

A NEW ROBUSTE CONTROL BASED ON SUPER TWISTING SLIDING MODE OF A DUAL STAR INDUCTION GENERATOR FOR WIND TURBINE

Housseyn. KAHAL Rachid. TALEB Zinelaabidine. BOUDJEMA Abdelkader. BOUYEKNI

Laboratoire Génie Electrique et Energies Renouvelables (LGEER), Electrical Engineering Department,
Hassiba Benbouali University, Chlef, Algeria.

h.kahal@yahoo.fr

r.taleb@univ-chlef.dz

boudjema1983@yahoo.fr

a.bouyekni@univ-chlef.dz

Abstract— Traditional field oriented control using proportional integral (PI) regulator for the voltage DSIGs driven have many disadvantages such parameter tuning complication, mediocre dynamic performances and reduced robustness. Therefore, based on a d - q model of the DSIG supplied by two AC-DC converters, this article proposes an advanced control scheme based on super-twisting sliding mode (STSMC). The usual sliding mode control (SMC) has large chattering on the DC voltage result on the exit of the two rectifiers. With the purpose to solve this problem, the super twisting sliding mode control is used. The simulation results show the advantage of the proposed method in the efficiency and robustness against parameters variation of the DSIG.

Keywords—Dual star induction generator (DSIG), super twisting sliding mode control(STSMC), field oriented control, PWM rectifier.

1. Introduction

In the last years, wind energy as the most widely utilized renewable resources and has been installed all over the world [2]. The reason is that the energy it produces does not cause greenhouse gases or other pollutants. Modern wind turbines use advanced power electronics to provide efficient generator control and to ensure compatible operation with the power system [1].

There are many wind generator technologies, among which the dual star induction generator (DSIG). The DSIG has a stator winding more than the ordinary induction generator; they are spatially shifted by 30 electrical degrees with isolated neutral points. Thus the state equations become more complicated as well as the coupling among the state variables. This paper concentrates on the mathematical model of DSIG whose stator windings are tight coupled. A simplified DSIG model is given as well.

In the past years the control strategy of a variable-structure using the sliding mode control (SMC) has been the subject of many studies and researches for machine control, The sliding mode control system advantage is that the controller is switched between two various control structures[19].

Though, this kind of control has an essential flaw, which is the chattering phenomenon produced by the discontinuous control action. To fix these difficulties, several Amendments to the original SMC law have been suggested, the most important being the boundary layer approach [20].

One manner to enhance SMC performance is to use a super twisting sliding mode controller (STSMC).

This paper is structured as follows. Modeling of the dual star induction and the vector control strategy (Fields and voltages equations is given and electromagnetic torque the expression) are shown in Section 2. The field oriented control (FOC) of a DSIG is presented in Section 3. The super twisting sliding mode control is developed in Section 4. The scheme presented in Fig. 2 and 4 are used for numerical simulation and the associated results are presented. Finally, the conclusions of this work are drawn.

2. Mathematecal model of the DSIG

The representation of the DSIG in the graduation Park is given in the following equivalent schemes.

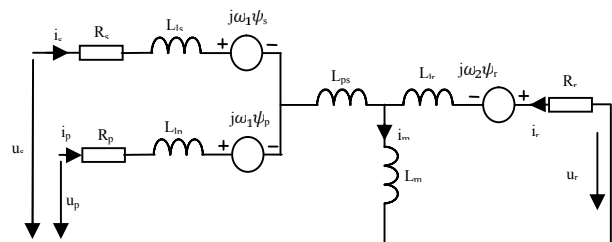


Fig.1. The d - q equivalent circuit of the DSIG

A. The voltages equations

The expressions of the stator and rotor voltage are defined by the following equation system:

$$\begin{cases} v_d = -R_s i_d + \frac{d}{dt} \phi_d - \omega_s \phi_q \\ v_q = -R_s i_q + \frac{d}{dt} \phi_q + \omega_s \phi_d \\ v_d = -R_s i_d + \frac{d}{dt} \phi_d - \omega_s \phi_q \\ v_q = -R_s i_q + \frac{d}{dt} \phi_q + \omega_s \phi_d \\ 0 = R_r i_d + \frac{d}{dt} \phi_d - (\omega_s - \omega_r) \phi_q \\ 0 = R_r i_q + \frac{d}{dt} \phi_q + (\omega_s - \omega_r) \phi_d \end{cases} \quad (1)$$

