**International Journal of Power Electronics and Drive Systems (IJPEDS)**
Vol. 14, No. 3, September 2023, pp. 1739~1747
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v14.i3.pp1739-1747 

# ANFIS based sliding mode control of a DFIG wind turbine excited by an indirect matrix converter

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**Article Info**

***Article history:***

Received Dec 1, 2022
Revised Feb 27, 2023
Accepted Mar 7, 2023

***Keywords:***

ANFIS
DFIG
Indirect matrix converter
SMC
Wind turbine

**ABSTRACT**

Doubly fed induction generator (DFIG) is very popular in commercial turbines installed worldwide. Indirect matrix converter (IMC) is a fully silicon-based converter without capacitor that could be used in wind turbines. In this paper a robust ANFIS based second order sliding mode controller is proposed to control the DFIG wind turbine excited by IMC converter. ANFIS is a combination of fuzzy logic control and artificial neural networks. This hybrid combination could decrease the complexity of the wind turbine system. This scheme does not need the exact mathematical model of the system as needed in classical control methods. The effectiveness of the proposed controller is verified by simulation results compared to the classical PI controller.



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## 1. INTRODUCTION

Wind energy is growing fast throuought the world as an attractive renewable resource of electricity energy. The manufacturing technology of the wind turbines improved during the last decade, especially in power electronics section and recyclable blades technology. The rate of installed capacity of wind turbines is about 30 percent worldwide. Nowadays, the variable speed technology is dominant in wind turbine industry worldwide due to their advantages Ove the initial fixed speed counterpart. The doubly fed induction generator (DFIG) is the most utilized generator because of variable speed operation and low-cost power electronics drive. Schematic of a DFIG wind turbine is drawn in Figure 1. In this structure, the stator winding connection to the utility is done directly or by a transformer and the rotor three phase winding connection to the utility is accomplished by a power electronics converter. The B2B converters are used commonly to control the generator. The bulky dc-link capacitor is a challenge in this structure in case of reducing the reliability of the overall system and increasing the cost of the converter [1].

In this paper, the B2B converter structure is substituted by an indirect matrix converter (IMC) to excite the generator. The IMC's reliability and robustness are more than B2B converter due to removing the bulky electrolytic capacitor. Also, the size and weight of the IMC are less than B2B counterpart. Furthermore, the power factor in the input side is controllable in IMC and the input currents with output voltage are nearly sinusoidal with just high frequency switching harmonics. Consequently, the IMC could be utilized in wind turbines instead of traditional B2B converter due to aforementioned characteristics.

Classical control methods are investigated in some previous published papers in case of DFIG wind turbines [2]–[8]. Based on exponential reaching law a sliding mode control is proposed in [9]. The presented scheme at first control the electromagnetic torque and power factor to achieve maximum power point tracking (MPPT) in different speeds of the wind. Secondly, the chattering phenomenon and reaching speed of the states are approved in this scheme. Chattering near the sliding surface is inevitable due to high-speed switching law. Therefore, it is a challenge in case of using this controller in commercial wind turbines to avoid high frequency dynamics of the system excited by chattering of the controller. A set of adaptive and nonlinear algorithms to control variable speed wind turbines is presented in [10]. Both mechanical and electrical dynamics of the system is considered to design the controller. Validation of the presented control method is done by simulation results in capturing maximum power available from the wind and smooth speed control of the generator in different scenarios. A direct control of active-reactive powers of the generator is proposed in [11]. This method is relied on nonlinear sliding mode control to calculate the rotor voltage in order to set the active power and reactive errors of the generator to zero. Consequently, this control method does not require the internal current controller and synchronous reference frame transformation that leads to a simple control method.

