Hybrid sliding neural network controller of a direct driven vertical axis wind turbine

Youcef Bakou[1,2], Mohamed Abid[1], Lakhdar Saihi[2], Abdel Ghani Aissaoui[1], Youcef Hammaoui[2]
[1]IRECOM Laboratory (Interaction Réseaux Electriques Convertisseurs Machines), Djillali Liabes University, Sidi-Bel-Abbès, Algeria
[2]Unité de Recherche en Energies Renouvelables en Milieu Saharien (URERMS), Centre de Développement des Energies Renouvelables (CDER), Adrar, Alegria

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ABSTRACT

This study aims to propose a robust hybrid sliding mode artificial neural network control (SM-ANN) scheme for controlling the stator power (active/reactive) of a doubly fed induction generator (DFIG)-based direct drive vertical axis wind turbine (VAWT) power system under a real-world scenario wind speed that will be installed in the Adrar region (Saharan zone) of Algeria. The SM-ANN scheme will control the stator power of the direct drive VAWT power. The chattering phenomenon is the most significant disadvantage associated with sliding mode control (SMC). In order to find a solution to this issue, the artificial neural network (ANN) method was applied to pick the appealing part of the SMC. MATLAB/Simulink is used to do an evaluation, after which the SM-ANN controller being suggested is compared to both traditional sliding mode (SM) and proportional-integral (PI) controllers. The results of the simulation demonstrated that the recommended SM-ANN controller has good performance in terms of enhancing the quality of energy that is delivered to the power network. This is in comparison to the traditional SM and PI controllers, which both have a long history of use. Notwithstanding the fact that there is DFIG parameter fluctuation present.

Corresponding Author:

Youcef Bakou
IRECOM Laboratory (Interaction Réseaux Electriques Convertisseurs Machines)
Djillali Liabes University of Sidi Bel-Abbès, Algeria
Email: youcefbakou@gmail.com

1. INTRODUCTION

Presently, one of the sustainable energy sources is wind power its production has seen fast growth in few past years [1], [2], where its production rate doubled between 1997 from 7.5 GW to 743 GW in 2020 [3]. Although Algeria has many regions where wind power can be exploited, especially in the southern regions as the Adrar region, where the wind speed in the most of the time is above 3 m/s and the capacity factor value is 48%, the quantity of electricity produced by wind energy is still low compared to Algeria's enormous potential, and wind power station in Kabarten at Adrar reminded the only project completed with a production capacity of 10 MW [4], [5]. Nowadays, wind turbines have seen increasing use in the production of electric field [6], [7], of all types; horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT), however VAWT has some disadvantages, especially the flow-field around VAWT, which must be taken into account as the aerodynamic problem and that there is no controlling for speed by pitching the rotor blades but it's preferred used for medium and small size installation [8], where that there is one part rotating, the blades are straight and untwisted moreover, the electrical and mechanical components at ground level, thus, it simple to making and designing, so that low maintenance and construction cost [9]. H-darrius wind turbine (H-DWT) is among VAWT that were used frequently due to many advantages, which among: i) less affected by mechanical stresses; ii) the more aerodynamic efficiency of the blades; iii) less noise; and iv) high solidity of the rotor [10].

Presently, the most popular wind turbine systems use doubly fed induction generator (DFIG) [11], due to their numerous benefits such as the smaller size and an aptitude to control their stator power through their rotor side converter, moreover, the power converter depends on operating speed rang, that limited to 30% under and above the synchronous speed, this is one of the main benefits of DFIG that permitted to size and cost of the converter to be smaller [12]. There are many controls strategy of DFIG that are studied and developed [13], [14]. The stator-flux oriented vector control based on a proportional-integral (PI) controller is frequently utilized in industrial applications because of its simple structure and it has an impressive performance in steady-stat [14], [15], however, the PI controller is based on the necessity of knowing machines parameters, that what makes it have a weak efficiency against the changing of parameters [16]. The problem of robustness of PI controller has been discussed in [13], [15], [17]. To solve the aforementioned issues, several techniques such as sliding mode control (SMC) have indeed been proposed [18]–[21].

Currently, among all non-linear control of DFIG, SMC is one of the most significant methods to easily implemented and it has a best robustness to face uncertain parameters variation or exogenous disturbances [22]. As opposed to that, the chattering phenomenon is still the major challenge of SMC that have to solve, to reduce the impact of chattering, numerous techniques have been suggested [23]. Research by Boubzizi *et al.* [24] sliding mode (SM) strategy is employed to regulate the stator power of DFIG connected directly to the grid compared with a PI and adaptive fuzzy logic (AFLC), the SM control gives the best results and presents high performances compared with PI and ALFC, despite that it doesn't limit the chattering effect which can make the system unstable [25].