B. The flux equations

The expressions of the stator and rotor flux are defined by the following equation system:

$$\begin{cases} \phi_{d1} = -l_{s1} i_{d1} - l_m (i_{d1} + i_{d2}) + L_m (-i_{d1} - i_{d2} + i_d) - L_d i_{q2} \\ \phi_{q1} = -l_{s1} i_{q1} - l_m (i_{q1} + i_{q2}) + L_m (-i_{q1} - i_{q2} + i_q) + L_d i_{d2} \\ \phi_{d2} = -l_{s2} i_{d2} - l_m (i_{d1} + i_{d2}) + L_m (-i_{d1} - i_{d2} + i_d) + L_d i_{q1} \\ \phi_{q2} = -l_{s2} i_{q2} - l_m (i_{q1} + i_{q2}) + L_m (-i_{q1} - i_{q2} + i_q) - L_d i_{d1} \\ \phi_d = l_r i_d + L_m (-i_{d1} - i_{d2} + i_d) \\ \phi_q = l_r i_q + L_m (-i_{q1} - i_{q2} + i_q) \end{cases} \quad (2)$$

C. Electromagnetic torque

The expression of electromagnetic torque of the DSIG is written:

$$C_e = \left(\frac{3}{2}\right) \left(\frac{p}{2}\right) \left(\frac{L_m}{L_d}\right) [(i_{q1} + i_{q2})] \phi_d - (i_{d1} + i_{d2}) \phi_q \quad (3)$$

3. Control strategy of the system

A. The control rotor field orientation

In this control strategy, the field vector coincides with d - q axis. Then the component ϕ_{qr} is zero and ϕ_{dr} is constant. The advantage of this presentation is to have a constant size in permanent regime.

$$\begin{cases} d = r \\ q = 0 \\ p_r = 0 \end{cases} \quad (4)$$

The application of the rotor field orientation on the model of the DSIG given by the voltages equations:

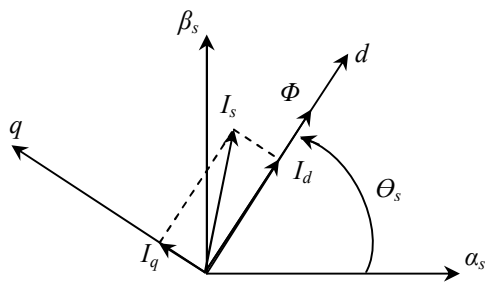


Fig.2. Fundament of Rotor Field Orientation.

We obtain:

$$\begin{cases} i_d = 0 \\ i_q = -\frac{(\omega_s - \omega_r) r}{R_r} \end{cases} \quad (5)$$

The final torque expression is written:

$$C_e = p \frac{L_m}{L_m + L_r} (i_{q1} + i_{q2}) r \quad (6)$$

B. The Control algorithm

The objective of our control is to maintain constant the voltage at the output of the two rectifiers.