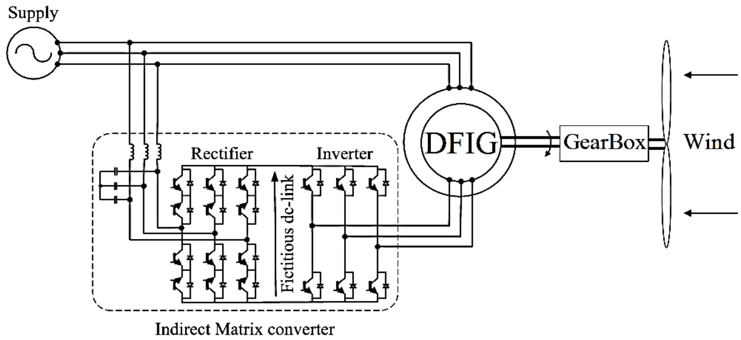



Figure 1. The IMC controlled DFIG wind turbine

The synchronizing of DFIGs without PLL to a distorted and unbalanced utility based on SMC is proposed [12]. The authors claimed that it could be avoided to mass calculations of positive and negative components by implementing in the original reference frame. The aim of this work is to synchronize the DFIG to the grid as mentioned. The behavior of the DFIG during fault based on sliding mode control is discussed in [13]. Modelling of the DFIG is done in a frame that the d-axis is aligned with the flux of the stator in this work. The stability of the system is proved by Lyapunov function. Model predictive control scheme is presented to control the DFIG wind turbine in [14]. To achieve the machine side converter control method, the model of the DFIG is linearized. So, this scheme could not be effective through wide operating area of the system and nonlinear behavior of the wind turbine for all conditions. Utilizing classical PI controller is well-known in the literature and discussed with details in [15]–[18].

Due to the merits of the matrix converters over the B2B structure, some authors investigated replacement of the B2B with the matrix converters [19]–[25]. Controlling the doubly-fed induction generators by the DTC and fuzzy logic utilizing IMC are proposed in [22], [23]. MPC Control of the DFIG using IMC is presented in [24]. The DFIG's dynamic performance utilizing IMC during grid fault has been investigated in [25]. In [26] an IMC is utilized driving a fixed speed WT. Simulation results of a DFIG wind turbine controlled by an IMC in [22] show that the harmonics content of the system is reduced.

Adaptive-neuro-fuzzy inference system based on sliding-mode-controller (ANFIS-SMC) is an interesting controller that could be used in wind turbine applications. ANFIS is a combination of fuzzy logic control and artificial neural networks. This hybrid combination could decrease the complexity of the wind turbine system. The exact model of the system is not required in the ANFIS; therefore, the realization of the control is simpler than the methods designed based on exact model. Furthermore, ANFIS based on Sugeno could bring better results compared with classical methods. Therefore, in this paper this controller is utilized for improving the dynamic response of a wind turbine system.

The remaining of the paper is categorized as follow. Control and modelling of the doubly fed induction generator is investigated in the next section. In section 3, the ANFIS-SMC control of the generator is presented in section 3. Simulation results in different wind speeds are presented in section 4. A brief conclusion of the given results is brought in the final section of the paper.

## 2. MODELING AND CONTROL OF THE SYSTEM

The dynamic model of a doubly fed induction generator is presented in this section. Connection of the stator winding of the DFIG to the utility is done directly or through a transformer, and the rotor winding connection to the grid is done by an IMC. The IMC rating is about 30 percent of the nominal power of the wind turbine due to this fact that the rotor winding must handle the slip power in this structure. The rotor's shaft of the DFIG is connected to the blades' shaft through a multi-stage gearbox that increase the low speed of the wind to the operation speed required for the DFIG.

### 2.1. DFIG model

The dynamic model of the DFIG is presented by a fifth-order system. The d-q components of electrical parameters of the DFIG in a reference frame that the d-axis is aligned to the flux of the stator and rotate with synchronous speed of the utility are as follows:

$$
\begin{aligned}
&v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} && \varphi_{ds} = L_m i_{dr} + L_s i_{ds} \\
&v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} && \varphi_{qs} = L_m i_{qr} + L_s i_{qs} \\
&v_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_s - \omega_r)\varphi_{qr} \quad ; && \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \\
&v_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega_s - \omega_r)\varphi_{dr} && \varphi_{qr} = L_r i_{qr} + L_m i_{qs} \\
&T_{em} = P(\varphi_{qr} i_{dr} - \varphi_{dr} i_{qr}) && L_s = L_m + L_{ls} \quad , \quad L_r = L_m + L_{lr}
\end{aligned} \tag{1}
$$

In these relations, $L_s$, $L_r$, $L_{ls}$, $L_{lr}$, $R_s$ and $R_r$ are the inductances and resistances of the rotor and stator windings, $L_m$ is the magnetizing inductance, ($v_{ds}$, $v_{qs}$, $v_{dr}$, $v_{qr}$), ($i_{ds}$, $i_{qs}$, $i_{dr}$, $i_{qr}$), ($\varphi_{ds}$, $\varphi_{qs}$, $\varphi_{dr}$, $\varphi_{qr}$) are two-axis components of the spatial vectors of the rotor and stator voltages, currents, and fluxes respectively. The angular synchronous speed of the utility is denoted by ωs while the electrical angular speed of the rotor is shown by $\omega_r$. Lastly, the number of pole pairs of the machine is defined by P.

