Synthesis of SMC algorithms applied to wind generator

Houaria Abdelli¹, Abdelkader Mezouar², Mokhtar Bendjebar³, Kheira Belgacem⁴
¹²³Diagnostic group LDEE, University of Science and Technology Mohamed Boudiaf, Oran, Algeria
⁴Laboratory of Electrical Engineering, Taher Moulay University, Saida, Algeria

ABSTRACT
The use of the classical (SMC) applied to control of stator’s powers of DFIG, gives the problem of chattering, therefore to avoid this phenomenon a robust algorithm (STSMC) is applied. This paper presents a comparison of conventional SMC with the proposed strategy of STSMC algorithm. The results are obtained using MATLAB and demonstrate stability and robustness of this algorithm.

This is an open access article under the CC BY-SA license.

Corresponding Author:
Abdelli Houaria
Department of Electrical Engineering,
University of Science and technology Mohamed Boudiaf
USTO (31000) Oran, Algeria.
Email: abdelli_houaria@yahoo.com

1. INTRODUCTION
Energy consumption has increased over the last decades considerably due to massive industrialization. A good alternative is to use renewable energies, which offer the possibility of producing electricity properly [1]. Among the renewable energies we find the wind turbine, which is becoming competitive in terms of production costs. It is reducing the emissions of greenhouse gases. Today, variable speed wind turbines based on (DFIG) offers many benefits, such as their efficient power density, the dimensioning of the converter on the rotor side is reduced to 30% of the nominal power of the machine [2], [3]. To have maximum wind power we use variable speed wind turbines [4], so to achieve this goal, the peak turbine speed ratio must be maintained at its optimum value despite the variation in wind speed [5], [6]. To solve the problem of tracking the maximum power point, different control techniques have been used, among them conventional (SMC). This controller offers some advantages: relative simplicity of implementation, robustness and external disturbances [7].

SMC is a robust control method [8], which guarantees the performance of the dynamic system by rejecting any disturbance acting on it. Despite the simplicity of its conception, the discontinuity of this command gives rise to the phenomenon of chattering. Several researchers have proposed solutions to avoid this phenomenon and guaranteed stability in steady state. [9], [10].

This paper presents a robust super-twisting sliding mode control of doubly fed induction generator (DFIG) based wind turbines. The simulation results showed a good STSMC control compared to the SMC algorithm. The rest of this article is organized as follows: Section 2 presents the wind turbine and DFIG modeling. The Section 3 describes the fundamental formulation of the proposed STSMC applied to the power...
based on DFIG. Section 4 presents the simulation results to demonstrate the performance of the proposed control scheme. At the end, conclusion is given in Section 5.

2. MATERIAL AND METHOD
2.1. The generator model

Block diagram of a wind turbine based on DFIG is given in figure 1. The model contains of a wind turbine, DFIG, converters, and a gearbox. The stator is connected to the network via a three-phase transformer and the rotor via another three-phase current source [11].

2.2. Turbine modeling

The expression of the aerodynamic power is presented by the (1) [12]:

\[ P_t = \frac{1}{2} C_p(\lambda) \rho \pi R^2 v^3 \]  

(1)

The \( C_p(\lambda) \) is power coefficient, is a nonlinear function of the relative speed ratio \( \lambda = \frac{\Omega R}{v} \), with \( v \) is wind speed (m/s), \( \rho \) is the air density (kg/m3), \( R \) is the radius of the rotor blades (m), \( \Omega \) is the angular frequency of the blades the mechanical rotation speed and (rad/s).

The power coefficient of the wind turbine is shown in the Figure 2. This figure indicates that the tip speed ratio is kept equal to \( \lambda_{opt} \), the \( C_p(\lambda) \) capture the maximum power [12], [13].

