Neuro-fuzzy Sliding Mode Controller Based on a Brushless Doubly Fed Induction Generator

L. Ouada*, S. Benaggoune, S. Belkacem

* Faculty of Technology, LSTE Laboratory, University of Mostefa Ben Boulaid Batna 2, Algeria
* LEB Research Laboratory, Electrical Engineering Department, University of Mostefa Ben Boulaid Batna 2, Algeria

1. INTRODUCTION

The renewable energy market has grown considerably in recent years. The intensive consumption of electrical energy and the increase in the price of hydrocarbons have led several countries to initiate national and international programs intended to produce electrical energy from renewable resources [1].

The double Fed induction generator (DFIG), the most useful model for the use of wind energy, is undeniable. However, because of the presence of a slip ring and...
brushes that require more control and maintenance; its application in hostile environments is limited [2]. Thus, the emergence of Brushless Doubly fed Induction Generator (BDFIG) has made it possible to offset the many disadvantages of conventional electrical machines, such as brushes and slip ring systems [3].

The BDFIGs offer an alternative for wind power generation due to their lower capital, operating costs and higher reliability compared to dual power induction generators. The stator of this machine comprises two sets of three-phase windings with a different number of poles, a power winding (PW) and a control winding (CW) [3].

To ensure the conversion of wind energy, several control strategies have been proposed in order to properly control the exchange of power between different elements of this system. Vector control, based on the classic PI controller is traditionally used for the control of the active and reactive powers of the BDFIG [4-6]. However, the main drawback of this controller is that its performance strongly depends on the parameters of the drive. Known for its robustness and simplicity of implementation, the Sliding Mode Control (SMC) has been widely used to control a large class of nonlinear systems [7-10].

This control law represents a drawback resided in the use of the sign function in the control law to ensure the transition from the phased approach to that of sliding. This gives rise to the chattering phenomenon, which consists of sudden and rapid variations in the control signal, which can excite the high frequencies of the process and damage it. Indeed, to remedy the drawback of this phenomenon, several works have been performed [11-15].

Artificial intelligence methods have been combined with sliding mode control-to-control non-linear systems with uncertainties and at least to eliminate the chattering phenomenon. Fuzzy logic control [16,17] is often used in complex systems to overcome the limitations of conventional mathematical tools. It nevertheless has limits, in particular on the accuracy of the information expressed in natural language, thus presenting a certain margin of instability. Fuzzy sliding mode controller (FSMC) [18] is designed to control the reactive and active powers of the BDFIG. The main drawback of FSMC is the lack of systematic methods for designing fuzzy and functional rule, Lyapunov methods [19]. Although this method reduces chattering, but the controller becomes continuous and the SMC characteristics, such as convergence, robustness, cannot be achieved and steady state errors may occur.

To overcome these drawbacks, the current trend is to integrate these tools into hybrid architectures to take advantage of the fuzzy logic and neural networks. The use of a fuzzy neural network offers the possibility of modeling a priori knowledge and linguistic decision rules obtained by experts in the field [20-25]. Various studies show that the ANFIS Neuro-fuzzy system, known as adaptive networks based on fuzzy inference, is able to quickly learn the behavior of a system with precision, and is even better than the other methods.

The NFSMC controller is proposed in this paper to regulate the active and reactive powers of a BDFIG.

2. MODELING OF THE BRUSHLESS DOUBLY FED INDUCTION GENERATOR

A BDFIG is depicted in Figure 1. The BDFIG dynamic equations in the reference d-q form can be written as follows [3]. The expressions for stators, rotor voltage and flux equations are given below.