### 2.2. Indirect matrix converter

In this paper, the B2B converter structure is substituted by an IMC to excite the generator. The IMC's reliability and robustness are more than B2B converter due to removing the bulky electrolytic capacitor. The schematic of an IMC is shown in Figure 2. In the input rectifier section bidirectional switches are used and the fictitious dc-link polarity is denoted by P and N for positive and negative rails. To simplify the calculations, it could be a logical assumption that the switching frequency is very greater than the frequencies of both the output current and input voltage. Based on this assumption, in each cycle of the switching, both the output current and the input voltage could be kept as constants.

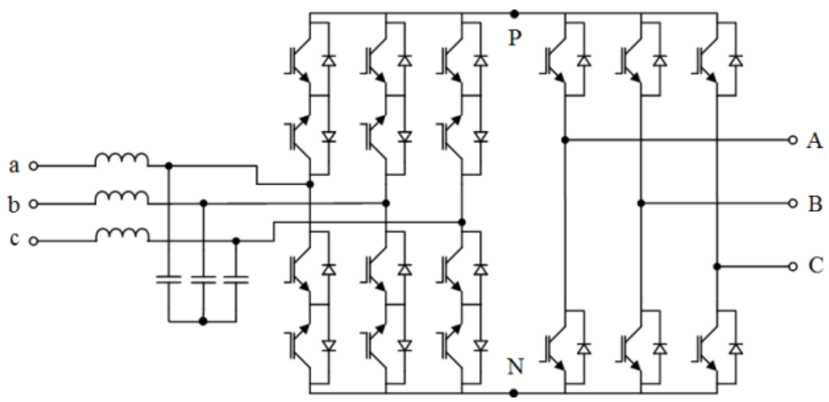



Figure 2. Schematic of a three-phase to three-phase IMC

The rectification part of the IMC must be switched to obtain maximum voltages in the fictitious dc-link and low harmonics of injected currents to the grid. In normal operation mode of the DFIG, the unit power factor is favorable at the rectifier side. To obtain the maximum dc-link voltage at each 60-degree intervals, the input phase voltage with highest absolute value is switched to the positive or negative rails of the fictitious dc-link. Assume the input voltages are as follows:

$$v_a = V_p \cos\delta_a = V_p \cos(\omega_i t)$$
$$v_b = V_p \cos\delta_b = V_p \cos(\omega_i t - \frac{2\pi}{3})$$
$$v_c = V_p \cos\delta_c = V_p \cos(\omega_i t + \frac{2\pi}{3}) \quad (2)$$

where $V_p$ is the phase peak of the input voltage. The frequency of the utility is denoted by $w_i$. To obtain at the input side unit power factor during normal operation mode, the phase difference between the currents and voltages in the input must be zero. Consequently, the injected currents to the grid are given by:

$$I_a = I_p \cos(\omega_i t)$$
$$I_b = I_p \cos(\omega_i t - \frac{2\pi}{3})$$
$$I_c = I_p \cos(\omega_i t + \frac{2\pi}{3}) \quad (3)$$

where $I_p$ is the peak of the currents injected to the grid. It should be noted that on the rectification part of the IMC two switches, one of the top switches and the other from the down switches, are always ON and the four remain switches are OFF.

## 3. ANFIS-SMC

SMC is a nonlinear variable structure controller. Realization of the control system in this method is simple. In contrast with classical control methods, this scheme does not need the exact mathematical model of the system. The main objective of the wind turbine controller is to decouple controlling of the active and reactive power injecting to the grid. Therefore, the sliding surfaces are considered as (4).

$$\begin{bmatrix} S_d \\ S_q \end{bmatrix} = \begin{bmatrix} I_{drref} - I_{dr} \\ I_{qrref} - I_{qr} \end{bmatrix} \quad (4)$$

Based on the defined surfaces as above, the derivation are as (5).

$$\begin{bmatrix} S_d \\ S_q \end{bmatrix} = \begin{bmatrix} I_{drref} - I_{dr} \\ I_{qrref} - I_{qr} \end{bmatrix} \quad (5)$$

Substituting the derivatives of the rotor active and reactive currents components, we obtain:

$$\begin{bmatrix} S_d \\ S_q \end{bmatrix} = \begin{bmatrix} I_{drref} - \frac{\alpha}{\sigma Lr}\left[V_{dr} - R_r.I_{qr} - g.ws.\sigma.L_r.I_{dr} - g\frac{M.V_S}{L_S}\right] \\ I_{qrref} - \frac{\alpha}{\sigma Lr}\left[V_{qr} - R_r.I_{dr} + g.ws.\sigma.L_r.I_{qr}\right] \end{bmatrix} \quad (6)$$