The expression of the reference power is written:

$$V_d i_d = P = P_e = C_e \Omega \quad (7)$$

The torque expression is:

$$C_e = \frac{P}{\Omega} \quad (8)$$

The torque is controlled by the quadrature of current i_{qs1} and i_{qs2} of the two stars:

$$i_{q1} + i_{q2} = \frac{(L_m + L_r) C_e}{p L_m r} \quad (9)$$

The flux ϕ_r^* is estimated from the currents i_{sd1} and i_{sd2} of the two stars:

$$r = \frac{R_r L_m}{(L_r + L_m) P + R_r} (i_{d1} + i_{d2}) \quad (10)$$

C. Sliding mode controller (SMC)

To avoid chattering some approaches were proposed. The main idea was to change the dynamics in small vicinity of the discontinuity surface in order to avoid real discontinuity and at the same time to preserve the main properties of the whole system.

$$\dot{x} = f(x, t) + B(x, t) V(x, t), x \in \mathbb{R}^n, V \in \mathbb{R}^m, r_1 (B(x, t)) = m \quad (11)$$

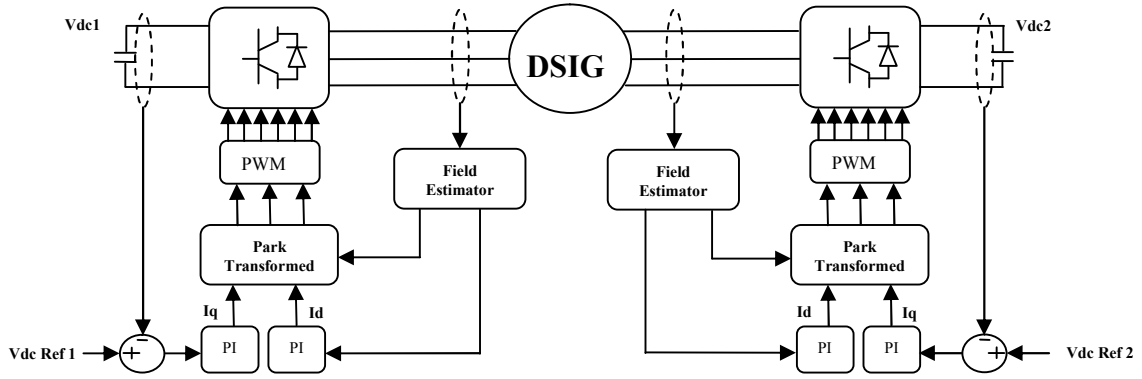


Fig.3. Block diagram of the DSIG voltage control.

With control in the sliding mode, the goal is to keep the system motion on the manifold S , which is defined as:

$$S = \{x: e(x, t) = 0\} \quad (12)$$

And

$$e = x - x^* \quad (13)$$

With

e : is the tracking error vector,

x^* is the desired state,

x is the state vector.

The sliding mode control should be chosen such that the candidate Lyapunov function satisfies the Lyapunov stability criteria:

$$\vartheta = \frac{1}{2} S(x)^2 \quad (14)$$

$$\dot{\vartheta} = S(x) \dot{S}(x) \quad (15)$$

This can be assured for:

$$\dot{\vartheta} = -\eta |S(x)| \quad (16)$$

With $\eta > 0$.

Essentially, equation (14) states that the squared “distance” to the surface, measured by $e(x)^2$, decreases along all system trajectories. Therefore (15), (16) satisfy the Lyapunov condition. With selected Lyapunov function the stability of the whole control system is guaranteed. The control function will satisfy reaching conditions in the following form:

$$U^{cc} = U^e + U^n \quad (17)$$

With :

U^{com} is the control vector.

U^{eq} is the equivalent control vector.

U^n is the correction factor and must be calculated so that the stability conditions for the selected control are satisfied.

$$U^n = K \text{ sat}(S(x)/\delta) \quad (18)$$

$\text{sat}(S(x)/\delta)$ is the proposed saturation function, δ is the boundary layer thickness. In this paper we propose the Slotine method [21]:

$$S(X) = \left(\frac{a}{d} + \lambda\right)^{n-1} e \quad (19)$$

Here, e is the tracking error vector, λ is a positive coefficient and n is the relative degree.