2.1. Stator Voltage Power SP

\[
\begin{align*}
V_{sp}^q &= R_{sp}I_{sp}^q + \frac{d\psi_{sc}^q}{dt}, \\
V_{sp}^d &= R_{sp}I_{sp}^d + \frac{d\psi_{sp}^d}{dt},
\end{align*}
\]

2.2. Rotor Voltage

\[
\begin{align*}
0 &= R_rI_r^q + \frac{d\psi_r^q}{dt} + \omega_L\psi_r^d, \\
0 &= R_rI_r^d + \frac{d\psi_r^d}{dt} - \omega_L\psi_r^q
\end{align*}
\]

2.3. Stator Voltage Control Power SC

\[
\begin{align*}
V_{sc}^q &= R_{sc}I_{sc}^q + \frac{d\psi_{sc}^q}{dt} + \omega_c\psi_r^d, \\
V_{sc}^d &= R_{sc}I_{sc}^d + \frac{d\psi_{sc}^d}{dt} - \omega_c\psi_r^q
\end{align*}
\]

2.4. Stator Power Magnetic Flux

\[
\begin{align*}
\psi_{sp}^q &= l_{scp}I_{sp}^q + l_{mp}\psi_r^d, \\
\psi_{sp}^d &= l_{scp}I_{sp}^d + l_{mp}\psi_r^q
\end{align*}
\]
2.5. Rotor Magnetic Flux

\[
\psi_q^d = L_r L_p^q + L_{mc} I_{sc}^q + L_{mp} I_{sp}^q
\]

\[
\psi_r^d = L_r L_p^r + L_{mr} I_{sc}^r + L_{mr} I_{sp}^r
\]

\[
\psi_{sc}^q = L_{sc} I_{sc}^q + L_{mc} I_{sc}^r
\]

\[
\psi_{sc}^d = L_{sc} I_{sc}^d + L_{mc} I_{sc}^r
\]

The stator active and reactive power can be written according to the stator currents as:

\[
P_{sp} = \frac{3}{2}(V_{sp}^q I_{sp}^q + V_{sp}^d I_{sp}^d)
\]

\[
Q_{sp} = \frac{3}{2}(V_{sp}^q I_{sp}^d - V_{sp}^d I_{sp}^q)
\]

The electromagnetic torque is given by:

\[
T_{em} = \frac{3}{2} (P_r L_{mp} (V_{sp}^q I_{sp}^r - V_{sp}^r I_{sp}^q) + P_c L_{mc} (I_{sc}^q I_{sc}^r - I_{sc}^r I_{sc}^q))
\]

3. VECTOR CONTROL STRATEGY OF BDFIG

The objective of the vector control (VC) of BDFIG is to obtain a decoupled control of the active and reactive powers as in DC machines [6]. The vector control of BDFIG consists of making:

\[
\psi_{sp}^d = \psi_{sp}^q = 0
\]

The stator flux equation of the winding power becomes:

\[
0 = L_{sp} I_{sp}^q + L_{mp} I_{sp}^d
\]

\[
\psi_{sp}^d = L_{sp} I_{sp}^d + L_{mp} I_{sp}^d
\]

By neglecting resistances of the stator phases, the stator voltage will be expressed by:

\[
V_{sp}^q = 0
\]

\[
V_{sp}^d = V_{sp} = \psi_{sp}^d, \omega_{sp}
\]

From Equation (10), Equation (6) becomes:

\[
P_{sp} = \frac{3}{2}(V_{sp}^q I_{sp}^q + V_{sp}^d I_{sp}^d)
\]

\[
Q_{sp} = \frac{3}{2}(V_{sp}^q I_{sp}^d - V_{sp}^d I_{sp}^q)
\]

The rotor currents by:

\[
I_{sp}^q = \frac{-L_{mp}}{L_{sp}} I_{sp}^q
\]

\[
I_{sp}^d = \frac{\psi_{sc}^d - L_{mp} I_{sp}^d}{L_{sp}}
\]

\[
I_r^q = \frac{\psi_{sc}^q - L_{mp} I_{sp}^q - L_{mc} I_{sc}^q}{L_r}
\]

\[
I_r^d = \frac{\psi_{sc}^d - L_{mp} I_{sp}^d - L_{mc} I_{sc}^d}{L_r}
\]