Moreover, numerous studies have been focused on improving the SMC disadvantages, through to use of hybrid control, which replaced the attractive control part of MS with another control strategy. In this way, H-infinity SMC [23], fuzzy-SMC [26], and a particle swarm optimization-adaptive sliding mode controller (PSO-ASMC) [27] have been studied, tested, and evaluated in the literature. Present paper proposed the sliding mode artificial neural network (SM-ANN) controller of stator power (active/reactive) of a small wind turbine based on DFIG. The application of real wind speed on direct drive wind system and reducing the chattering effect of SMC is the main aim of this work. Simulation results demonstrate the effectiveness of SM-ANN controller in reducing chattering effect compared to SMC conventional, moreover, the sliding mode artificial neural network control (SM-ANNC) has a high performance against parameters variation versus PI and SM controllers.

2. MATHEMATICAL MODEL OF DIRECT-DRIVE VERTICAL AXIS WIND POWER

2.1. Modeling H-rotor wind turbine

VAWT system especially H-rotor usually consist of 3 blades fixed on vertical shaft rotor that turned a generator convert the wind power into electrical energy [28]. The mathematical of the wind power is given by [29] (1):

$$P_{aro} = \frac{1}{2} C_p \rho R h V^3 \quad (1)$$

where; C_p the power coefficient, ρ the air density (1.225 kg/m^3), R turbine rotor radius, h is the turbine height and, V the wind speed (m/s).

The aerodynamic torque can be written (2):

$$T_{aer} = \frac{P_{ae}}{\Omega_t} = \frac{C_p \rho R h V^3}{2\Omega_t} \quad (2)$$

with; Ω_t is the speed of turbine (tr/min) and λ is the tip speed ratio can be written (3):

$$\lambda = \frac{R\Omega_t}{V} \quad (3)$$

2.2. DFIG modeling

The DFIG model was presented in the literature [13], [30], [31], in d-q reference, where the equations are developed in a reference related to the rotating field. In the Park frame, the stator and rotor voltage equations are written (4):

$$\begin{cases} V_{ds} = R_s . i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s . \varphi_{qs} \\ V_{qs} = R_s . i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s . \varphi_{ds} \\ V_{dr} = R_r . i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_s - \omega_r) . \varphi_{qr} \\ V_{qr} = R_r . i_{qr} + \frac{d\varphi_{qr}}{dt} - (\omega_s - \omega_r) . \varphi_{dr} \end{cases} \quad (4)$$

where; φ_{qs} , φ_{ds}, i_{qs}, i_{ds} are the quadrature and direct components stator flux, current respectively, R_s is the stator resistance, ω_s is the synchronous angular speed. i_{qr}, i_{dr}, φ_{qr}, φ_{dr} are the quadrature and direct components rotor current, flux respectively, R_r is the rotor resistance, ω_r is the rotational speed. The stator power (active/reactive) is given as (5):

$$\begin{cases} P_s = \frac{3}{2}(V_{ds} . i_{ds} + V_{qs} . i_{qs}) \\ Q_s = \frac{3}{2}(V_{qs} . i_{ds} - V_{ds} . i_{qs}) \end{cases} \quad (5)$$

The electromagnetic torque is expressed by (6):

$$T_{em} = p \frac{3L_m}{2L_s} (\Phi_{qs} i_{dr} - \Phi_{ds} i_{qs}) \quad (6)$$

Starting from (4), the strong linkage between the stator and rotor components is appearing, which makes DFIG difficult to control, in order to simplify DFIG controlling. The field orientation technique was applied in literature [12], [30]. By orienting the stator flux Φ_s with the direct d axis and when taken into account the stator resistance, R_s is ignored, we have (7) and (8) [32]:

$$\begin{cases} \Phi_{ds} = \Phi_s \\ \Phi_{qs} = 0 \end{cases}, \text{ and } \begin{cases} V_{ds} = 0 \\ V_{qs} = V_s = \omega_s . \varphi_s \end{cases} \quad (7)$$

$$\begin{cases} i_{ds} = \frac{\Phi_s}{L_s} - \frac{L_m}{L_s} i_{dr} \\ i_{qs} = -\frac{L_m}{L_s} i_{qr} \end{cases} \quad (8)$$

Based on (7) and (8), the stator power can be given as (9):

$$\begin{cases} P_s = -\frac{3}{2} V_s \frac{L_m}{L_s} i_{qr} \\ Q_s = -\frac{3}{2} V_s \frac{L_m}{L_s} i_{dr} + \frac{V_s^2}{L_s \omega_s} \end{cases} \quad (9)$$