In our study, we choose the error between the measured and reference voltage of the DSIG as sliding mode surface, so we can write the following expression:

$$S = V_d - V_d \quad (20)$$

The first order derivate, gives :

$$\dot{S} = \dot{V}_d - \dot{V}_d \quad (21)$$

The sliding mode will exist only if the following condition is met:

$$S \cdot \dot{S} < 0 \quad (22)$$

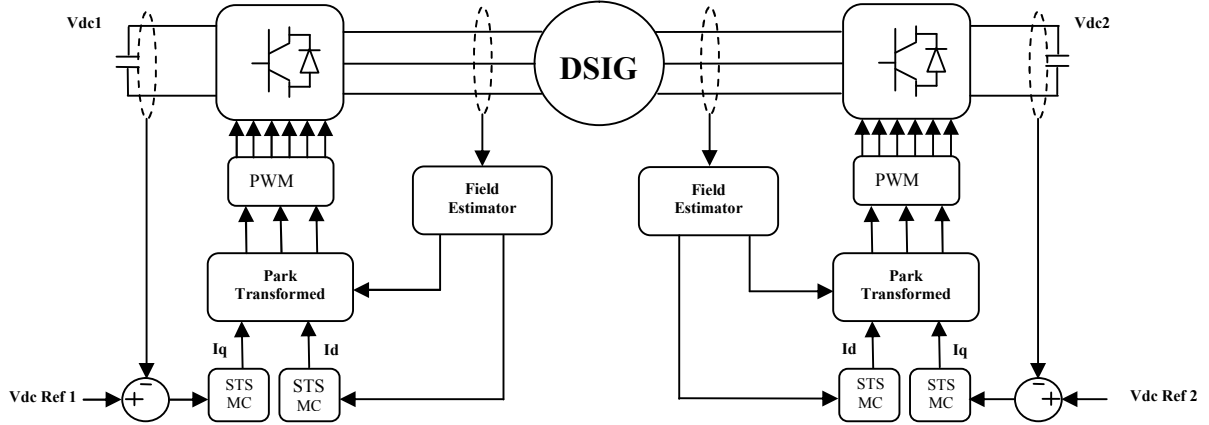


Fig.4. Block diagram of the DSIG voltage control with STSMC

D. Super twisting sliding mode controller (STSMC)

This method generalizes the essential sliding mode idea by acting on the higher order time derivatives of the sliding manifold, instead of influencing the first time derivative as it is the case in SMC, therefore reducing chattering and avoiding strong mechanical efforts while preserving SMC advantages.

In order to ensure the DSIG voltage convergence to their reference, a second order sliding mode control (STSMC) is used. Considering the sliding mode surface given by (21), the following expression can be written:

$$\begin{cases} \dot{S} = V_d - V_d \\ \ddot{S} = Y(t, x) + \Lambda(t, x)I_R \end{cases} \quad (23)$$

Where $Y(t, x)$ and $\Lambda(t, x)$ are uncertain functions which satisfy:

$$Y > 0, |Y| > \lambda, 0 < K_m < \Lambda < K_M \quad (24)$$

Basing on the super twisting algorithm introduced by Levant in [10], the proposed high order sliding mode controller contains two parts:

$$I_R = v_1 + v_2 \quad (25)$$

With

$$\begin{aligned} v_1 &= -k \cdot s \quad (S) \\ v_2 &= -l \cdot |S|^\gamma \cdot s \quad (S) \end{aligned}$$

In order to ensure the convergence of the sliding manifolds to zero in finite time, the gains can be chosen as follows [11].

$$\begin{cases} k > \frac{\lambda}{K_m} \\ l > \frac{4\lambda K_M(k+\lambda)}{K_m^2 K_m(k-\lambda)} \\ 0 < \gamma < 0.5 \end{cases} \quad (26)$$

4. Simulation results and discussions

The simulation is realized by a generator 158V/50Hz whose characteristic is given in Table 1. The scheme proposed for the simulation of the DSIG as shown in Fig 3, the assembly has two rectifiers connected to the two stars of the DSIG. The goal is to make a comparison between the two control methods; with PI controller and higher order sliding mode controller, two tests have been realized: pursuit test, and robustness against machine parameter variations.