We replace the expressions of the currents in Equation (12) we find:

\[
I_{sp}^q \left(1 - \frac{L_{mp}}{L_{sp}}\right) = \frac{-L_{mp}}{L_{sp}} \psi_r^q + \frac{-L_{mp} L_{mc}}{L_{sp} L_r} I_{sc}^q
\]

\[
I_{sp}^d \left(1 - \frac{L_{mp}}{L_{sp}}\right) = L_r \psi_{sp}^d = L_{mp} \psi_r^d + L_{mp} L_{mc} I_{sc}^q
\]

After simplification, we obtain:

\[
I_{sp}^q = \frac{-L_{mp}}{L_{sp} L_r - L_{mp}^2} \psi_r^q + \frac{L_{mp} L_{mc}}{L_{sp} L_r - L_{mp}^2} I_{sc}^q
\]

\[
I_{sp}^d = \frac{L_r}{L_{mp} L_r - L_{mp}^2} \psi_r^d + \frac{L_{mp} L_{mc}}{L_{sp} L_r - L_{mp}^2} I_{sc}^d
\]

where:

\[
\delta_1 = \frac{L_{mp} L_{mc}}{L_{sp} L_r - L_{mp}^2}, \delta_2 = \frac{L_{mp}^2}{L_{sp} L_r - L_{mp}^2}, \delta_3 = L_{sc} - \frac{L_{mp} L_{mc}}{L_{sp} L_r - L_{mp}^2}
\]

The stator active and reactive powers can be written according to the stator currents as:

\[
P_{sp} = \frac{3}{2} V_{sp}^d \left[-\delta_3 \psi_r^d + \delta_1 I_{sc}^q\right]
\]

\[
Q_{sp} = \frac{3}{2} V_{sp}^d \left[\delta_3 \psi_r^d - \delta_1 \psi_r^d + \delta_3 I_{sc}^d\right]
\]

We replace the expression of the current (I_{sp}^q, I_{sp}^d) of Equation (13) in Equation (5), we obtain:

\[\psi_{sc}^q = L_{sc} I_{sc}^q + L_{mc} \left(\psi_{sc}^d - L_{mp} I_{sp}^d - L_{mc} I_{sc}^d\right)\]

\[\psi_{sc}^d = L_{sc} I_{sc}^d + L_{mc} \left(\psi_{sc}^q - L_{mp} I_{sp}^q - L_{mc} I_{sc}^q\right)\]

We put the current expression (I_{sp}^q, I_{sp}^d) of Equation (15) in Equation (18), we obtain:

\[
\psi_r^q = L_r I_r^q + \frac{L_r}{L_r} \left[\psi_{sc}^q - \frac{L_r}{L_r} \left(-I_{sp}^q \psi_{sp}^q - L_r I_{sp}^q\right)\right]
\]

\[
\psi_r^d = L_r I_r^d + \frac{L_r}{L_r} \left[\psi_{sc}^d - \frac{L_r}{L_r} \left(-I_{sp}^d \psi_{sp}^d - L_r I_{sp}^d\right)\right]
\]

Finally:

\[\psi_{sc}^q = \delta_1 I_{sp}^q + \delta_2 \psi_r^q\]

\[\psi_{sc}^d = \delta_1 I_{sp}^d + \delta_2 \psi_r^d - \delta_1 \psi_{sp}^d\]

We put the expression of the flux (\psi_{sc}^q, \psi_{sc}^d) in Equation (3), we obtain the stator voltage as follows:

\[
V_{sp}^q = R_{sc} I_{sc}^q + \frac{d}{dt} \left(\psi_{sc}^q + \delta_1 I_{sp}^q + \delta_2 \psi_r^q + \omega_c \delta_1 I_{sp}^d + \delta_2 \psi_r^d\right)
\]

\[
V_{sp}^d = R_{sc} I_{sc}^d + \frac{d}{dt} \left(\psi_{sc}^d + \delta_1 I_{sp}^d + \delta_2 \psi_r^d - \delta_1 \psi_{sp}^d\right)
\]
\[ V_{sc}^q = R_{sc} I_{sc}^q + \frac{d}{dt} \left( \delta_2 I_{sc}^q + \delta_2 \psi_2^d - \delta_1 I_{sc}^d \right) - \omega_c \left( \delta_1 I_{sc}^d + \delta_2 \psi_2^q \right) \]

Block diagram of the vector control of BDFIG is shown in Figure 2.

