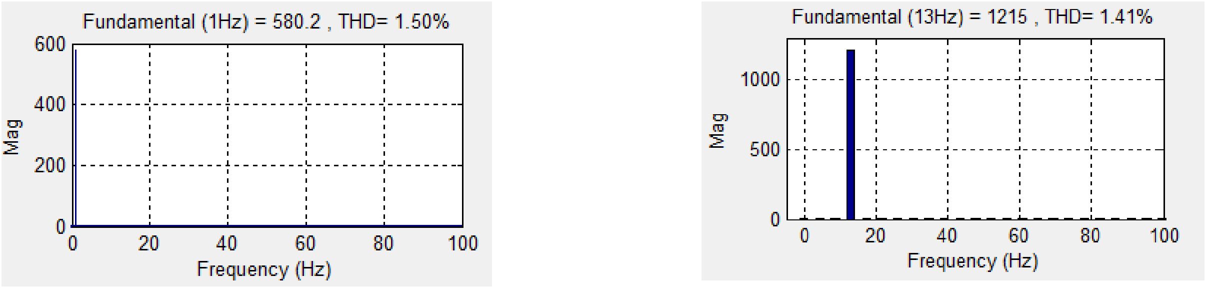


*Figure.10 the rotor currents with his zoom.*



*(a)with  v= 7m/s*     *(b) with  v= 9m/s*

*Figure.11 Total harmonic distortion of the rotor currents.*

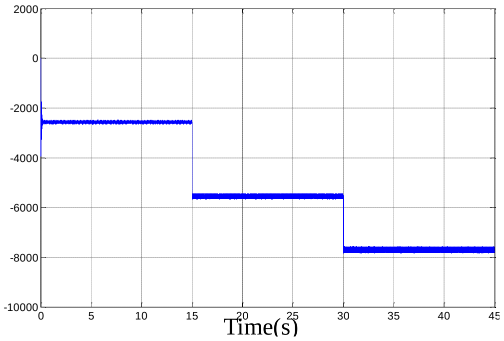


*Figure 12 : The electromagnetic torque.*

## 8. Conclusion:

A fractional second order sliding mode controller for indirect power control of a DFIG - wind turbine system is proposed in this work. As a consequence, the chattering phenomenon, which appears in the generator torque and currents, is avoided. The simulation results given by the proposed model show that the stator active and reactive powers follow perfectly the reference values with zero steady state error.

**References**

[1] Beltran B., Benbouzid M.E.H., Ahmed Ali.T., “Second order sliding mode control of a doubly fed induction generator driven wind turbine”, IEEE Transactions on Energy Conversion. Vol. 27, No. 2, pp. 261-269, 2012.

[2] Benbouzid M.E.H., Beltran B., Amirat Y., Yao G., Han J. and Mangel H., “Second order sliding mode control for DFIG based wind turbines fault ride through capability enhancement”, *ISA transactions, Vol. 53, No. 3, pp. 827-833, 2014.*

[3] Djurovic M., Joksimovic G., “Optimal performance of double fed induction generator in windmills”, *Renewable Energy, Vol. 9, pp. 862– 865, 1996.*

[4] Pena R. S., Clare J. C., Asher G. M., “Vector control of a variable speed doubly fed induction machine for wind generation systems” *EPE Journal, Vol. 6, no. 3-4, pp. 60-67, Dec. 1996.*

[5] Rifai M. B., Ortmeyer T. H., “Dynamic analysis of a doubly fed generator in power system applications”, *Electric machines and power systems, Vol. 21, no.1, pp. 141-150,1993.*

[6] Atkinson D. J., Lakin R. A., Jones R., “A vector controlled doubly-fed induction generator for a variable speed wind turbine application”, *Transactions of the Institute of Measurement and Control, Vol. 19, No. 1, pp. 2-12, 1997.*

[7] Boukhezzar B., Houria S., “Nonlinear control with wind estimation of a DFIG variable speed wind turbine for power capture optimization”, *Energy Conversion and Management, Vol. 50, No. 4, pp. 885-892, 2009.*

[8] Hu J, et al. “Direct active and reactive power regulation of DFIG using sliding mode control approach”, *Energy Conversion, IEEE Transactions, Vol. 25, No. 4, pp. 1028-1039, 2010.*

[9] Jeong H.G, et al., “A sliding mode approach to control the active and reactive powers for a DFIG in wind turbines”, The international conference on *Power Electronics Specialists (PESC), in Rhodes, 15-19 June 2008, pp. 120 – 125 IEEE.*

[10] Martinez M.I., Ana S., Tapia G., “Sliding Mode Control for DFIG Rotor and Grid Side Converters Under Unbalanced and Harmonically Distorted Grid Voltage”, *IEEE Transactions on Energy Conversion. Vol. 27, No. 2, pp. 328-339, 2012.*

[11] Ruiz-Cruz R., Edgar N.S., and Alexander G.L., “Real time sliding mode control with neural networks for a doubly fed induction generator”, *The 52nd international conference on Decision and Control (CDC),in Firenze, 10-13 Dec 2013, pp. 6786-6791, IEEE.*

[12] Kairous D., Wamkeue R., “DFIG based fuzzy sliding mode control of WECS with a flywheel energy storage”, *Electric Power Systems Research, Vol. 93, pp.* 16-23*, 2012.*

[13] Benbouzid M.E.H., “*High Order Sliding Mode Control of DFIG-Based Wind Turbines, Wind Turbine Control and Monitoring*”, *Chap. 2, p. 23-48, ISBN 978-3-319-08421-1, Advances in Industrial Control, Springer, 2014.*

[14] Ana S., Martinez M.I., Zubia I. and Tapia G., “Design and tuning of fixed switching frequency second order sliding mode controller for doubly fed induction generator power control”, *IET electric power applications, Vol. 6, No. 9, pp. 696-706, 2012.*

[15] Evangelista C., Valenciaga F. and Puleston P., “Active and reactive power control for wind turbine based on a MIMO 2 sliding mode algorithm with variable gains”, *IEEE Transactions on Energy Conversion, Vol. 28, No. 3, pp.* 682-689*, 2013.*

[16] Valenciaga F., “Second order sliding power control for a variable speed-constant frequency energy conversion system”, *Energy Conversion and Management, Vol. 51, No. 12, pp.* 3000-3008*, 2010.*

[17] Evangelista C. A., Valenciaga F., Puleston P., “Multivariable double sliding mode control for a wind energy system based on a double fed induction generator”, *international journal of hydrogen energy, Vol. 37, No.13, pp.* 10070-10075*, 2012.*

[18] Kassem A.M., Hasaneen K.M., Yousef A.M., “Dynamic modeling and robust power control of DFIG driven by wind turbine at infinite grid”, *International Journal of Electrical Power and Energy Systems. Vol. 44, No. 01, pp. 375-382, 2013.*

[19] Weng Y. T., Hsu Y. Y., “Sliding mode regulator for maximum power tracking and copper loss minimization of a doubly fed induction generator”, *Renewable Power Generation, Vol. 9, No. 04, pp.* 297-305*, 2014.*

[20] TRIA Fatma Zahra, et al.,“An Hybrid Control Based on Fuzzy Logic and a Second Order Sliding Mode for MPPT in Wind Energy Conversion Systems”, International Journal on Electrical Engineering & Informatics,Vol. 8(4),2016.

[21] Tria F. Z., et al. "An integral sliding mode controller with super-twisting algorithm for direct power control of wind generator based on a doubly fed induction generator." International Journal of System Assurance Engineering and Management 8.4 (2017): 762-769.