A. Pursuit test

In this test the two reference voltages is defined V_{dc1} and V_{dc2} desired in the output of the two rectifiers, in this study the torque is equal to zero. The voltages and currents across the two stars of the DSIG are presented in Fig 5 and 6. The results for this test show that the voltages at the exit of the two rectifiers perfectly follow their references as shown in Fig 7. It is clear that the STSMC controller reacts faster than the PI controller; the static error is almost zero for two regulators. From these results we can say that the STSMC controller is more efficient than a PI controller.

B. Robustness test

In order to test the behavior of the machine during the saturation, initially we will modify the parameters of the DFIG as following; we decreased the stator and rotor inductances by 5%, increase resistance by 10%. The results presented in Fig 8 show that the parametric variation presents an effect on the V_{dc} voltage response time of the two controllers. Comparing the performance of each controller as shown in the Fig 9 we deduced that STSMC controller is faster and more stable than a PI controller, so we can conclude that STSMC regulator is more efficient than a PI regulator against this parameter variation.

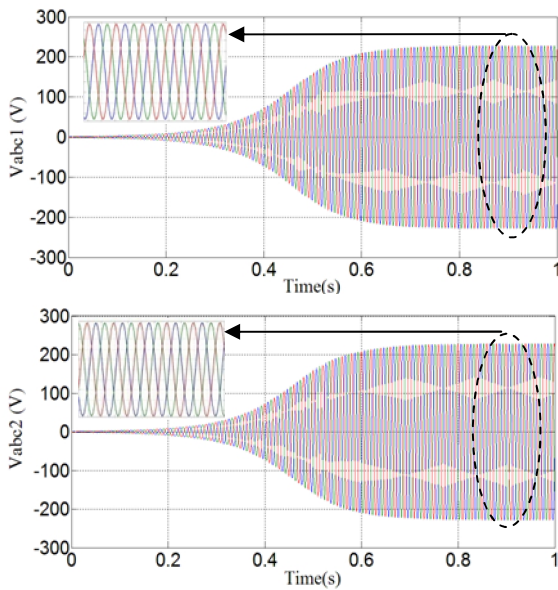


Fig.5. Voltage of stator 1 and 2 respectively.

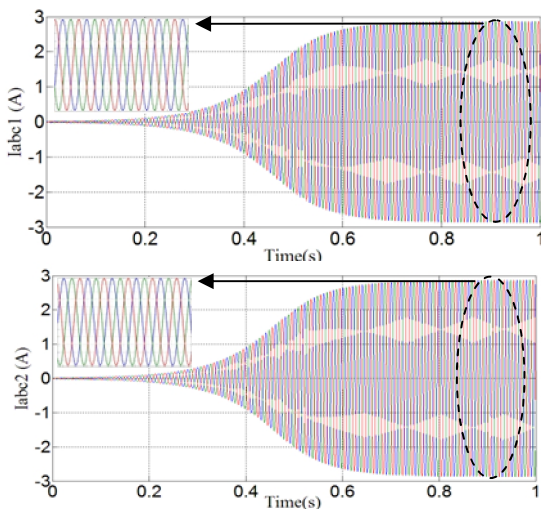


Fig.6. Current of stator 1 and 2 respectively.

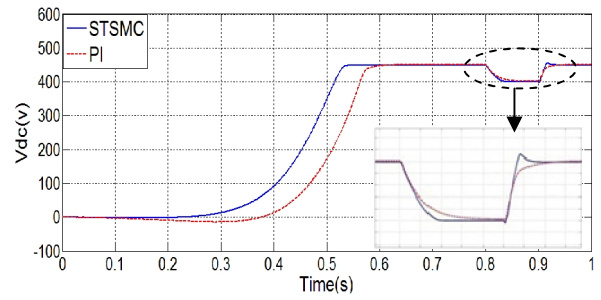


Fig.7. Pursuit test.