If the $K_1$ and $K_2$ functions are defined as follows:

$$\begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = \begin{bmatrix} I_{drref} - \frac{\alpha}{\sigma Lr}\left[-R_r.I_{qr} - g.ws.\sigma.L_r.I_{dr} - g\frac{M.V_S}{L_S}\right] \\ I_{qrref} - \frac{\alpha}{\sigma Lr}\left[-R_r.I_{dr} + g.ws.\sigma.L_r.I_{qr}\right] \end{bmatrix} \quad (7)$$

then the equation based on these functions and d-q components of the rotor voltages are as (8).

$$\begin{bmatrix} S_d \\ S_q \end{bmatrix} = \begin{bmatrix} \frac{\alpha}{\sigma Lr}V_{dr} + K_1 \\ \frac{\alpha}{\sigma Lr}V_{qr} + K_2 \end{bmatrix} \quad (8)$$

ANFIS-SMC is similar to the classical SMC method that the switching term in controller is substituted with an ANFIS controller shown in Figure 3. Additionally, oscillations of control parameters in ANFIS-SMC controller are much lower than classical SMC. Block diagram of ANFIS controller is presented in Figure 4.

Fuzzy system contains 49 rules and membership functions are chosen to be triangular. The SMC controller is based on super-twisting algorithm proposed be LEVANT as follows:

$$\begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} -\lambda_1 sign(S_d) - \delta_1 |S_d|^{0.5} sign(S_d) \\ -\lambda_2 sign(S_q) - \delta_2 |S_q|^{0.5} sign(S_q) \end{bmatrix} \tag{9}$$

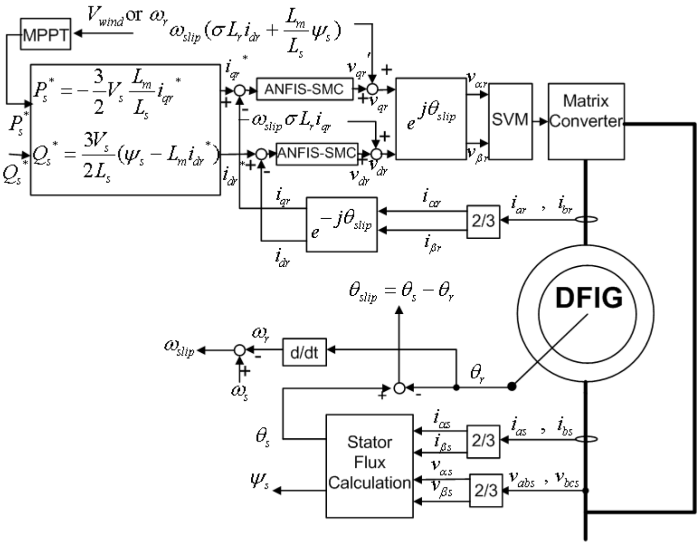



Figure 3. Block diagram of ANFIS-SMC

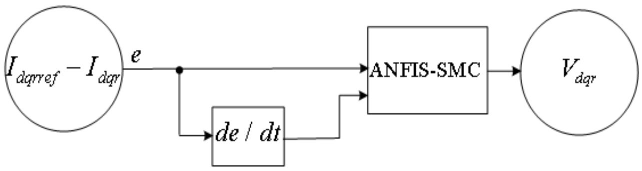



Figure 4. Schematic of ANFIS controller

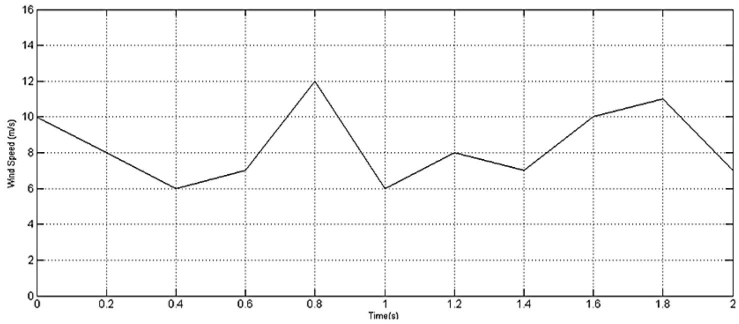
## 4. SIMULATION RESULTS

In order to verify the dynamic performance of the proposed controller, a 1.5 MW DFIG wind turbine is simulated in MATLAB/Simulink software. To validate the overall performance of the controller a variable wind profile for two seconds period is selected as presented in Figure 5(a). In order to clearly model the system, the power electronics converter is modeled based on real-time switches. Therefore, the total simulation time is increased compared with average model studies. The speed of the rotor is depicted in Figure 5(b) as it clears the inertia of the generator and control system make the speed variation smooth.

