# Backstepping Approach Based on Direct Power Control of a DFIG in WECS

Farida Mazouz * , Sebti Belkacem *, Ghoulemallah Boukhalfa*, Ilhami Colak**

* LEB. Electrical Engineering Department. University Batna-2, Batna, Algeria

** Dept. Electrical Engineering Nisantasi University, Istanbul, Turkey

(f.mazouz@univ-batna2.dz, s.belkasem@univ-batna2.dz, ghoulem1987@gmail.com, ilhcol@gmail.com )

‡ Corresponding Author; Farida Mazouz, LEB. Electrical Engineering Department. University Batna-2, Batna, Algeria, f.mazouz@univ-batna2.dz

*Received: 25.12.2022 Accepted:27.03.2023*

**Abstract-** The work presented in this paper aims to highlight new solutions that improve the performance and reliability of wind turbine systems based on a DFIG. Direct power control using hysteresis regulators in power control laws has many disadvantages, for example, variable frequency and ripple in control variable. To overcome these problems, the trend of current research has been carried out in the field of controls of robust nonlinear systems which give acceptable results in large operating domains. We present backstepping using SVM. A comparative study based on the simulation results is presented, thus making it possible to judge the robustness of the control in each case and for the different operating regimes of the DFIG; these results reflect the good performance of this method and which can be improved the system performance.

**Keywords** Backstepping; DFIG; Wind Energy; Direct Power Control; Parametric Variation.

## 1. Introduction

Renewable energies designate a set of means of producing energy from theoretically unlimited sources or resources, available without time limit or replenishable more quickly than they are consumed. We generally speak of renewable energies as opposed to energies derived from fossil fuels whose stocks are limited and non-renewable on a human time scale: coal, oil, natural gas... On the contrary, renewable energies are produced from sources such as the rays of the sun, or the wind, which are theoretically unlimited on a human scale. [1].

A large part of the wind turbines installed today is equipped with double-fed asynchronous machines (DFIG). This generator allows electricity production at variable speed, which then makes it possible to better exploit wind resources for different wind conditions. In addition, if we manage to ensure that wind turbines can provide system services to the network, such as the supply of reactive power for power factor correction and the improvement of energy quality by the filtering of current harmonics then its insertion in the networks will surely be simpler. [2-4].

Recently, new advanced control techniques are grouped under the name of direct torque control (DTC and Direct Power Control (DPC) [5]. The concept of DTC was proposed in 1986 by [6] and then applied to other problems.

The goal is to cancel the PWM control by replacing them with a switch table. It allows the DFIG to have a rapid power response. Recent research works have been developed for the application of this control technique to DFIG [7-9]. Next, another technique applied to DPC. In the DPC, the control of the inverter switches via a selection table based on hysteresis comparators in order to obtain a unity power factor. This technique has several drawbacks such as the presence of fluctuations in the control performance [10].

Several control methods have been proposed; in [11] DPC using voltage control (V-DPC): references and establishes the configurations of the DPC according to the position of the voltage vector in the stationary frame (α-β). The article [12] illustrates to combine the principle of DPC with (SVM) to obtain acceptable performances without the use of a classical command. Other tracers based on predictive approaches have been treated in [13]. In [14] proposes a method (DPC) based on second-order fuzzy logic control in sliding mode (FSOSMC).

The backstepping method has been implemented in several works [15-20]. In Ref. [21], the improved adaptive backstepping control parameters of PMSM using DTCs, which show the advantage of force and torque response.

## 2. DFIG-Based Wind Turbine Description

Fig. 1. Shows proposed methods for WECS based on DFIG. The RSC is controlled by the PWM technique, the instructions of which come from a DPC command. It is used to control the powers. The wind energy conversion chain consists of the wind turbine, and the DFIG associated with a voltage inverter to supply the rotor. We introduced a second power converter to connect the rotor to the power grid. [11]..

