Robust Sensor-less SMC of DFIG based on FKE in Variable-Speed Wind Turbine Systems

Lakhdar Saihi
Unité de Recherche en Energies Renouvelables en Milieu Saharien (URERMS) Centre de Développement des Energies Renouvelables (CDER), Adrar, Algeria
sadysaihi@live.fr

Youcef Bakou
Unité de Recherche en Energies Renouvelables en Milieu Saharien (URERMS) Centre de Développement des Energies Renouvelables (CDER), Adrar, Algeria
youcefbakou@gmail.com

Abdelkader Harrouz
Department of Hydrocarbon and Renewable energy, Ahmed Draïa University,
LDDI laboratory
Adrar, Algeria
abd.harrouz@univ-adrar.edu.dz

Mohammed Boura
Department of Sciences Technology University of Tahri Mohammed
Béchar, Algeria
b.mido@yahoo.fr

Ilhami COLAK
Department of Electrical Electronics Eng., Faculty of Engineering Architecture, Nisantasi University, Istanbul, Turkey
ilhcol@gmail.com

Korhan Kayisli
Department of Electrical Electronics Eng., Faculty of Engineering, Gazi University, Ankara, Turkey
korhankayisli@gmail.com

***Abstract*— This paper study the robust nonlinear sensor-less sliding mode control (SMC) of the wind turbine chain associated with doubly fed induction generator (DFIG), the energy transfer between the grid and stator of DFIG is done by acting on the rotor via a reversible signal converter. The extended Kalman filter (EKF) is used the error between the estimated and measured voltages/currents to the production of estimation speed and position values. The simulations of results confirmed the performance of the control (SMC) of a DFIG sensor-less speed based on extended Kalman filter and validate a good dynamic performance.**

Keywords— DFIG, Sensor-less sliding mode control (SMC), extended Kalman filter (EKF).

I. INTRODUCTION

The wind energy considered among renewable energies and deserved solution to classical energy sources that pollute the climate, the wind is free availability in all world [1], [2]. The majority of wind turbines systems are fixed speed, when we use speed variable in turbines chain is augmenting due to many advantages. Doubly fed induction generators (DFIG) widely applied in variable speed wind of wind turbine chain. There are many advantages to using of DFIG in a wind energy chain [1], [2].

The robust sensor-less control of the DFIG necessary the information of position/speed rotor. That can be obtained by using the encoders (mechanical sensors). But these encoders increase the global price and the size of the DFIG, decrease the performance, the system to be sensitive to disturbances [2]. From this point of view, the sensor-less techniques draw the attention the researchers. Therefore, many strategies used for observed the mechanical parameters (speed/position) in the literature [3].

In this paper, we have illustrated the modeling of the wind turbine system (mechanical part) and the DFIG (electrical part). In the next section, we have presented the robust sliding mode control (SMC) of wind energy system based on DFIG. In the second part, the extended Kalman filter (EKF) technique used for estimating the position and speed of the rotor, by using the error between the measured and reference currents and voltages.

Finally, the results of simulation and conclusion are confirmed the performance of the sensor-less SMC of a DFIG provide with EKF and validate a good dynamic performance.

II. WIND CONVERSION CHAIN MODEL

Fig.1 show the wind power chain provide with DFIG [5], [6]:

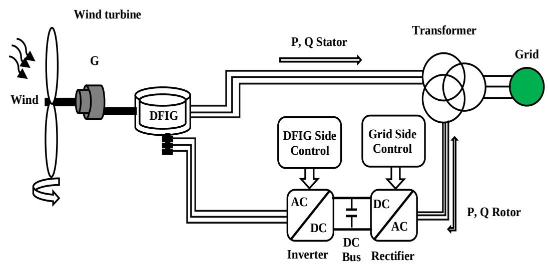

Fig. 1. Wind turbine power chain provide with DFIG.