2.3. Modeling of the DFIG

The active and reactive stator and rotor powers are represented as (6), (7) [14]:

Figure 1. Scheme diagram of DFIG-based wind turbine

Figure 2. Power coefficient of wind turbine
the electromagnetic torque is given by (8):

$$T_{em} = p ( \varphi_{ds} q - \varphi_{qs} d )$$  \hspace{1cm} (8)

### 3. DFIG CONTROL STRATEGY

#### 3.1. Vector control of the active and reactive powers

To independently control the active and reactive stator powers, we use the vector control which makes the DFIG similar to a DC motor

$$\varphi_s = \varphi_{ds} \Rightarrow \varphi_{qs} = 0$$  \hspace{1cm} (9)

The torque is simplified as shown below:

$$\begin{align*}
\varphi_{ds} &= L_s i_{ds} + M i_{dr} \\
0 &= L_s i_{qs} + M i_{qr}
\end{align*}$$  \hspace{1cm} (10)

Neglecting the stator resistance gives the (12)

$$\begin{align*}
V_{ds} &= 0 \\
V_{qs} &= V_s
\end{align*}$$  \hspace{1cm} (11)

The equations (12) are obtained when replacing the rotor flux (5) in (3), the rotor voltages are:

$$\begin{align*}
v_{dr} &= \sigma L_r \frac{d i_{dr}}{dt} + R_r i_{dr} - \sigma L_r \omega_r i_{qr} + \frac{M}{L_s} \frac{d \varphi_{ds}}{dt} \\
v_{qr} &= \sigma L_r \frac{d i_{qr}}{dt} + R_r i_{qr} + \sigma L_r \omega_r i_{dr} + \frac{M}{L_s} \omega_r \varphi_{ds}
\end{align*}$$  \hspace{1cm} (12)

where: \( \omega_r = \omega_s - \omega = g \omega_s \) is the slip frequency, \( g \) is the slip range and \( \sigma = 1 - \frac{M^2}{L_s L_r} \) is the leakage coefficient. The rotor voltages can be rewritten as follows (13):

$$\begin{align*}
v_{dr} &= \sigma L_r \frac{d i_{dr}}{dt} + R_r i_{dr} + f_{em,d} \\
v_{qr} &= \sigma L_r \frac{d i_{qr}}{dt} + R_r i_{qr} + f_{em,q}
\end{align*}$$  \hspace{1cm} (13)

with \( f_{em,d} \) and \( f_{em,q} \) are the coupling terms (14):

$$\begin{align*}
f_{em,d} &= -\sigma L_r \omega_r i_{qr} + \frac{M}{L_s} \frac{d \varphi_{ds}}{dt} \\
f_{em,q} &= -\sigma L_r \omega_r i_{dr} + \frac{M}{L_s} \omega_r \varphi_{ds}
\end{align*}$$  \hspace{1cm} (14)

The stator active and reactive powers are given by the (15):

$$\begin{align*}
P_s &= -V_s \cdot \frac{M}{L_s} i_{rq} \\
Q_s &= -V_s \cdot \frac{M}{L_s} \left( i_{rd} - \frac{\varphi_s}{M} \right)
\end{align*}$$  \hspace{1cm} (15)

The rotor current along the d and q axes is represented by (16) and (17)
\[ i_{rd} = \frac{1}{\sigma_L} \left( v_{dr} - R_r i_{rd} + \sigma L_r \omega_r i_{rq} \right) \]  
\[ i_{rq} = \left( v_{rq} - R_r i_{rq} - \sigma L_r \omega_r i_{rd} - g \frac{M}{L_s} v_s \right) \frac{1}{\sigma_L} \]

4. WIND TURBINE CONTROL BASED ON DFIG

4.1. SMC control
Sliding mode control is a mode of operation of variable structure control systems (VSCS). It is robust in view of the insensitivity to parametric variations and to external disturbances.

4.2. Choice of switching surface
The sliding surface given by Slotine is defined as (18) [15]:
\[ S(X) = (\frac{\partial}{\partial t} + \lambda_x)^{r-1} e(X) \]  
where: \( e(X) \) is the error tracking; \( r \): system order and \( \lambda_x \) is a positive coefficient.