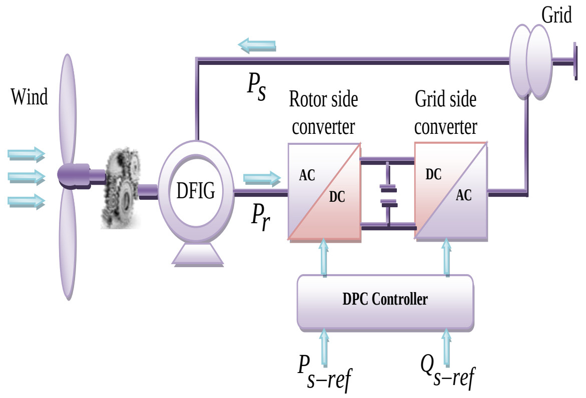



**Fig. 1.** DPC for a grid-connected DFIG system.

## 3. Principle of Backstepping Method

The Backstepping technique is a relatively recent control method for nonlinear systems. It allows, in a sequential and systematic way, by the choice of a Lyapunov function, to determine the control law of the system. Its principle is to establish in a constructive way the control law of the nonlinear system by considering some state variables as being virtual controls and designing intermediate control laws for them. [22-25].

The rotor voltage expression becomes:

$$\begin{cases} V_{rd} = R_r I_{rd} + L_r\sigma \dfrac{dI_{rd}}{dt} - \mathrm{g.\,w_s} L_r\sigma.\, I_{rq} \\ V_{rq} = R_r I_{rq} + L_r\sigma \dfrac{dI_{rq}}{dt} + \mathrm{g.\,w_s} L_r\sigma.\, I_{rd} + \mathrm{g.}\dfrac{\mathrm{M.V_s}}{\mathrm{L_s}} \end{cases} \quad (1)$$

The derivatives of the rotor currents expressions are given by/

$$\dot{i}_{rd} = -\frac{1}{\sigma T_r}\mathrm{i}_{rd} + g w_s i_{rq} + \frac{1}{\sigma L_r}V_{rd}$$
$$\dot{i}_{rq} = -\frac{1}{\sigma}\left(\frac{1}{T_r} + \frac{M^2}{L_s T_s L_r}\right) i_{rq} - g w_s i_{rd} + \frac{1}{\sigma L_r}V_{rq} \quad (2)$$

With:

$$\sigma = 1 - \frac{M^2}{L_s L_r};\ T_r = \frac{L_r}{R_r};\ g = \frac{W_s - W}{W_s}; T_s = \frac{L_s}{R_s}$$

The powers expressions are:

$$\mathrm{P}_s = -V_s \frac{\mathrm{M}}{L_s}\mathrm{i}_{rq} \quad (3)$$

$$Q_s = \frac{V_s^2}{w_s L_s} - V_s \frac{\mathrm{M}}{L_s}\mathrm{i}_{rd} \quad (4)$$

Its derivatives are:

$$\frac{dP_s}{dt} = -V_s \frac{M}{L_s}\dot{I_{rq}} \quad (5)$$

$$\frac{dQ_s}{dt} = -V_s \frac{M}{L_s}\dot{I_{rd}} \quad (6)$$

### A. *Step1: Backstepping active power controller*

The error of active power is:

$$\begin{cases} e_1 = P_{s-ref} - P_S \\ \dot{e}_1 = \dot{P}_{s-ref} - \dot{P}_s \end{cases} \quad (7)$$

V1 in given as:

$$\mathrm{V}_1 = \frac{1}{2}e_1^2 \quad (8)$$

Then

$$\dot{\mathrm{V}}_1 = \mathrm{e}_1\dot{\mathrm{e}}_1 = \mathrm{e}_1(\dot{P}_{\mathrm{s\_ref}} + V_s \tfrac{M}{L_s}\dot{I_{rq}}) \quad (9)$$

By replacing the expression of Irq in equation (9):

$$\dot{\mathrm{V}}_1 = \mathrm{e}_1\left[\dot{P}_{s\_ref} + \frac{V_s M}{L_s L_r \sigma}V_{rq} - \frac{V_s M}{L_s L_r \sigma}R_r I_{rq} - \frac{V_s M}{L_s} g\omega_s I_{rd} - \left(\frac{V_s M}{L_s}\right)^2 . \frac{g}{L_r \sigma}\right] \quad (10)$$