4. Sliding Mode Control

Sliding mode control has been widely used in robust control approaches in many non-linear control methods, the basic idea that if we can force a system to evolve towards an equilibrium point according to a dynamic chosen by the designer using the continuous control law.

The proposed sliding surface is used in this work [8]:

\[ S(x) = \left( \frac{d}{dt} + \lambda \right)^{n-1} e \]  

(22)

\( \lambda \): is a positive coefficient, 
\( e = x_d - x \): is the error, 
\( x_d \): is the desired state, 
\( n \): is the system order.

4. 1. Switching Surface

Let the monovariable dynamic system described by the following state equation [8]:

\[ \dot{x} = f(x,t) + B(x,t)u(x,t) \]  

(23)

where: \( x \in \mathbb{R}^n \) is the state variable, \( u(x,t) \in \mathbb{R}^n \) is the control vector, \( B(x,t) \) are system parameter. The generalized SMC law is given as:

\[ U = U_n + U_{eq} \]

\[ U_n = K \times \text{sign}(s(x,t)) \]  

(24)

where, \( U \) is the control vector, \( U_{eq} \) is the equivalent control vector, \( \text{sign} \) is the signum function, \( K \) is the controller gain, \( s \) is the sliding surface. Figure 3 shows the sliding mode control block.

4. 2. Indirect Power Control with SMC of a BDFIG

In this section, the sliding surfaces are designed according to the current references of the stator control. The objective of this design is to independently control the generated active and reactive powers.

4. 2. 1. Choice of the Sliding Surface Control

Two sliding currents surfaces are used a first order is defined as:

\[ S(I_{sc}^d) = (I_{sc}^{q,ref} - I_{sc}^q) \]

\[ S(I_{sc}^q) = (I_{sc}^{d,ref} - I_{sc}^d) \]  

(25)

where \( I_{sc}^{q,ref}, I_{sc}^{d,ref} \) are the expected currents of control power reference.

We have voltages in Equation (21), it can be used to extract the expressions of control current:

\[ I_{sc}^q = \frac{1}{\delta_2} \left[ V_{sc}^q - R_{sc} I_{sc}^q - \delta_2 \psi_2^d - \omega_c (\delta_1 I_{sc}^d + \delta_2 \psi_2^d - \delta_2 \psi_2^q) \right] \]  

\[ I_{sc}^d = \frac{1}{\delta_1} \left[ V_{sc}^d - R_{sc} I_{sc}^d - \delta_1 \psi_2^d + \omega_c (\delta_1 I_{sc}^q + \delta_2 \psi_2^q) \right] \]  

(26)

5. Conditions of Convergence of This Control

To guarantee the convergence of the selected variables towards the references, the two sliding surfaces must be zero as follows:

\[ S(I_{sc}^{q,ref} - I_{sc}^q) = 0 \Rightarrow \frac{d}{dt}(I_{sc}^{q,ref} - I_{sc}^q) = 0 \]  

\[ S(I_{sc}^{d,ref} - I_{sc}^d) = 0 \Rightarrow \frac{d}{dt}(I_{sc}^{d,ref} - I_{sc}^d) = 0 \]  

(27)

The sliding area of the current control can be defined as follows:

\[ S(I_{sc}^q) = (I_{sc}^{q,ref} - I_{sc}^q) \]

\[ S(I_{sc}^d) = (I_{sc}^{d,ref} - I_{sc}^d) \]  