4.3. Condition of convergence
The existence of SMC can be proved by using a Lyapunov function (19).
\[ V(X) = \frac{1}{2} S^2(X) \]  
The derivative is given by (20):
\[ \dot{V}(X) = S(X) \dot{S}(X) \]  
To make the Lyapunov function derivative of (19) the negative definite, we have to find adequate control input. To ensure stability, the control is designed as follows (21) [16], [17]:
\[ S(X) \dot{S}(X) < 0 \]  
The sliding mode control algorithm consists of two terms: a discontinuous term which ensures the stability of the system and an equivalent term which brings back the state of the system on the sliding surface [18], [19]:

The control algorithm is defined by (22):
\[ u = u_{eq} + u_n \]  
where:
\[ u_n = K \text{sign}(S(X)) \]  

5. SUPER-TWISTING SLIDING MODE CONTROL DESIGN
To remedy the problem of chattering during the implementation of the control sliding mode, we use other more efficient techniques called super-twisting ST algorithm [20], [21].
The control \( u_{ST} \) control contains the sum of two terms (24) [22], [23]:
\[
\begin{aligned}
\dot{u}_{eq} &= u_1 + u_2 \\
\dot{u}_1 &= -\lambda \text{sign}(S) \\
u_2 &= -\alpha |S| \text{sign}(S)
\end{aligned}
\]  
where:
\[ \alpha > 0, \lambda > 0 \]
The convergence condition is given by (25) [24] [25]:

**Synthesis of SMC algorithms applied to wind generator (Houaria Abdelli)**
\[
\begin{aligned}
\lambda &> \frac{C}{K_m} \\
\alpha^2 &\geq \frac{4CK_M(\lambda + C)}{K_m^3(\lambda - C)}
\end{aligned}
\]  

where $C, K_M, K_m$ are the constants values of super-twisting sliding mode controller. Figure 3 show the state trajectory of the $S$ and $\dot{S}$ phase plane.

![Figure 3](image)

Figure 3. Trajectory phase plane of ST algorithm

5.1. Super-Twisting sliding mode control design

The errors of the powers are given by (26):

\[
\begin{aligned}
S(P_s) &= e_{PS} = P_s^* - P_s \\
S(Q_s) &= e_{QS} = Q_s^* - Q_s
\end{aligned}
\]

(26)

where $P_s^*$ and $Q_s^*$ are the reference values of the stator active and reactive powers. Then we will have:

\[
\dot{S}(P_s) = \dot{P}_s^* - \dot{P}_s
\]

(27)

\[
\dot{S}(Q_s) = \dot{Q}_s^* - \dot{Q}_s
\]

(28)

Substituting (15) and (17) into (27) leads to:

\[
\dot{S}(P_s) = \dot{P}_s^* + \left(v_{rq} - R_r i_{rq} - \sigma L_r \omega_r i_{rd} - g \frac{M V_s}{L_s} \dot{V}_s \right) \frac{1}{\sigma \omega_r}
\]

(29)

When the state of the system is on the surface of sliding, then:

\[
S(P_s) = 0; \dot{S}(P_s) = 0; v^{n}_{rq} = 0
\]

so, the equivalent command is given by:

\[
v^{eq}_{rq} = R_r i_{rq} + \sigma L_r \omega_r i_{dr} + g \frac{M V_s}{L_s} + i_{rq} \frac{V_s M}{L_s}
\]

(30)

Therefore:

\[
v^{n}_{rq} = -\lambda |S|^2 \text{sign}(S) - \int \alpha \text{sign}(S)
\]

(31)

The stator reactive power of the DFIG is represented by substituting (15) and (16) into (28) leads to:
\[ \dot{S}(Q_s) = Q_s^* + V_{sM} \left( v_{rd} - R_s i_{rd} + \sigma L_s \omega_r i_{rq} \right) \] (32)

when:

\[ S(P_s) = 0; \dot{S}(P_s) = 0; v^n_{rd} = 0 \]

The equivalent command is \( v^{eq}_{rd} \) is defined as:

\[ v^{eq}_{rd} = -\frac{\sigma L_s}{M} \left( \lambda \dot{\psi}_s - \lambda M i_{rd} - \dot{\psi}_s \frac{M R_s}{\sigma L_s} i_{rd} + M \omega_r i_{rq} \right) \] (33)

hence:

\[ v^n_{rd} = -\lambda |S|^{\rho \text{sign}(S)} - \int \alpha \text{sign}(S) \] (34)

Figure 4 shown the block diagram of the DFIG controlled by the second order sliding mode which uses the super-twisting algorithm.