Then

$$\dot{\mathrm{V}}_1 = -Z_1 \mathrm{e}_1^2 < 0 \quad (11)$$

V1 must be negative; such as:

$$\dot{\mathrm{V}}_1 = \mathrm{e}_1\left[\dot{P}_{s\_ref} + \frac{V_s M}{L_s L_r \sigma}V_{rq} - \frac{V_s M}{L_s L_r \sigma}R_r I_{rq} - \frac{V_s M}{L_s} g\omega_s I_{rd} - \left(\frac{V_s M}{L_s}\right)^2 . \frac{g}{L_r \sigma}\right] = -\mathrm{Z}_1\mathrm{e}_1^2 \quad (12)$$

$V_{rq}$, namely:

$$\mathrm{V_{rq}} = -\frac{\mathrm{L_s L_r \sigma}}{\mathrm{V_s M}}(\dot{\mathrm{P}}_{\mathrm{s_{ref}}} + \mathrm{Z_1 e_1}) + \mathrm{R_r I_{rq}} + \mathrm{L_r \sigma g \omega_s I_{rd}} + \mathrm{g}\frac{\mathrm{MV_s}}{\mathrm{L_s}} \quad (13)$$

### B. *Step2: Backstepping reactive power controller*

The reactive power tracking error is:

$$\begin{cases} \mathrm{e}_2 = Q_{\mathrm{s\_ref}} - Q_{\mathrm{s}} \\ \dot{\mathrm{e}}_2 = \dot{Q}_{\mathrm{s\_ref}} - \dot{Q}_{\mathrm{s}} \end{cases} \quad (14)$$

Then

$$V_2 = \frac{1}{2}e_2^2 \quad (15)$$

The Lyapunov candidate derivative are:

$$\dot{V}_2 = e_2\dot{e}_2 = e_2(\dot{Q}_{s\_ref} + V_s\frac{M}{L_s}\dot{I}_{rd}) \quad (16)$$

By replacing the expression of the current derivative Ird in equation (9):

$$\dot{V}_2 = e_2\left[\dot{Q}_{s_{ref}} + \frac{V_s M}{L_s L_r \sigma}V_{rd} - \frac{V_s M}{L_s L_r \sigma}R_r I_{rd} + \frac{V_s M}{L_s}g\omega_s I_{rq}\right] \quad (17)$$

$$\dot{V}_2 = -Z_2 e_2^2 < 0 \quad (18)$$

To guarantee a stable follow-up of the derivative of $V_2$ which must be negative; this allows the synthesis of references (variable virtual control), such as:

$$\dot{V}_2 = e_2\left[\dot{Q}_{s\_ref} + \frac{V_s M}{L_s L_r \sigma}V_{rd} - \frac{V_s M}{L_s L_r \sigma}R_r I_{rd} + \frac{V_s M}{L_s}g\omega_s I_{rq}\right] = -Z_2 e_2^2 \quad (19)$$

$V_{rd}$, namely:

$$V_{rd} = -\frac{L_s L_r \sigma}{V_s M}(\dot{Q}_{s_{ref}} + Z_2 e_2) + R_r I_{rd} - L_r \sigma g \omega_s I_{rq} \quad (20)$$