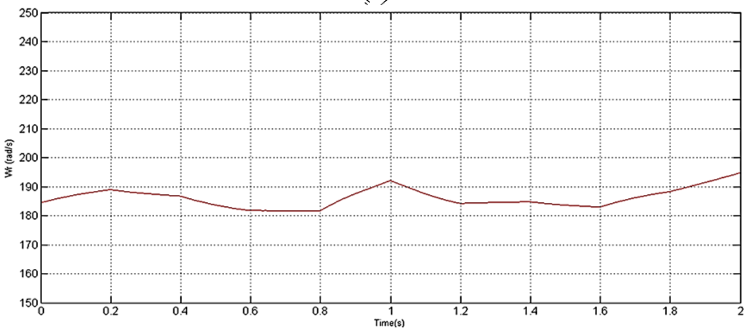
One of the main goals of a wind-turbine's controller is to decouple controlling of active and reactive powers. In order to investigate this capability of the controller, the active and reactive powers are monitored. To compare the results of the proposed controller, a well-tuned PI controller is also implemented for the same system. Figure 6 shows the reference and actual waveforms of the active power. The refence of the active power is generated from the MPPT algorithm to capture the maximum available power from the turbine. The MPPT algorithm used in this study is based on a look-up table method as it is common in commercial large wind turbines. The input of the look-up table could be the wind speed or the generator speed. In this study, the generator speed is selected as the input of MPPT block. The peak-to-peak error of the actual and the reference powers are 5% in PI method that is decreased to 1% in the proposed ANFIS-SMC controller. Therefore, the injected power to the grid is more smother in the proposed method that could increase the power quality of the wind turbine. This is an interesting result of the proposed controller that reduced the harmonics contents of the injected power to the grid significantly.

The results of the reactive power in both methods are depicted in Figure 7. The reference value of the reactive power is set to zero but as it is clear in the figure, the reactive power of the generator is -0.1 MVAr.

This is the required reactive power of the generator for magnetization of the core. However, the generator is capable of the reactive power injecting to the grid. But, in this study due to operation near the nominal active power the reactive power is set to zero. The currents of the generator are presented in Figure 8. The currents are pure sine waves for the stator and the rotor. The stator currents are with the grid frequency in spite of the rotor currents with the slip frequency.

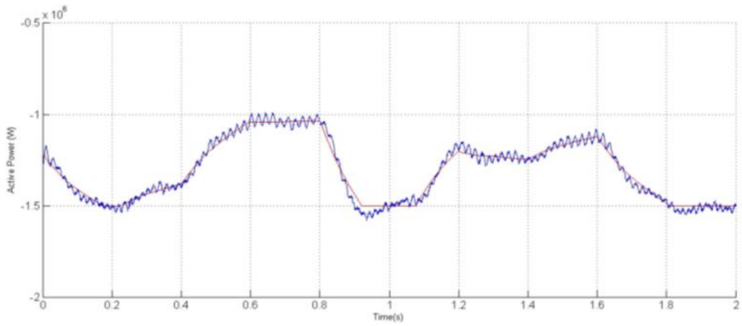



(a)

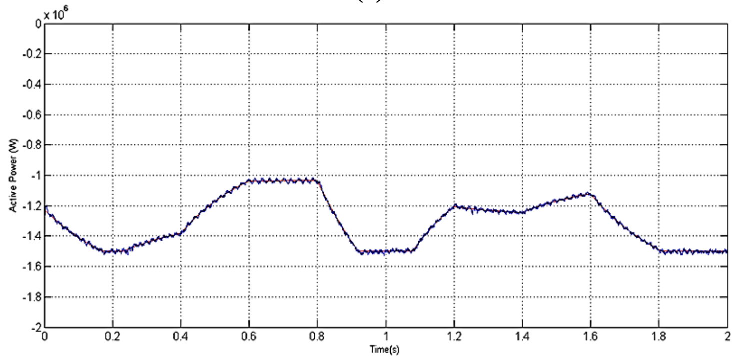



(b)

Figure 5. Variable speed operation of the system (a) wind speed profile and (b) rotor speed of the DFIG