![Figure 4. Structure of STSM control](image)

6. RESULTS AND DISCUSSION

The block diagram (Figure 4) is validated by a simulation using the parameters indicated in the appendix. A comparison between the two controllers STSMC and classic SMC is applied to a DFIG. This comparison shows that the STSMC is more efficient and robust than SMC. Figure 5 illustrates the reference of the active and reactive power.

| Table 1. DFIG parameters nominal | Table 2. Parameters turbine | Table 3. (DFIG+Turbine) |
|----------------------------------|-----------------------------|--------------------------|
| **P = 2**                        | **Diameter = 14 m**         | **f = 50 kg · m²**       |
| 7.5 KW                           | **Gearbox = 28**            | **f = 0.071 N · m · s/rd** |
| 400/690V                         | **Number of blades = 3**    |                          |
| 50 Hz                            |                            |                          |
| **M = 0.078 H**                  | **f = 0.071 N · m · s/rd**  |                          |
| **L_s = 0.084 H**                |                            |                          |
| **L_r = 0.081 H**                |                            |                          |

![Figure 5. Reference of stator’s powers](image)

*Synthesis of SMC algorithms applied to wind generator (Houaria Abdelli)*
As clearly shown in Figure 6 and Figure 7, the super-twisting sliding mode control-based system has almost similar tracking performance as the conventional sliding mode control-based system of DFIG stator’s powers. It is found that classical sliding mode control-based system suffers from chattering effect; whereas STSMC based system is free from this phenomenon. Figure 8 and Figure 9 illustrate the direct and quadrature rotor current. Figure 10 shows the dynamic responses of the electromagnetic torque. The control by the super-twisting sliding mode of the DFIG gives a good pursuit and is better than SMC controller.

Figure 6. Active power tracking performance

Figure 7. Reactive power tracking performance

Figure 8. Current idr

Figure 9. Current iqq
7. CONCLUSION

The application of the STSMC algorithm on a DFIG has been shown in this article. The STSMC algorithm is used for stator’s powers control. The proposed approach gives good performance (good tracking, disturbance rejection and minimizes the chattering phenomenon).

REFERENCES
[1] A. Gupta, S.N. Singhand, D.K. Khatod, “Modeling and simulation of doubly fed induction generator coupled with wind turbine—an overview” Journal of Engineering, Computers & Applied Sciences (JEC&AS), vol. 2, no. 8, pp. 45-54, 2013.
[2] F. Poitier, T. Bouaouchiche, M. Machmou, “Advanced control of a doubly-fed induction generator for wind energy conversion,” Electric Power System Research., vol. 79, no. 7, pp.1085-1096,2009.
[3] G. Pannell, D. Atkinson, B. Zahawi, Analytical Study of Grid-Fault Response of Wind Turbine Doubly Fed Induction Generator,” IEEE Transactions on Energy Conversion, vol. 25, no. 4, pp. 1081-1091, 2010.
[4] B. Beltran, M. Benbouzid, T. Ahmed-Ali, H. Mangel, “DFIG-Based Wind Turbine Robust Control Using High-Order Sliding Modes and a High Gain Observer,” International Review on Modelling and Simulations, vol. 4, no. 3, pp. 1148-1155, Nov.2011.
[5] J. A. Moreno and M. Osorio, “Strict Lyapunov functions for the super-twisting algorithm,” IEEE Transactions on Automatic Control, vol. 57, no. 4, pp. 1035–1040, 2012.
[6] C. Evangelista, P. Puleston, F. Valenciaga, and L. M. Fridman, “Lyapunov-designed super-twisting sliding mode control for wind energy conversion optimization,” IEEE Transactions on Industrial Electronics, vol. 60, no. 2, pp. 538–5545, 2013.
[7] K. Belgacem, A. Mezouar, A. Massoum, “Sliding Mode Control of a Doubly-fed Induction Generator for Wind Energy Conversion,” International Journal of Engineering Energy, vol. 3, no. 1, pp. 30-36, 2013.
[8] Utkin, V. I., “Sliding modes and their application in variable structure systems,” MIR, Moscou, 1978.
[9] S. Benelghali, M.E.H. Benbouzid, T. Ahmed-Ali and J.F. Charpentier, “High-order sliding mode control of a marine current turbine driven doubly-fed induction generator,” IEEE J. Ocean. Eng., vol. 35, no. 2, pp. 402-411, Apr. 2010.
[10] B. Beltran, M.E.H. Benbouzid, T. Ahmed-Ali, “Second-Order Sliding Mode Power and Grid Fault-tolerance of a DFIG-based Wind Turbine,” Revue de sciences and Technology, vol. 2, no. 1, January, 2011.
[11] I. Koley, S. Ghosh, A.G. Roy, P.K. Saha, G.Kr. Panda, “Matlab Modeling and Simulation of Grid Connected Wind Power Generation Using Doubly Fed Induction Generator,” International Journal of Computational Engineering Research, vol. 4, no. 7, pp. 28-34, July 2014.
[12] B. Hamane, M. L. Doumbia, M. Bouhamida, M. Benganhem, “Control of Wind Turbine Based on DFIG Using Fuzzy-PI and Sliding Mode Controllers,” IEEE Proceedings Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte-Carlo (Monaco), French, pp. 440-448, 2014.
[13] B. Beltran, A. Benbouzid, “A Second-order sliding mode control of a doubly fed induction generator driven wind turbine,” IEEE Transactions on Energy Conversion, vol. 27, no. 2, pp. 261-269, 2012.
[14] K. Belgacem, A. Mezouar, N. Essoubouli, “Design and Analysis of Adaptive Sliding Mode with Exponential Reaching Law Control for Double-Fed Induction Generator Based Wind Turbine,” International Journal of Power Electronics and Drive System (IJPEDS), vol. 9, no. 4, pp. 1534 -1544, 2018.
[15] B. Belkacem, “Hybrid Fuzzy Sliding Mode Control of a DFIG Integrated into the Network,” International Journal of Power Electronics and Drive System (IJPEDS), vol. 3, no. 4, pp. 351-364, 2013.
[16] Y. Krim, D. Abbes, S. Krim, M. Faouzi Mimouni, “Classical vector, first-order sliding mode and high-order sliding-mode control for a grid-connected variable speed wind energy conversion system: A comparative study,” Wind Engineering, vol. 42, no. 1, pp. 16–37, 2018.
BIOGRAPHIES OF AUTHORS