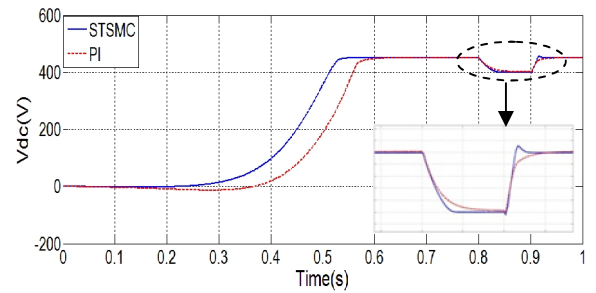


Fig8. Pursuit test with parametric variation.

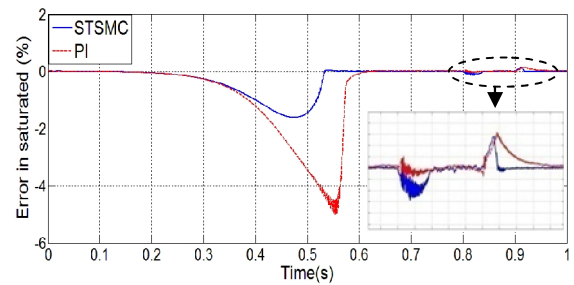


Fig9. Robustness test.

5. Conclusion

In this paper we present a simple scheme control of DFIG supplied by two power rectifiers. We used two control techniques; the field oriented control (FOC) and the high order sliding mode control (STSMC). The results obtained after simulation show the efficiency using a high order sliding mode control regulator compared to a simple PI regulator. According to the robustness test which shows that the STSMC regulator is more robust than the PI regulator with the parameter variations (stators and rotor resistances).

Appendix

Table 1. Nomenclature.

Symbol	Significance
d, q	Direct and quadrate indices for orthogonal components,
R_{s1}, R_{s2}, R_r	resistances of the star 1 and 2 and the rotor,
l_{s1}, l_{s2}, l_r	Stator leakage inductances (star 1 and 2) and rotor respectively
l_m	The mutual leakage inductance to the two stars,
L_{dq}	Cyclic inter saturation inductance,
$\phi_{s1}, \phi_{s2}, \phi_r$	Flux of the star 1 and 2 and the rotor,
ω_s	Stator current frequency (rad/s),
ω_r	The rotor rotation speed
J	Inertia (J_n nominal value of J),
C_{em}	Electromagnetic torque.

Table 2. The DFIG parameters.

Parameters	Value	IS-Unit
Stator voltage	158	V
Stator/rotor frequency	50	Hz
Star 1 resistance	1.9	Ω
Star 2 resistance	1.9	Ω
Rotor resistance	2.1	Ω
Star 1 inductance	0.0132	H
Star 2 inductance	0.0132	H
Rotor inductance	0.0132	H
Mutual inductance	0.011	H
Inertia	0.038	Kg.m^2