A. Turbine Model

The expression of the mechanical power extracted from the wind energy [6], [7]:

$$P_m = \frac{1}{2}\, \rho\, S\, v^3\, C_p \tag{1}$$

where ρ the density of air; v speed of wind (m.s^{-1}); $S = \pi R^2$ Sweep space for turbo blade (m^2); C_p coefficient of power based on λ, β is presented by:

$$C_p(\lambda,\beta) = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\,\beta - 5\right) e^{-\left(\frac{21}{\lambda_i}\right)} \tag{2}$$

$$\lambda_i = \left(\frac{1}{\lambda+0.08\,\beta} - \frac{0.035}{\beta^3+1}\right) \tag{3}$$

The speed ratio is the coefficient between the speeds of turbine and wind and can be expressed as [7], [8]:

$$\lambda = \frac{R\,\Omega_t}{v} \tag{4}$$

with; Ω_t speed of mechanical turbine (rad/s);

B. DFIG Model

By using the electrical/mechanical equations we give the model of the DFIG in Park reference (d-q) [7], [8], [9]:

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \ \varphi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s \ \varphi_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_s - \omega_r) \ \varphi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} - (\omega_s - \omega_r) \ \varphi_{dr} \end{cases} \quad (5)$$

with; $\varphi_{dr} = l_s i_{ds} + l_m i_{dr}$, $\varphi_{qs} = l_s i_{qs} + l_m i_{qr}$, $\varphi_{dr} = l_r i_{dr} + l_m i_{ds}$, $\varphi_{qr} = l_r i_{qr} + l_m i_{qs}$.

III. Control Strategy of DFIG

A. SMC of DFIG

The technique sliding mode is a nonlinear control (SMC). In general, the sliding mode control is divided in three steps [7], [8], [9]:

- Choice of sliding surface;
- The existence conditions (Stability of Lyapunov function);
- Laws of control (SMC).

B. Control of Stator power (Active/Reactive)

The surface expressions of stator powers we obtain [9], [10]:

$$\begin{cases} S(P) = (P_s^{ref} - P_s) \\ S(Q) = (Q_s^{ref} - Q_s) \end{cases} \quad (6)$$

The derivative of Eq (6), written:

$$\begin{cases} \dot{S}(P) = (\dot{P}_s^{ref} + v_s.\frac{l_m}{l_s}.i_{qr}) \\ \dot{S}(P) = (\dot{Q}_s^{ref} + v_s.\frac{l_m}{l_s}.i_{dr}) \end{cases} \quad (7)$$

By using the expression of the currents i_{qr}, i_{dr}, we obtain:

$$\begin{cases} \dot{S}(P) = (\dot{P}_s^{ref} + v_s.\frac{l_m}{l_s.l_r.\sigma}.(v_{qr} - R_r.i_{qr}) \\ \dot{S}(Q) = (\dot{Q}_s^{ref} + v_s.\frac{l_m}{l_s.l_r.\sigma}.(v_{dr} - R_r.i_{dr}) \end{cases} \quad (8)$$

With replacing v_{qr} by $v_{qr}^{eq} + v_{qr}^{n}$, and v_{dr} by $v_{dr}^{eq} + v_{dr}^{n}$:

$$\begin{cases} \dot{S}(P) = (\dot{P}_s^{ref} + v_s.\frac{l_m}{l_s.l_r.\sigma}.\left((v_{qr}^{eq} + v_{qr}^{n}) - R_r.i_{qr}\right) \\ \dot{S}(Q) = (\dot{Q}_s^{ref} + v_s.\frac{l_m}{l_s.l_r.\sigma}.((v_{dr}^{eq} + v_{dr}^{n}) - R_r.i_{dr}) \end{cases} \quad (9)$$