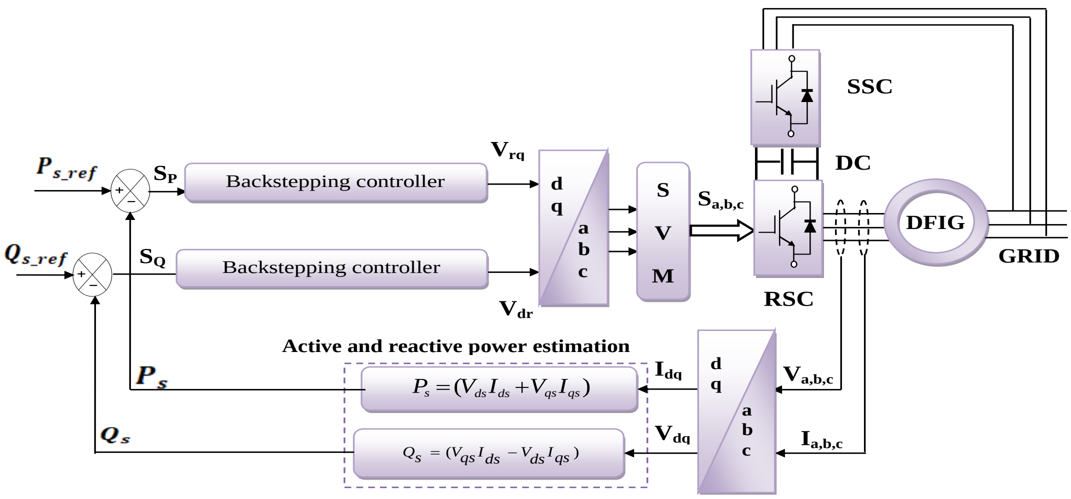



**Fig. 2.** Backstepping approach for DFIG.

### *3.1. Simulation Results Under Normal Condition*

The simulation results shown in Figures 3, 4 illustrate the active and reactive powers with strong coupling at high performance. The magnitudes of the powers follow their reference trajectory well without overshoot and fast response time, the remarkable chattering effect in the classic DPC control due to the use of hysteresis regulators, on the other hand, is reduced with the proposed bachstepping technique.

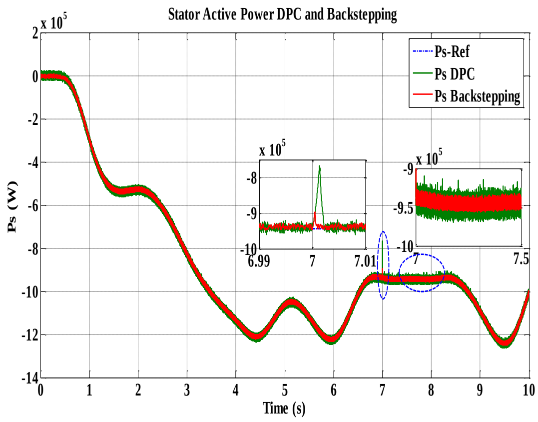



**Fig. 3**. Active power simulated results of C-DPC with Backstepping-DPC.

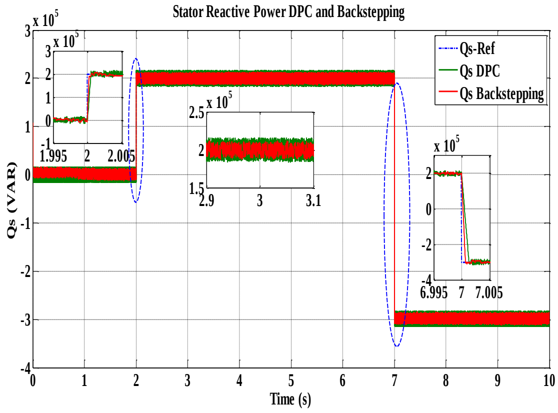



**Fig. 4.** Reactive power simulated results of C-DPC with Backstepping-DPC

The stator currents for both DPC and Backstepping techniques are present in Figures 5, 6, we notice that the backstepping technique has a reducible fluctuation compared to that of the Classic DPC.