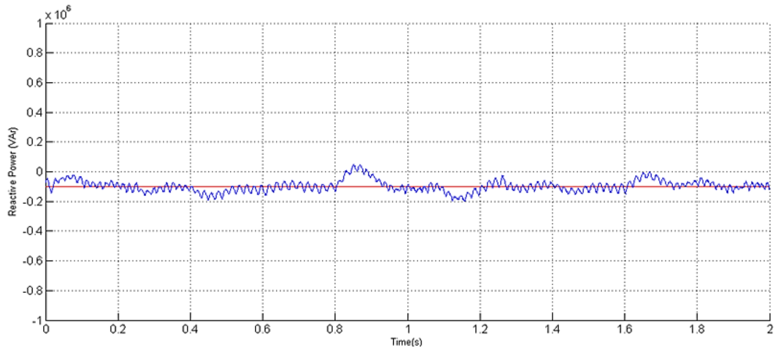



(a)

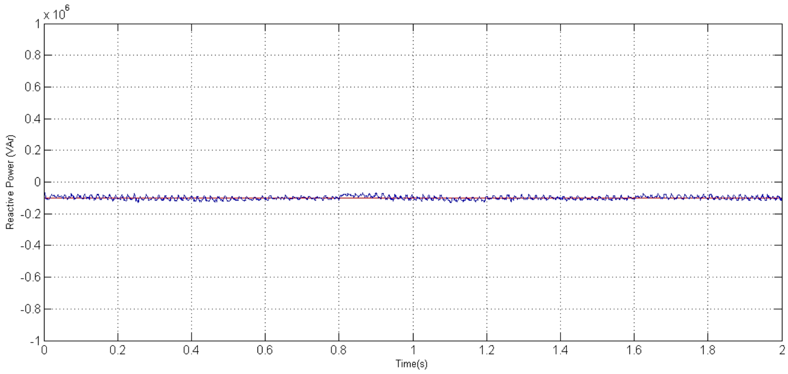



(b)

Figure 6. The generator active power injected to the grid: (a) PI controller and (b) ANFIS-SMC controller

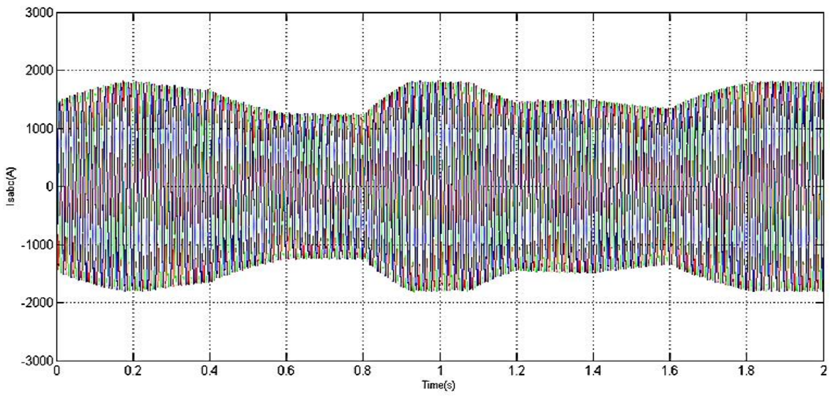



(a)

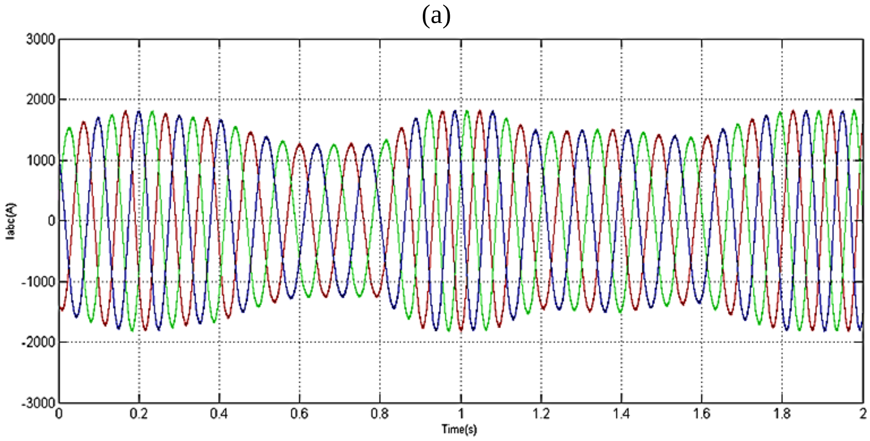



(b)

Figure 7. The generator reactive power injected to the grid: (a) PI controller and (b) ANFIS-SMC controller