(28)

\[ S(I_{sc}^q) = \frac{1}{\delta_2} \left[ V_{sc}^q - R_{sc} I_{sc}^q - \delta_2 \psi_2^d - \omega_c (\delta_1 I_{sc}^d + \delta_2 \psi_2^d - \delta_2 \psi_2^q) \right] \]

\[ S(I_{sc}^d) = \frac{1}{\delta_1} \left[ V_{sc}^d - R_{sc} I_{sc}^d - \delta_1 \psi_2^d + \omega_c (\delta_1 I_{sc}^q + \delta_2 \psi_2^q) \right] \]  

(29)
5. 1. Control Law

The satisfactions of the control voltage and sign function are presented in the following:

\[ V_{sc}^d = V_{sc}^{d, eq} + V_{sc}^{d, att} \]
\[ V_{sc}^{d, eq} = K_d \times \text{sign}(s(x, t)) \]
\[ V_{sc}^{d, att} = K_d \times \text{sign}(s(x, t)) \]

with

\[ V_{sc}^{d, eq}, V_{sc}^{d, att} : \text{Control vectors relation.} \]
\[ V_{sc}^{d, eq}, V_{sc}^{d, att} : \text{Switching control.} \]
\[ K_d, K_q : \text{Positive constant.} \]

From Equation (30), the voltage equivalent control is given by:

\[ \dot{V}_{sc}^{d, ref} = \delta_1 \dot{I}_{sc}^{d, ref} + R_{sc} I_{sc}^{d} + \delta_2 \psi_r^q + \omega_c (\delta_3 I_{sc}^{d} + \delta_2 \psi_r^q - \delta_4 \psi_r^d) \]
\[ \dot{V}_{sc}^{d, eq} = \delta_1 \dot{I}_{sc}^{d, ref} + R_{sc} I_{sc}^{d} + \delta_2 \psi_r^q - \omega_c (\delta_3 I_{sc}^{d} + \delta_2 \psi_r^q) \]

6. 1. Adaptive Neuro-fuzzy Sliding Mode Control Inference System

A typical diagram of an ANFIS is shown in Figure 5, in which a circle indicates a fixed node on one hand and a square implies an adaptation node on the other hand [13]. In addition, x, y stand for two inputs and one output, Sugeno fuzzy is often used in various fuzzy inference models for the following reasons: high interpretability, increased efficiency and adaptation techniques where the number of epochs is set to 40 and error tolerance of 10^-6 [23].

The direct current error (e, de) is two inputs of ANFIS control in our system defined as:

\[ e = i_{sc}^{d, ref} - I_{sc}^d \rightarrow de = i_{sc}^{d, ref} - I_{sc}^d \]

where, (e,de) is the first order Sugeno case fuzzy inference employed by ANFIS, and the function fuzzy rule is:

If e is A_i and de is B_i, then y=f(e,de). Corresponding to the architecture of ANFIS which consists of five layers. The steps of ANFIS structure are:

Layer 1: Each corresponding node during this layer creates the membership range for the input vectors A_i, i=1,...,7.

Figure 4. Block diagram of BDFIG sliding mode control

Figure 5. ANFIS architecture
Layer 2: The node generates the crossing by multiplying all the incoming signals: \( O^2_l = w_l = \mu_A(x)\mu_B(y) \), for \( l = 1, \ldots, 49 \).

**Average nodes (Layer 3):** Divided by the sum of all other entries.

\[
O^3_i = \bar{w}_i = \frac{1}{\sum_{j=1}^{49} w_{ij}} \tag{33}
\]

**Consequent nodes (Layer 4):** Compute the contribution of the \( i \)-th rule in the output with the following node function.

\[
O^4_i = \bar{w}_i y_i = \bar{w}_i (p_i e + q_i \frac{de}{dt} + r_i)
\]

where, \( \bar{w}_i \) is the output of layer 3, and \( (p_i, q_i, r_i) \) are the parameter set of the ‘\( i \)-th’ node.