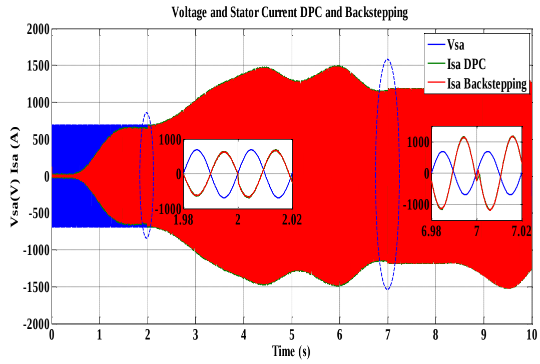



**Fig. 5.** Voltage and stator current simulated results of C-DPC with Backstepping-DPC

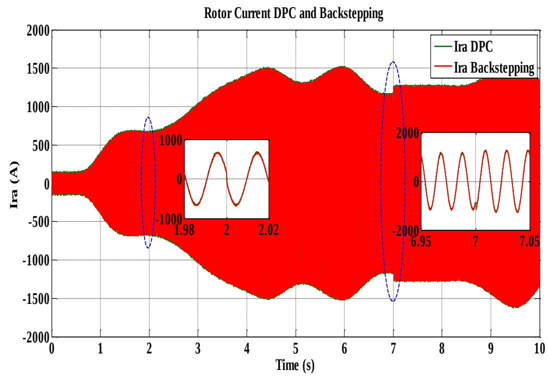
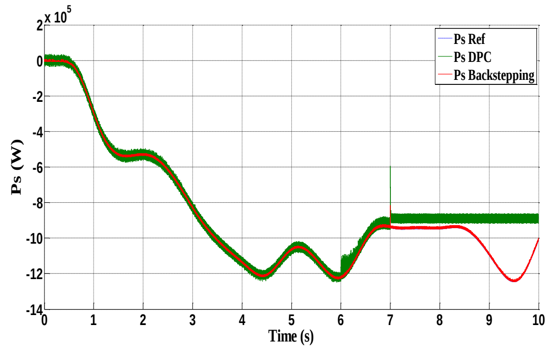



**Fig. 6.** Rotor current simulated results of C-DPC with Backstepping-DPC

*3.2. Simulation Results Under Parametric Variation On Rr*

The parametric variation test simulated for the two types of regulation: classic DPC based on hysteresis regulator and DPC based on the backstepping method are shown in figure 7, the rotor resistance is increased by 150% at time t=6 s, it was noticed that the backstepping throttle technique was not influenced by the increase in rotor resistance



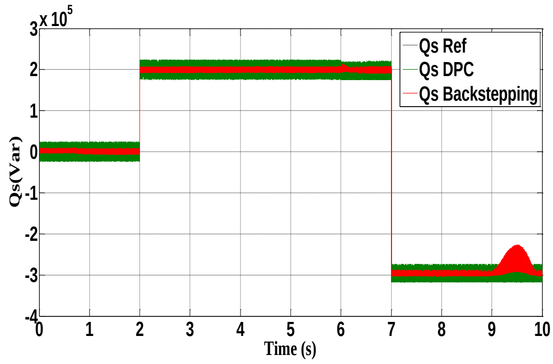
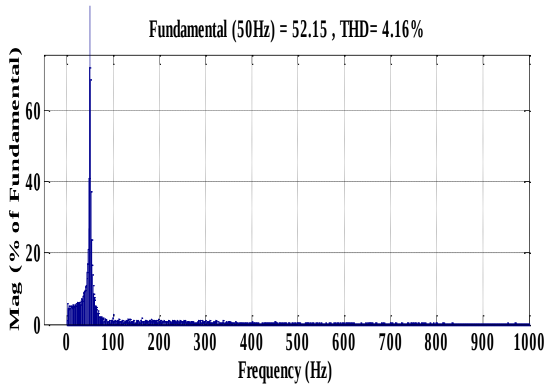




**Fig. 7.** Active and Reactive power of C-DPC with Backstepping-DPC

The results of the spectral analysis for the stator phase current shown in Figure 8 shows that the backstepping command guarantees a better waveform quality of the stator current.