By using the sliding mode condition, we found: $S(P) = 0$, $\dot{S}(P) = 0, v_{qr}^{n} = 0$ and $S(Q) = 0$, $\dot{S}(Q) = 0$, $v_{dr}^{n} = 0$. The equivalent control v_{qr}^{eq} and v_{dr}^{eq} are get from the following equations [10], [11]:

$$\begin{cases} v_{qr}^{eq} = -\dot{P}_s^{ref}.\frac{l_s.l_r.\sigma}{v_s.l_m} + R_r.i_{qr} \\ v_{dr}^{eq} = -\dot{Q}_s^{ref}.\frac{l_s.l_r.\sigma}{v_s.l_m} + R_r.i_{dr} \end{cases} \quad (10)$$

The term of commutation of v_{qr}^{n} and v_{dr}^{n} are:

$$\begin{cases} v_{qr}^{n} = Kv_{qr}\ sign(S(P)) \\ v_{dr}^{n} = Kv_{dr}\ sign(S(Q)) \end{cases} \quad (11)$$

where; Kv_{qr} and Kv_{dr} must be positive.

IV. Sensor-less Speed Control Associated with Filtre Kalman Extended

A. Extended Kalman Filter

Extended Kalman Filter (FKE) (non-linear system), is a mathematical tool capable of determining evolving non-measurable states from measurable physical quantities. This filter is based on a number of hypotheses, particularly on the noises [14], [15], [16]. Indeed, it assumes that the presence of noise on the state and on the output [17], [18], [19].

The observer of Kalman is one of the stochastic observers based on the exit error of the exit and relative to them, he takes into account the characteristics of the noises that come to corrupt the system, it allows to find the matrix of the gain. K optimal in the sense of minimizing the breaks on the measures and uncertainty on the states of the system [20], [21], [22].

The extended Kalman filter principle is to correct the trajectory of the model by combining the observations with the information provided by the model so as to minimize the error between the true state and the filtered state [23], [24]. The FKE algorithm can be executed using a prediction-correction structure shown in Fig. 5:

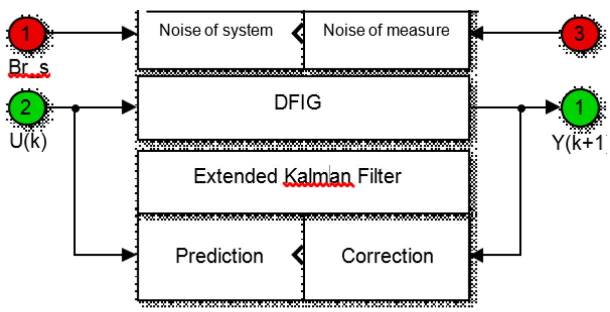

Fig. 2. Global structure of the EKF.

EKF is implanted as an "S-Function" and then, it is inserted into the global simulation diagram in Simulink as an "S-Function" block (Fig. 3) [12], [14].

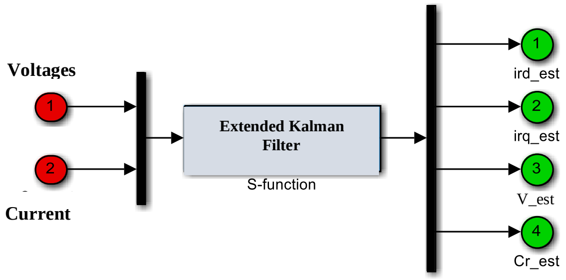

Fig. 3. Representation of the EKF in the form of S-Function.

B. Global sensor-less SMC control based on EKF:

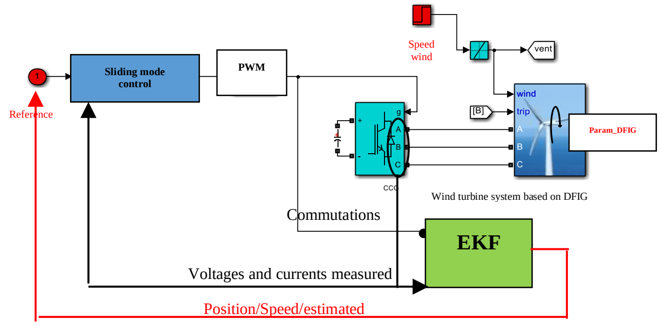

Fig. 4. Global sensor-less SMC control provide with FKE.