**Output node (Layer 5):** The neuron of layer 5 is a fixed node, at a given input; it delivers the network response given by:

\[
O^5_i = \sum_{i=1}^{49} \bar{w}_i f_i = \frac{\sum_{i=1}^{49} \bar{w}_i f_i}{\sum_{i=1}^{49} \bar{w}_i} \tag{34}
\]

6. **Description of the Control System**

Figure 6 shows the proposed Neuro-Fuzzy-Sliding Mode Control for controlling the active and reactive powers of the BDFIG. NFSMC controller replaces the switching control of SMC, the first input is the error of the current and the second input is the derivative of the error. Figure 6 shows the neuro-fuzzy sliding mode control.

7. **SIMULATION RESULTS**

Different power control methods have been studied and modeled with Matlab / Simulink software under the same test conditions powered by an PWM inverter. Simulations were applied to the 2.5 kW BDFIG system incorporating the NFSMC compared with the SMC and PI control. The parameters of the BDFIG system are illustrated and appended to Table 1 where the speed is fixed at 73 rad/s.

Figure 7 presents the NFSMC test with training and checking of reactive and active power reference error data sets after 40 epochs to guarantee good performance of results.

Figures 8 and 9 show the active and reactive powers produced by BDFIG with the different control strategies, VC, SMC and NFSMC. In these figures, we can notice that the ripple is not the same for the three techniques, it is clear that the VC suffers from two problems: stabilizing error and high ripples in the active power. On the other hand, the NFSMC offers an almost

**TABLE 1.** BDFIG parameters

| Power Winding (PW) | Control Winding (CW) | Rotor |
|--------------------|----------------------|-------|
| \( R_{sp} \) = 1.732(Ω) | \( R_{sc} \) = 1.079(Ω) | \( R_{r} \) = 0.473(Ω) |
| \( L_{sp} \) = 714.8(mH) | \( L_{sc} \) = 121.7(mH) | \( L_{r} \) = 132.6(mH) |
| \( L_{mp} \) = 242.1(mH) | \( L_{mc} \) = 59.8(mH) | \( p_e \) = 3; \( P_n \) = 2.5KW | \( p_s \) = 1 |

![Figure 6. Neuro-Fuzzy-Sliding Mode Control](image)

![Figure 7. NF-SMC training and checking error of active power](image)

![Figure 8. Reactive power response](image)

![Figure 9. Active power response under VC, SMC and NFSMC strategies](image)
perfect behavior in terms of performance and good follow-up compared to the PI and SMC.

Figure 10 shows the stator current on phase A, with sinusoidal shapes for the three strategies. We can observe that the current ripple also has a significant reduction of the NFSMC controller compared to the other controller.

7. Simulation Results with Parametric Uncertainty

To study the influence of the electrical parameter variation on the behavior of the BDFIG, we also simulated the system for a +100% of the nominal stator resistance at time \( t = 2.5 \) s.

Figures 11 and 12 illustrate the evolution of the powers. We note from this result that the scheme (PI) has a slight variation due to the variations of stator resistance. The proposed NFSMC method is robust against parameter variations and allows a fast and suitable dynamic response.

Table 2 presents the quantitative analysis of the three approaches. The comparison implicates that the proposed NFSMC gives less chattering with a seamless transient response.

| Approach                  | VC  | SMC | NFSMC |
|---------------------------|-----|-----|-------|
| Robustness to parameters mismatch | High | Low | Low  |
| Chattering                | Medium chattering | Considerable chattering | Small chattering |
| Transient performance of the active power | Relatively fast with medium settling time | Relatively fast with low settling time | Fast with low settling time |
| Rising time of the active power | 0.16 s | 0.12 s | 0.01 s |
| Transient performance of the reactive power | Relatively fast with medium settling time | Relatively fast with low settling time | Fast with low settling time |
| Rising time of the reactive power | 0.18 s | 0.14 s | 0.016 s |
| Implementation Complexity | High | Low | Low  |

8. CONCLUSION

In this paper, Neuro-Fuzzy Sliding Mode Control NFSMC for BDFIG has been presented. The suggested control has been compared with the classical vector control based on PI controller and sliding mode control. Simulation results demonstrate that the powers’ ripples is lower in NFSMC compared with the other controls. The efficiency of the proposed NFSMC has been validated by simulation tests carried out with a 2.5 KW BDFIG system. Moreover, to validate the influence of BDFIG parameter variations on the performances of the proposed NFSMC, sensitivity of the stator resistance parameter has been tested for the three schemes for +100% variations in stator resistance. It has been shown that the proposed approach is robust and capable to reject the influences of uncertainty in system parameters.