(a)




(b)

Figure 8. The generator currents: (a) stator currents and (b) rotor currents

## 5. CONCLUSION

To improve the overall performance and increased reliability of the system, it is proposed in this paper to replace the conventional back-to-back converter with IMC. IMC is a fully silicon-based converter without capacitor that could be used in wind turbines. In this paper a robust ANFIS based sliding mode controller is designed to control the DFIG wind turbine excited by IMC converter. ANFIS is a combination of fuzzy logic control and artificial neural networks. The proposed controller is tested in variable wind speed for two seconds via exact model of switching converter. Simulation results show that in addition to very well reference tracking, the steady state error of the control parameters is reduced about 80 percent. Therefore, the effectiveness of the proposed controller compared to the classical PI controller is verified.

## REFERENCES


[1] K. Shi, X. Yin, L. Jiang, Y. Liu, Y. Hu, and H. Wen, "Perturbation Estimation Based Nonlinear Adaptive Power Decoupling Control for DFIG Wind Turbine," *IEEE Transactions on Power Electronics*, vol. 35, no. 1, pp. 319–333, 2020, doi: 10.1109/TPEL.2019.2911886.

[2] Z. En-Nay, I. Moufid, A. El Makrini, and H. El Markhi, "Improved crowbar protection technique for DFIG using fuzzy logic," *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 3, pp. 1779–1790, 2022, doi: 10.11591/ijpeds.v13.i3.pp1779-1790.

[3] A. Khajeh, R. Ghazi, M. Hosseini Abardeh, and M. Oukati Sadegh, "Evaluation of Synchronization and MPPT algorithms in a DFIG Wind Turbine Controlled by an Indirect Matrix Converter," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 9, no. 2, p. 784, Jun. 2018, doi: 10.11591/ijpeds.v9.i2.pp784-794.

[4] P. P. Pradhan, B. Subudhi, and A. Ghosh, "A Robust Multiloop Disturbance Rejection Controller for a Doubly Fed Induction Generator-Based Wind Energy Conversion System," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 5, pp. 6266–6273, 2022, doi: 10.1109/JESTPE.2022.3155561.

[5] A. T. Nguyen and D. C. Lee, "Sensorless Control of DFIG Wind Turbine Systems Based on SOGI and Rotor Position Correction," *IEEE Transactions on Power Electronics*, vol. 36, no. 5, pp. 5486–5495, 2021, doi: 10.1109/TPEL.2020.3027888.

[6] M. Abdeen, M. Sayyed, J. L. Dominguez-Garcia, and S. Kamel, "Supplemental Control for System Frequency Support of DFIG-Based Wind Turbines," *IEEE Access*, vol. 10, pp. 69364–69372, 2022, doi: 10.1109/ACCESS.2022.3185780.

[7] A. Khajeh and R. Ghazi, "GA-based optimal LQR controller to improve LVRT capability of DFIG wind turbines," *Iranian Journal of Electrical and Electronic Engineering*, vol. 9, no. 3, pp. 167–176, 2013.

[8] M. A. Beniss, H. El Moussaoui, T. Lamhamdi, and H. El Markhi, "Performance analysis and enhancement of direct power control of dfig based wind system," *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 2, pp. 1034–1044, 2021, doi: 10.11591/ijpeds.v12.i2.pp1034-1044.

[9] G. Tapia, G. Santamaría, M. Telleria, and A. Susperregui, "Methodology for smooth connection of doubly fed induction generators to the grid," *IEEE Transactions on Energy Conversion*, vol. 24, no. 4, pp. 959–971, 2009, doi: 10.1109/TEC.2009.2025334.

[10] J. A. Cortajarena, J. De Marcos, P. Alvarez, F. J. Vicandi, and P. Alkorta, "Start up and control of a DFIG wind turbine test rig," *IECON Proceedings (Industrial Electronics Conference)*, pp. 2030–2035, 2011, doi: 10.1109/IECON.2011.6119620.

[11] S. Z. Chen, N. C. Cheung, K. C. Wong, and J. Wu, "Grid synchronization of doubly-fed induction generator using integral variable structure control," *IEEE Transactions on Energy Conversion*, vol. 24, no. 4, pp. 875–883, 2009, doi: 10.1109/TEC.2009.2025316.

[12] A. Susperregui, M. Itsaso Martinez, G. Tapia-Otaegui, and A. Etxeberria, "Sliding-Mode Control Algorithm for DFIG Synchronization to Unbalanced and Harmonically Distorted Grids," *IEEE Transactions on Sustainable Energy*, vol. 13, no. 3, pp. 1566–1579, 2022, doi: 10.1109/TSTE.2022.3166217.