V. SIMULATIONS RESULTS

To test the robustness of sensor-less SMC controller of the DFIG used in wind turbine chain, by using Matlab&Simulink. The profile of wind is exercised on the wind turbine presents in Fig (5).

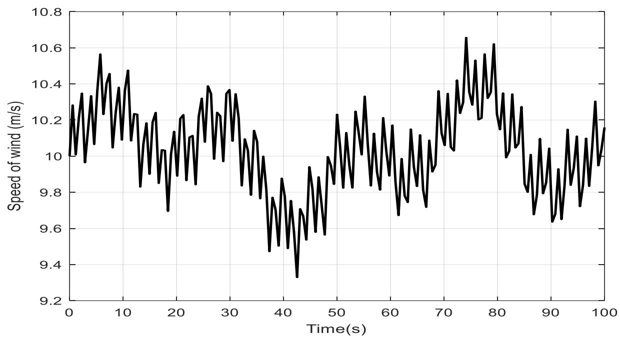

Fig. 5. Profile of wind speed.

Fig (6) and Fig (7) shows the response of active and reactive stator powers by using the sensor-less SMC controller and current in axe d/q and electromagnetic torque.

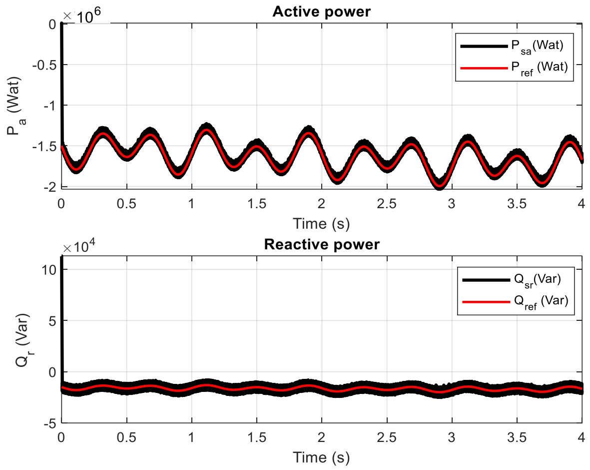

Fig. 6. Active and reactive power control of DFIG using SMC.

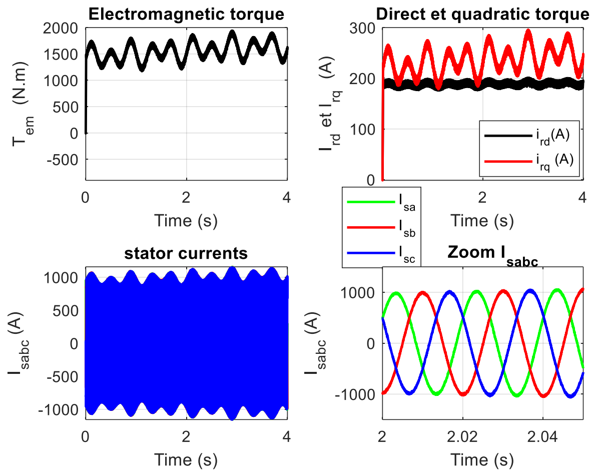

Fig. 7. The control of DFIG using SMC.

These figures confirm a good tracking, and perfect decoupling, and the time of transient state is null, the static error neglected, the currents is strictly sinusoidal, therefore improvement of the energy quality.

In this part, the wind turbine chain provides with DFIG, this machine will be validated according to an industrial Benchmark shown in Fig (8), with speed range [+104 -20] (rad/s), to examine the robustness and performance of the proposed sensor-less controller (SMC/EKF).