9. REFERENCES

1. Protsenko, K. and Xu, D., "Modeling and control of brushless doubly-fed induction generators in wind energy applications", IEEE Transactions on Power Electronics, Vol 23, No3, (2008), 1191–1197.
2. Tazil, M., Kumar, V., and Kong, S. "Three-Phase doubly fed induction generator: An over view", IET Electric Power Application, (2009), 75–89.
3. Jing, C., Xuefan, W., Tantan, Z., Zhenping, L., Ming, K. and Pengcheng, N., "Application of Brushless Doubly-Fed Machine System, Hybrid Power Generation", 2nd International Conference on Electrical Machines and Systems (ICEMS). IEEE, (2019), 1-4.

4. Sheng, H., and Guorong Z., "A Vector Control Strategy of Grid-Connected Brushless Doubly Fed Induction Generator Based on the Vector Control of Doubly Fed Induction Generator", 2016 IEEE Applied Power Electronics Conference and Exposition (APEC).

5. Chen, J. F., Zhang, W., Chen, B. J., and Ma, Y. L., "Improved vector control of brushless doubly fed induction generator under unbalanced grid conditions for offshore wind power generation", IEEE Trans. Energy Conv. Vol.31, (2016), 293-302.

6. Shyi, S., Ehsan, A., Farhad, B. , and Richard, M., "Stator-Flux Oriented Vector Control for Brushless Doubly Fed Induction Generator", IEEE Transactions on Industrial Electronics, Vol. 56,(2009),4220 – 4228.

7. Mahboub, M. A. and Drid, S. "Sliding mode control of a Brushless doubly fed induction generator", Proceedings of IEEE (ICSC) the 3rd Intel Conference on Systems and Control, Algeria, 2013.

8. Mazouz, F., Belkacem, S., Colak, I., and Drid, S., "Direct Power Control of DFIG by Sliding Mode Control and Space Vector Modulation", 7th International conference on system and control, IEEE (ICSC), Valencia – Spain, October, (2016),24-30.

9. Daoud, A., and Derbel, N., "Direct Power Control of DFIG Using Sliding Mode Control Approach", In Modeling, Identification and Control Methods in Renewable Energy Systems Springer, Singapore, (2019), 193-204.

10. Douadi, T., Y. Harbouche, R. Abbessemde, and I. Bakhti, "Improvement performances of active and reactive power control applied to DFIG for variable speed wind turbine using sliding mode control and POC, " International Journal of Engineering- Transactions A: Basics, Vol. 31, No.10, (2018), 1689-1697.

11. Yang, J., Jian, Y., Wei, T., Guanguan, Z., Yao, S., Sul, A., and Frede, B., "Sensorless Control of Brushless Doubly Fed Induction Machine Using a Control Winding Current MRAS Observer, IEEE Transaction on Industrial Electronics, Vol. 66, No.1, (2019), 728-738.

12. Juan, I., T. Paul, F.P., Marcelo, G.C., and José, A., "A Dual-Stator Winding Induction Generator Based Wind-Turbine Controlled via Super-Twisting Sliding Mode", Energies, Vol.12, (2019), 223-230.

13. Roberto, C., Pena, R., Wheeler, and Clare, P., "Control of a wind generation system based on a Brushless Doubly-Fed Induction Generator fed by a matrix converter", Electric Power Systems Research, Vol.103, (2013), 49-60.

14. Maryam, M., Rasool, K., and Mohammad, R.A. "Model-based predictive direct power control of brushless doubly fed reluctance generator for wind PMSG", Alexandria Engineering Journal, Vol. 55, (2016), 2497-2507.