Houaria Abdelli was born in Algeria in 1969. She is Ph.D student in the Department of Electrical Engineering at the University of Sciences and Technology (USTO-MB) of Oran, Algeria. She received Magister degree in Industrial control of electrical drives and diagnosis from the University of Science and Technology of Oran (USTO-MB), Algeria in 2011. Her major research interests are modeling, control of electrical machines and control of wind turbines.

Abdelkader MEZOUAR was born in Mascara, Algeria, in 1974. He received the B.S. and M.S. degrees in Electrical Engineering from National Polytechnic School, Algiers, Algeria, in 1997 and 1999 respectively. Subsequently, he received the Ph.D. degree and the university habilitation from DjillaliLiabes University, Sidi Bel Abbès, Algeria, in 2006 and 2008 respectively. He is currently the president of the Laboratory of Electrical Engineering, Taher Moulay University, Saida, Algeria. His research interests include electrical machines and drives, sliding mode control, observer techniques and renewable energy.

Mokhtar Bendjebbar was born on August, 16, 1965 in Relizane Algeria. He received received the B.S degree in electrical engineering and the M.S. and PhD degrees in electrical and control systems from the University of Sciences and Technology of Oran M.B., Algeria, in 1989, 1993, and 2007, respectively. He is currently Professor of Electrical Engineering at the University of Sciences and Technology of Oran. His research interests include Electrical machines and Drives Control, Power Electronics, as well as Intelligent Control and Diagnosis.

Kheira Belgaecm was born in Saida Algeria in 1977. Received B.S. degree in Electrical Engineering from Taher Moulay University, Saida, Algeria, in 2001 and the M.S. degree from High National Schools of Technical Studies (ENSET) in 2009. Subsequently, she received the Ph.D. degree from DjillaliLiabes University, Sidi Bel Abbès, Algeria, in 2014. She is currently a member of the Laboratory of Electrical Engineering, Taher Moulay University Saida, Algeria. His research interests include electrical machines and drives, sliding mode control, modelling and control of wind turbines, and renewable energy.