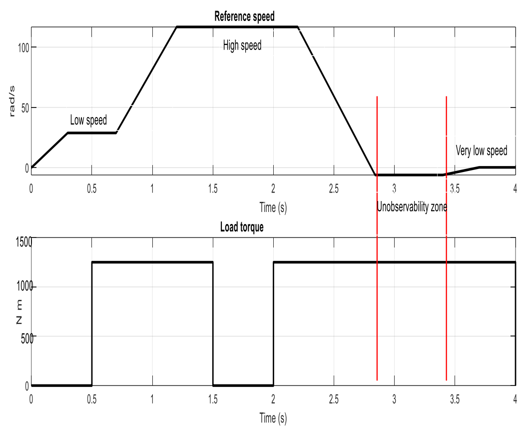

Fig. 8. Industrial Benchmark.

Fig (9) illustrates the speed estimated by using Extended Kalman Filter (EKF). We note that the response of the estimated speed is identical between speed measured with speed of reference, the error is almost zero, and confirm the robustness of the sensor-less sliding mode provide with EKF.

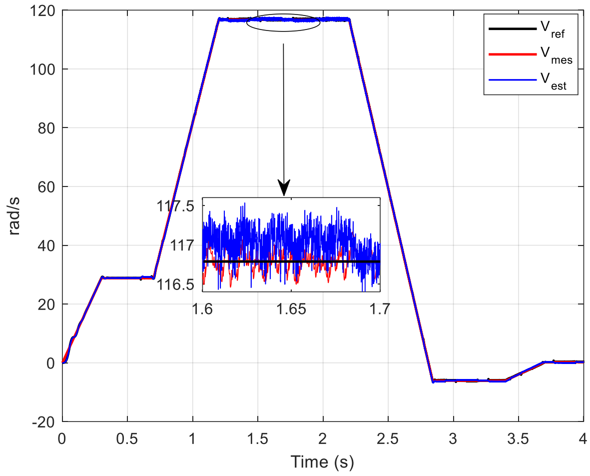

Fig. 9. The rotational speed (Real, Estimated, Reference) based on EKF.

Fig (10) presents an observation and the tracking errors (V_{mes}-V_{est} and V_{mes}-V_{ref}), the torque of load is applicated at t = 0.5 s/t = 2 s and cancels in t = 1.5 s/t = 4 s, in steady state, the pic in observation speed (± 0.5 rad/s). This figure confirm the performance and robustness of the control sensor-less SM based on EKF.

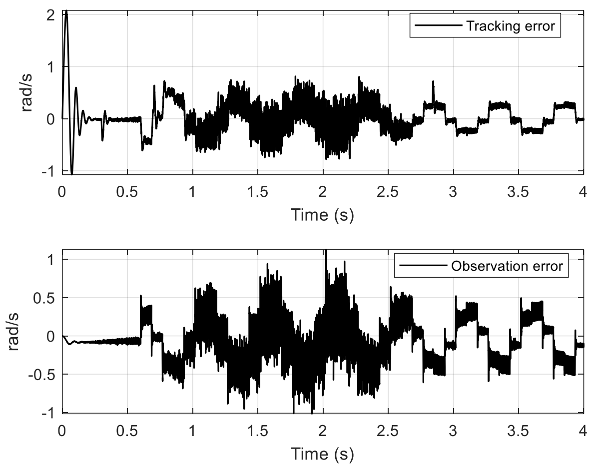

Fig. 10. The observation error and the tracking error based on EKF.

VI. Conclusion

The main purpose of this study is to reduce the cost and the size of machine (DFIG) by replace the encoder (mechanical sensor), by using state observer (EKF). The sensor-less speed sliding mode control of wind turbine system based on a DFIG provided with the Extended Kalman filter (EKF) is confirmed its performance and robustness, good dynamic performance.

The results present an excellent estimation when we used different conditions (low speed, high speed), and low sensitivity when we applicate load torque (good disturbance rejection).

References

[1] L. Saihi, B .Berbaoui, and H. Glaoui, 2020. Robust Control H∞ Fuzzy of a Doubly Fed Induction Generator Integrated to Wind Power System, Majlesi Journal of Electrical Engineering 14.1,59-69.