(a) Backstepping-DPC




(b) C-DPC

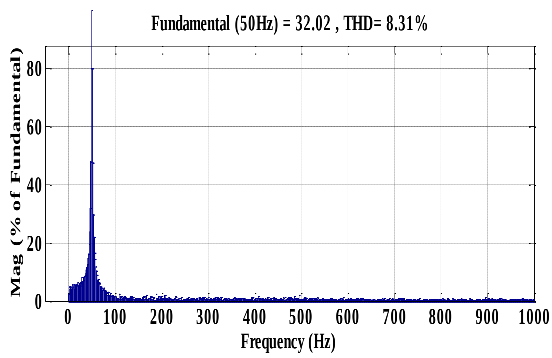



**Fig. 8.** Stator current FFT analysis, (a) Backstepping-DPC, (b) C-DPC.

The comparison of static and dynamic performance of the two power control methods of DFIG is shown in Table 1. It can be noted that the suggested technique gives much less chatter with fast transient response compared to the classical DPC technique.

**Table 1**. Performance analysis of simulation results

| **Approach** | **Classical DPC** | **Backstepping DPC** |
|---|---|---|
| Robustness to parameters mismatch | Larg | Small |
| Chattering | Considerable chattering | Small chattering |
| Transient performance of the powers | Relatively fast with medium settling time | Fast with low settling time |
| Harmonic of stator current | High | Low |
| Rising time of the active power | 6 e-4 s | 3 e-4 s |

## 4. Conclusion

The backstepping control model has been developed in this article with the aim of analyzing its dynamic behavior in order to present generalities on the principle of the technique; namely: the method of analysis of Lyapunov which is the essential element of the backstepping technique. The numerical validation of the global system studied was carried out by a simulation under the MATLAB/SIMULINK environment. The results of the various simulations carried out were commented on and made it possible to validate the mathematical models of the proposed system. The strategy of the backstepping control allowing to improve the classical DPC control performance and to control the output power, according to a chosen energy conversion structure consisting of a double-fed generator. The modeling was developed of the different elements of the wind chain. The simulation results carried out during the application of this technique to the system show good monitoring of the powers generated at the corresponding reference values. Also, we have observed that the tracking error is low and that the decoupling between the powers is always maintained as well as the reduced "chattering" effect which is the objective of this control with great robustness with respect to the parametric variations.

## References

[1] H. Wanger, J. Mathur, Introduction to wind energy systems. Green Energy and Technology, Berlin Heidelberg: Springer, 2013.

[2] T. Ackermann, Wind Power in Power Systems. John Wiley and Sons, 2005.

[3] A. Tapia, G. Tapia, J. X. Ostolaza, and J. R. Saenz, Modeling and Control of a Wind Turbine Driven Doubly Fed Induction Generator, IEEE Transactions on Energy Conversion, Vol. 18, no. 2, pp. 194-204, 2003.

[4] R. Cárdenas, Peña R, Alepuz S, Asher G. Overview of control systems for the operation of DFIGs in wind energy applications, IEEE Trans Ind Electron, Vol. 7, 2776–98, 2013.

[5] N. Mekkaoui, M.S. Naït-Saïd, Direct S-power control for a doubly fed induction generator, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg. Vol. 62, No. 4, pp. 365–370, Bucarest, 2017.

[6] T. Takahashi, I. Noguchi, A new quick-response and high-efficiency control of an induction motor, IEEE Trans. Industry Applications, IA-22, Vol. 5, pp. 820–827, 1986.

[7] E. Aydin, A. Polat, L.T. Ergene,"Vector control of DFIG in wind power applications", IEEE International Conference on Renewable Energy Research and Applications (ICRERA), doi :10.1109 /ICRERA. 2016.7884383, pp. 478-483, 23 Nov 2016.

[8] Y. Bakou;M. Abid;A. Harrouz;I. Yaichi;I. Colak;K. Kayisli;A. Aissaoui, DTC Control of the DFIG, Application to the Production of Electrical Energy 2019 8th International Conference on Renewable Energy Research and Applications (ICRERA) 2019.

[9] F. Mazouz, S. Belkacem, Y. Harbouche, R. Abdessemed, S. Ouchen, Active and Reactive Power Control of a DFIG For Variable Speed Wind Energy Conversion, IEEE 6thInternational conference on systems and control (ICSC'2017), Algeria, 2017.

[10] F. Amrane, B. Francois, A. Chaiba. Experimental investigation of efficient and simple wind-turbine based on DFIG-direct power control using LCL-filter for stand-alone mode. ISA transaction 2021.