15. Mahyar, G., Ashk naz, O., Sajjad, T., Hashem, O., and Richard A.M., "An analytical study for low voltage ride through of the brushless doubly-fed induction generator during asymmetrical voltage dips", Renewable Energy, Vol. 115, (2018), 64-75.

16. Belkacem, S., Naceri, F., and Abdessamed, R., "Reduction of torque ripple in DTC for induction motor using input-output feedback linearization", Turkish Journal of Electrical Engineering & Computer Sciences, Vol. 20, No. 3, (2012)1123-1130.

17. Youb, L., Belkacem, S., Naceri, F. Cernat, M. and Guasch, L. P. "Design of an Adaptive Fuzzy Control System for Dual Star Induction Motor Drives", Advances in Electrical and Computer Engineering, Vol. 18, No. 3, (2018).

18. Larbi, D. and Loukianov, A.G., "Neural Sliding Mode Control of a DFIG Based Wind Turbine with Measurement Delay", International Federation of Accountants, Vol. 51, (2018), 456-461.

19. Abdelbasset, M., Drid, S., Sid, M.A., and Radha, C. "Robust direct power control based on the Lyapunov theory of a grid-connected brushless doubly fed induction generator", Frontiers in Energy, Vol.10, (2016), 298-307.

20. Tiwari, N. K., Parveen, S., Bhupendra, K. S., Subodh, R. and Krishna, K. S."Estimation of Tunnel Desilted Sediment Removal Efficiency by ANFIS. Iranian Journal of Science and Technology, Transactions of Civil Engineering", (2019), 1-16.

21. Asar, M. F., Elawady, W.M., and Sarhan, A.M. “ANFIS-based an adaptive continuous sliding-mode controller for robot manipulators in operational space”. Multibody System Dynamics, (2019), 10-21.

22. Sana, B., and Anis, S., "Adaptive Neuro-Fuzzy Sliding Mode Controller", International Journal of System Dynamics Applications, Vol. 7, (2018).

23. Ilte, K.A., Uddin, M.N. , and Marsadek, M. "ANFIS Based Neuro-Fuzzy Control of DFIG for Wind Power Generation in Standalone Mode", 2019 IEEE International Electric Machines & Drives Conference (IEMDC).

24. Ibrahim, F.B., Ahmed, A., Ahmed, T., and Ahmed, L., "Robust neuro-fuzzy sliding mode control with extended state observer for an electric drive system", Energy, Vol. 169, (2018).

25. Mazouz, F., Belkacem, S., Drid, S., Chrif, A.L. and Colak L, "Fuzzy Sliding Mode Control of DFIG applied to the WECS", Proceedings of the 8th International Conference on Systems and Control, Marrakech, Morocco, October 23-25, 2019.
Neuro-fuzzy Sliding Mode Controller Based on a Brushless Doubly Fed Induction Generator

L. Ouada a, S. Benaggoune a, S. Belkacem b

Faculty of Technology, LSTE Laboratory, University of Mostefa Ben Boughlaï Batna 2, Algeria

LEB Research Laboratory, Electrical Engineering Department, University of Mostefa Ben Boughlaï Batna 2, Algeria

Keywords: Brushless Doubly Fed Induction Generator, Neuro-fuzzy Sliding Mode Control, Parameters Uncertainty, Sliding Mode Control, Vector Control

Abstract: A Neuro-Fuzzy Sliding Mode Controller (NFSMC) for a Brushless Doubly Fed Induction Generator (BDFIG) is proposed. An adaptive Neuro-Fuzzy (NF) Sliding Mode Controller (NFSMC) is presented to reduce the chattering effect of the traditional sliding mode control. The proposed controller is more robust against parameter uncertainties and external disturbances. Simulation results confirm the effectiveness of the proposed controller in comparison with the conventional sliding mode controller.

doi: 10.5829/ije.2020.33.02b.09