[2] Y. Bakou, L. Saihi, K. Koussa, F. Ferroudji, K. Roumani, M. Meguellati, and A. Aissaoui, 2019. Design of Robust Control Based on R∞ Approach of DFIG for Wind Energy System, 1st Global Power, Energy and Communication Conference (GPECOM), pp. 337-341. IEEE.

[3] C. Wei, C. Yankun, L. Hongfeng, S. Zhanfeng, "Sensorless Control of Permanent Magnet Synchronous Motor Based on Sliding Mode Observer", 2012 IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia June 2-5, 2012, Harbin, China.

[4] M. Ezzat1, J. Leon, N. Gonzalez, A. Glumineau, " Sensorless Speed Control of Permanent Magnet Synchronous Motor by using Sliding Mode Observer", 2010 11th International Workshop on Variable Structure Systems Mexico City, Mexico, June 26 - 28, 2010 IEEE.

[5] L. Saihi, B. Berbaoui, H. Glaoui, L. Djilali and S. Abdeldjalil, 2019. Robust sliding mode H∞ controller of DFIG based on variable speed wind energy conversion system, Periodica Polytechnica Electrical Engineering and Computer Science.

[6] L. Saihi; Y. Bakou; F. Ferroudji; B. Berbaoui; L. Djilali, 2019. MPPTF & Pitch Fuzzy Controller of a Wind Turbine System Using DFIG, 1st International Conference on Sustainable Renewable Energy Systems and Applications (ICSRESA).

[7] L. Saihi, and A. Boutera, 2016. Robust control of a variable-speed wind turbine with fixed pitch angle and strategy MPPT control associated on a PMSG, In 8th International Conference on Modelling, Identification and Control (ICMIC), pp. 326-331. IEEE.

[8] L. Saihi, F. Ferroudji, B. Berbaoui, Y. Bakou, K. Koussa, M. Meguellati, and K. Roumani, 2019. Hybrid control based on sliding mode fuzzy of DFIG power associated WECS, In AIP Conference Proceedings, vol.2123, no.1, pp. 030015.

[9] L. Saihi, Y. Bakou, A. Harrouz, I. Colak, K. Kayisli and R. Bayindir, A Comparative Study Between Robust Control Sliding Mode and Backstepping of a DFIG Integrated to Wind Power System,"2019 7th International Conference on Smart Grid (icSmartGrid), 2019, pp. 137-143, https://doi.org/10.1109/icSmartGrid48354.2019.8990810.

[10] Saihi L., Ferroudji F., Berbaoui B., Koussa K., Roummani K., Bakou Y. (2022) Sliding Mode Fuzzy MPPT Controller of a Wind Turbine System Based on DFIG. In: Hatti M. (eds) Artificial Intelligence and Heuristics for Smart Energy Efficiency in Smart Cities. IC-AIRES 2021. Lecture Notes in Networks and Systems, vol 361. Springer, Cham. https://doi.org/10.1007/978-3-030-92038-8_60.

[11] Saihi L. Berbaoui, B., Ferroudji F., Koussa K., Roummani K., Bakou Y (2020) Super Twisting High Order Sliding Mode Control of Vertical Axis Wind Turbine with Direct Attack Based on Doubly Fed Induction Generators. In: Hatti M. (eds) Smart Energy Empowerment in Smart and Resilient Cities. ICAIRES 2019. Lecture Notes in Networks and Systems, vol 102. Springer, Cham. https://doi.org/10.1007/978-3-030-37207-1_19.

[12] L. Saihi, A. Bouhenna, M. Chenafa, and A Mansouri, 2015. A robust sensorless SMC of PMSM based on sliding mode observer and extended Kalman filter," In 4th International Conference on Electrical Engineering (ICEE), pp.1-4, IEEE.