[13] D. Jiang, W. Yu, J. Wang, G. Zhong, and Z. Zhou, "Dynamic Analysis of DFIG Fault Detection and Its Suppression Using Sliding Mode Control," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 1, pp. 643–656, 2023, doi: 10.1109/JESTPE.2020.3035205.

[14] Y. Hu, T. K. Chau, X. Zhang, H. H. C. Iu, T. Fernando, and D. Fan, "A Novel Adaptive Model Predictive Control Strategy for DFIG Wind Turbine with Parameter Variations in Complex Power Systems," *IEEE Transactions on Power Systems*, 2022, doi: 10.1109/TPWRS.2022.3213085.

[15] W. Sadara and B. Neammanee, "Implementation of a three phase grid synchronization for doubly-fed induction generators in wind energy system," *ECTI-CON 2010 - The 2010 ECTI International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, pp. 1016–1020, 2010.

[16] A. Khajeh and Z. Shabani, "Adaptive Gain Scheduling Control of Doubly Fed Induction Generator Based Wind Turbines to Improve Fault Ride Through Performance," *International Journal of Industrial Electronics, Control and Optimization ?c*, vol. 1, no. 1, pp. 61–70, 2018.

[17] H. Mirnezhad, M. H. Ravanji, and M. Parniani, "Improved Generic Model of Variable Speed Wind Turbines for Dynamic Studies," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2162–2173, 2020, doi: 10.1109/TSTE.2019.2952144.

[18] M. Shahroozi, R. Ghobadi, and A. Radan, "Using virtual direct power control for synchronizing DFIG with grid," *PEDSTC 2014 - 5th Annual International Power Electronics, Drive Systems and Technologies Conference*, pp. 96–101, 2014, doi: 10.1109/PEDSTC.2014.6799351.

[19] A. Khajeh and R. Ghazi, "Control of DFIG wind turbines based on indirect matrix converters in short circuit mode to improve the LVRT capability," *Advances in Power Electronics*, vol. 2013, 2013, doi: 10.1155/2013/157431.

[20] J. Amini, R. Kazemzahed, and H. Madadi Kojabadi, "Performance enhancement of indirect matrix converter based variable speed Doubly-Fed induction generator," *PEDSTC 2010 - 1st Power Electronics and Drive Systems and Technologies Conference*, pp. 450–455, 2010, doi: 10.1109/PEDSTC.2010.5471772.

[21] E. Reyes, R. Pena, R. Cardenas, J. Clare, and P. Wheeler, "Control of a doubly-fed induction generator with an indirect matrix converter with changing DC voltage," *IEEE International Symposium on Industrial Electronics*, pp. 1230–1235, 2010, doi: 10.1109/ISIE.2010.5636925.

[22] A. Yarahmadi, D. A. Khaburi, and H. Behnia, "Direct Virtual Torque Control of DFIG grid connection using Indirect Matrix Converter," *2012 3rd Power Electronics and Drive Systems Technology, PEDSTC 2012*, pp. 115–120, 2012, doi: 10.1109/PEDSTC.2012.6183309.

[23] C. F. Calvillo *et al.*, "Rotor current fuzzy control of a DFIG with an Indirect Matrix Converter," *IECON Proceedings (Industrial Electronics Conference)*, pp. 4296–4301, 2011, doi: 10.1109/IECON.2011.6120014.
[24] M. Rivera *et al.*, "Model predictive control of a Doubly Fed Induction Generator with an Indirect Matrix Converter," *IECON Proceedings (Industrial Electronics Conference)*, pp. 2959–2965, 2010, doi: 10.1109/IECON.2010.5674942.
[25] A. Khajeh, R. Ghazi, and M. H. Abardeh, "Implementation of the maximum power point tracking algorithm on indirect matrix converter controlled DFIG wind turbine," *4th Iranian Conference on Renewable Energy and Distributed Generation, ICREDG 2016*, pp. 11–15, 2016, doi: 10.1109/ICREDG.2016.7875912.
[26] F. M. Savio, V. R. Rajan, B. Arun Kumaran, and C. S. A. Sekhar, "Performance analysis of an improved low harmonic indirect matrix converter for drive system in WECS," *Proceedings - NCET NRES EM 2014: 2nd IEEE National Conference on Emerging Trends in New and Renewable Energy Sources and Energy Management*, pp. 214–220, 2015, doi: 10.1109/NCETNRESEM.2014.7088770.

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