References

- Anaya-Lara, O., Jenkins, N., Ekanayake, J., Cartwright, P., Hughes, M.: *Wind energy generation*. In: Wiley, 2009.
- Y. Bendjedou.: *Contribution à l'étude des performances d'un générateur asynchrone*. In: mémoire de magister, Université Hadj Lakhdar Batna, 2013.
- M. Benkahla, R. Taleb and Z. Boudjema : *Comparative Study of Robust Control Strategies for a DFIG-Based Wind Turbine*. In: International Journal of Advanced Computer Science and Applications (IJACSA), vol. 7, no. 2, pp. 455-462, 2016.
- F.Bu, Y.Hu, W.Huang, S.Zhuang, K.Shi.: *Wide speed rang operatin dual stator winding generator DC generating system for wind power applications*. In: IEEE transactions on power electronics, vol.30, NO.2, FEBRUARY 2015.
- N.Sul, W.Huangl, S.Zhuang.: *A nouvel vector control strategy for variable frequency AC power system based on the dual stator-winding induction generator*. In: 18 th International conference on electrical machines and systems (ICEMS), Oct.25-28, 2015, Pattaya City, Thailand.
- A. Chatterjee,D. Chatterjee.: *Photovoltaic assisted excitation control of 1 phase dual winding induction generator for wind based microgeneration*. In: Council of scientific and industrial research (CSIR); India: file no.: 9/96(735)/2012-EMR-I.
- L.Liu, J. Li,C. Lu.: *Research on the real time simulation system of dual stator winding induction generator with variable speed*. In: The ninth international conference on electronic measurement and instruments.
- H. Xu, F. Bu, W. Huang, Y. Hu, H. Liu, Y. Zhao.: *Analysis, comparison and discussion of control strategies for dual stator winding induction generator DC generating system*. In: IEEE, Journal of emerging and selected topics in power electronics; JESTPE.2015.2497272.
- M.H. Zamani, G.H. Riahy, M. Abedi.: *Rotor speed stability improvement of dual stator winding induction generator based wind farms by control windings voltage oriented control*. In: IEEE, Transactions on power electronics; TPEL.2015.2495256.
- A. Levant.: *Higher-order sliding modes, differentiation and output feedback control*. In: Int J Control, vol. 76, 2003, pp. 924-941.
- S. Benelghali, M.E.H. Benbouzid, J.F. Charpentier, T. Ahmed-Ali, I. Munteanu.: *Experimental validation of a marine current turbine simulator: Application to a PMSG-based system second-order sliding mode control*. In: IEEE Trans. Ind. Electron., vol. 58, no. 1, January 2011, pp. 118-126.
- H. Amimeur, F. Hamoudi.: *Fuzzy logic control of a dual-stator induction generator for wind energy conversion systems*. In: Journal of Electrical Engineering, Vol. 16, No. 3, pp. 409-419, 2016.
- A. Yahdou, B. Hemici, Z. Boudjema.: *Second order sliding mode control of a dual-rotor wind turbine system by employing a matrix converter*. In: Journal of Electrical Engineering, Vol. 16, No. 3, pp. 89-100, 2016.
- E. Merabet, R. Abdessemed, L. Bentouhami, Y.Bendjedou. : *Speed control of dual stator windings induction machine using fuzzy logic controller*. In: Journal of Electrical Engineering, Vol. 13, No. 1, pp. 22-28, 2013.
- A.D. Martin, D.L. Vitan, L.N. Tutelea, N.Munteanu.: *Double stator winding induction generator for renewable energy conversion systems*. In: Journal of Electrical Engineering, Vol. 15, No. 3, pp. 318-326, 2015.
- H. Amimeur, R. Abdessemed, D. Aouzellag, E. Merabet, F. Hamoudi.: *Modeling and Analysis of Dual-Stator Windings Self-Excited Induction Generator*. In: Journal of Electrical Engineering, Vol. 8, No. 3, pp. 18-24, 2008.

17. F. Ameer, K. Kouzi, K.M. Nachida.: *Optimization Fuzzy Speed Vector Control of Dual Stator Induction Generator System*. In: Journal of Electrical Engineering, Vol. 14, No. 1, pp. 336-344, 2014.
18. Z. Boudjema, R. Taleb, A. Yahdou, H. Kahal.: *High order sliding mode control of a DFIMsupplied by two power inverters*. In: Carpathian Journal of Electronic and Computer Engineering 8/1 , pp.23-30, 2015.
19. T. Laamyad, F. Naceri, R. Abdessemed, S. Belkacem.: *A fuzzy sliding mode strategy for control of the dual star induction machine*. In: Journal of Electrical Engineering, Vol. 13, No. 1, pp. 216-224, 2013.
20. Sun, T., Chen, Z., Blaabjerg, F. :*Flicker study on variable speed wind turbines with doubly fed induction generators*.In: IEEE Transactions on Energy Conversion,pp. 896-905 , 20 December, 2005, 896–905.
21. J. J. E. Slotine and W. Li, Applied Nonlinear Control. Englewood Cliffs, NJ: Prentice–Hall, 1991.