[13] Bakou, Y., Saihi, L., Hammaoui, Y., Harrouz, A., Colak, I., Kayisli, K., ... & Bayindir, R. A. M. A. Z. A. N. (2019, December). Robust Controller Based on Sliding Mode Technique of DFIG Integrated to Wind Energy System. In 2019 7th International Conference on Smart Grid (icSmartGrid) (pp. 144-148). IEEE.S

[14] Saihi, L., and A. Boutera, 2016. Robust sensorless sliding mode control of PMSM with MRAS and Luenberger extended observer, In 8thInternational Conference on Modelling, Identification and Control (ICMIC), pp. 174-179. IEEE.

[15] Yaichi, S. AbdelHafid, Y. Hammaoui, M. Djlaila, A. Harrouz, S. Mansouri and Y. Bakou, " Modelling and control doubly fed induction machine, application for a wind turbine system", Journal "IEEE Xplore'' of the International Renewable and Sustainable energy Conference (IRSEC'16), 2017, ISSN: 2380-7393. DOI: 10.1109/IRSEC.2016.7983953

[16] Tahiri, F. Bekraoui, F. Boussaid I, Ouledali, O. A. Harrouz. Direct Torque Control (DTC) SVM Predictive of a PMSM Powered by a photovoltaic source. Algerian Journal of Renewable Energy and

Sustainable Development, 2019, 1(1),1-7. https://doi.org/10.46657/ajresd.2019.1.1.1

[17] A. Harrouz, Tahiri, F. Bekraoui, F. Boussaid I. Modelling and Simulation of Synchronous Inductor Machines. Algerian Journal of Renewable Energy and Sustainable Development, 2019, 1(1),8-23. https://doi.org/10.46657/ajresd.2019.1.1.2

[18] Belatrache D, A. Harrouz, Abderrahmane A, Manaa S. Numerical Simulation of a Pseudo Plastic Fluid Through Sudden Enlargement. Algerian Journal of Renewable Energy and Sustainable Development, 2019, 1(1),92-98. https://doi.org/10.46657/ajresd.2019.1.1.9

[19] Bouzidi M, A. Harrouz, Mansouri S. Control and automation of Asynchronous motor using Fuzzy logic. Algerian Journal of Renewable Energy and Sustainable Development, 2019, 1(2),154-171 https://doi.org/10.46657/ajresd.2019.1.2.5

[20] Dahbi M, Sellam M, Benatiallah A, A. Harrouz. Investigation on Wind Power Generation for Different Heights on Bechar, South West of Algeria. Algerian Journal of Renewable Energy and Sustainable Development, 2019, 1(2),198-203. https://doi.org/10.46657/ajresd.2019.1.2.9

[21] Benatiallah D, Bouchouicha K, Benatiallah A, A. Harrouz, Nasri B. Forecasting of Solar Radiation using an Empirical Model. Algerian Journal of Renewable Energy and Sustainable Development, 2019, 1(2),212-219. https://doi.org/10.46657/ajresd.2019.1.2.11

[22] I. Boussaid, A. Harrouz, and P. Wira, "Advanced Control of Doubly Fed Induction Generator for Wind Power Systems: Optimal Control of Power Using PSO Algorithm," Applied Mechanics and Materials, vol. 905, pp. 29-42, 2022, DOI: https://doi.org/10.4028/v-era743.

[23] A. Harrouz, I. Yaichi, I. Boussaid, Abdelhafid Semmah, Patrice Wira ,K Kayisli, I Colak, “An Improved DTC Strategy for a DFIG using an Artificial Neural Network Controller”, IEEE Xplore of International Conference.icSmartGrid2021. DOI:10.1109/icSmartGrid52357.2021.9551251

[24] A. Harrouz, I Colak, K. Kayisli, “Energy Modelling output of Wind system based on Wind Speed ”, IEEE EXPLORE of 8th International Conference on Renewable Energy Research and Applications (ICRERA), Brasov, Romania, 2019. DOI: 10.1109/ICRERA47325.2019.899652