[11] Farida Mazouz Sebti Belkacem aIlhami Colakb Said Dridc Youcef Harbouche,Adaptive direct power control for double fed induction generator used in wind turbine, International Journal of Electrical Power & Energy Systems, Volume 114, January 2020.

[12] Y. Han, and R. Ma, Adaptive-Gain Second-Order Sliding Mode Direct Power Control for Wind-Turbine-Driven DFIG under Balanced and Unbalanced Grid Voltage, Energies, 12(20) (2019).

[13] M. Mason, R. Kazemzadeh, M.R. Azizian, Model-based predictive direct power control of brushless doubly fed reluctance generator for wind power applications, Alexandria Engineering Journal, Vol. 55, pp. 2497–2507, 2016.

[14] Habib Benbouhenni, Zinelaabidine Boudjema, Abdelkader Belaidi, DPC Based on ANFIS Super-Twisting Sliding Mode Algorithm of a Doubly-Fed Induction Generator for Wind Energy System, Journal Européen des Systèmes Automatisés, Vol. 53, No. 1, February, 2020, pp. 69-80

[15] M. Benakcha, L. Benalia, D. E. Tourqui, A. Benakcha,"Backstepping Control of Dual Stator Induction Generator Used in Wind Energy Conversion System". International Journal of Renewable Energy Research, Vol.8, No 1, pp. 384-395, March 2018.

[16] Xiaoming Zheng, Lei Xue, Peng Wang, Jia Li and Zeyuan Shen , Parameters adaptive backstepping control of PMSM using DTC method, E3S Web of Conferences 23 6 , 04028 (2021) ICERSD 2020.

[17] Nur Sarma;Judith M. Apsley;Sinisa Djurovic, Implementation of a conventional DFIG stator flux oriented control scheme using industrial converters.2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA).2016.

[18] Rogério Vani Jacomini;Alfeu J. Sguarezi Filho,Direct Power Control Strategy to Enhance the Dynamic Behavior of DFIG During Voltage Sag. 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA).2018.

[19] Mohmed Ashglaf;Cristian Nichita;Brayima Dakyo,Control Strategies Design for a Small-Scale Wind Turbine with a Doubly Fed Induction Generator 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA).

[20] N.e Layadi, A Djerioui, S. zeghlache, H mekki, A houari, M- F Benkhoris, F. berrabah. New fault tolerant control based on backstepping controller for double star induction machine Rev. Roum. Sci. Techn.– Électrotechn. et Énerg. Vol. 64, 3, pp. 275–280, Bucarest, 2019.

[21] Herizi Abdelghafour, Bouguerra Abderrahmen1, Zeghlache Samir, Rouabhi Riyadh, Backstepping control of a doubly-fed induction machine based on fuzzy controller. European Journal of Electrical Engineering – n°5-6/2018, 645-657.

[22] El Mourabit Younessa DerouichAziz El Ghzizal Abdelaziz Bouchnaif Jamal El Ouanjli Najib Zamzoum Othmane Mezioui Khalid Badre Bossoufi, Implementation and validation of backstepping control for PMSG wind turbine using dSPACE controller board. Energy Reports Vol. 5, 2019, Pages 807-821.

[23] M. Ayadi,N. Derbel. Nonlinear adaptive backstepping control for variable-speed wind energy conversion system-based permanent magnet synchronous generator. The International Journal of Advanced Manufacturing Technology volume 92, pages 39–46 (2017).

[24] N. Ouanjli, A. Derouich , A. Ghzizal , J. Bouchnaif , Y. El Mourabit , M. Taoussi , and B. Bossoufi, Real-time implementation in dSPACE of DTC-backstepping for a doubly fed induction motor Eur. Phys. J. Plus (2019) 134: 566.

[25] K E. Okedu, A Variable Speed Wind Turbine Flywheel Based Coordinated Control System for Enhancing Grid , INTERNATIONAL JOURNAL of SMART GRID, Vol.2, No.2, 2018.