In (9) prove that the DFIG stator power can be regulated via the control of the currents rotor. The relationship between the rotor voltages and its current is given as (10):

$$\begin{cases} V_{dr} = R_r . i_{dr} + \frac{di_{dr}}{dt} - (g\omega_s \sigma L_r i_{qr}) \\ V_{qr} = R_r . i_{qr} + \frac{di_{qr}}{dt} - (g\omega_s \sigma L_r i_{dr}) + \frac{gV_s L_m}{L_s} \end{cases} \quad (10)$$

where; $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the dispersion coefficient. Thus, the electromagnetic torque can then be expressed by (11):

$$T_{em} = -p \frac{3L_m}{2L_s} \Phi_s i_{qr} \quad (11)$$

3. DFIG CONTROL STRATEGY

SMC is a robust technique whose principle of function is based on forcing the answer signal of the system to track the expected responses through a choosing sliding surface, and keeps it in this region [33]. It provides several advantages such as robustness, good dynamic response, and simple implementation. The aim of the SMC is to regulate the DFIG stator power (active/reactive), the sliding surfaces S_P, S_Q of the stator power (active/reactive) are defined as (12):

$$\begin{cases} S_P = P_{s-ref} - P_s \\ S_Q = Q_{s-ref} - Q_s \end{cases} \tag{12}$$

where; P_{s-ref} and Q_{s-ref} are the references of S_P,S_Q respectively.

To guarantee the attractiveness of the system to the entire sliding surface, the following criteria must be fulfilled (13):

$$\begin{cases} \dot{S_p}\ S_P \leq 0 \\ \dot{S_Q}\ S_Q \leq 0 \end{cases} \tag{13}$$

The sliding surface derivative is calculated as (14):

$$\begin{cases} \dot{P}_s = \dot{P}_{s-ref} + \frac{3}{2} V_s \frac{L_m}{L_s} i_{qr} \\ \dot{Q}_s = \dot{Q}_{s-ref} + \frac{3}{2} V_s \frac{L_m}{L_s} i_{dr} \end{cases} \tag{14}$$

Starting from (10), we can rewrite the sliding surface derivative as (15):

$$\begin{cases} \dot{P}_s = \dot{P}_{s-ref} + \frac{3}{2} V_s \frac{L_m}{\sigma L_r L_s} ((v_{qr}^{eq} + v_{qr}^{n}) - R_r i_{qr}) \\ \dot{Q}_s = \dot{Q}_{s-ref} + \frac{3}{2} V_s \frac{L_m}{\sigma L_r L_s} ((v_{dr}^{eq} + v_{dr}^{n}) - R_r i_{dr}) \end{cases} \text{and} \begin{cases} V_{qr} = v_{qr}^{eq} + v_{qr}^{n} \\ V_{dr} = v_{dr}^{eq} + v_{dr}^{n} \end{cases} \tag{15}$$

During the convergence mode, and the condition of (13) is verified, we put (16):

$$\begin{cases} \dot{P}_s = -\frac{3}{2} V_s \frac{L_m}{\sigma L_r L_s} v_{qr}^{n} \\ \dot{Q}_s = -\frac{3}{2} V_s \frac{L_m}{\sigma L_r L_s} v_{dr}^{n} \end{cases} \tag{16}$$

So, the switching term defined as (17):

$$\begin{cases} v_{qr}^{n} = K_{vqr}\ \mathrm{sing}(S_P) \\ v_{dr}^{n} = K_{vdr}\ \mathrm{sing}(S_Q) \end{cases} \tag{17}$$

To verify the state of system stability, the K_{vqr}, K_{vdr} parameters have to be positive [32], [33]. The equivalent control is calculated when the system in a steady state, so we have [19] (18):

$$\begin{cases} S_P = 0, \dot{S_p} = 0, v_{qr}^{n} = 0 \\ S_Q = 0, \dot{S_Q} = 0, v_{dr}^{n} = 0 \end{cases} \tag{18}$$

The equivalent control written as:

$$\begin{cases} v_{qr}^{eq} = -\frac{2}{3} \frac{\sigma L_r L_s}{V_s L_m} \dot{P}_{s-ref} + R_r i_{qr} \\ v_{dr}^{eq} = -\frac{2}{3} \frac{\sigma L_r L_s}{V_s L_m} \dot{Q}_{s-ref} + R_r i_{qr} \end{cases} \tag{19}$$

3.1. Designing of SM-ANN controller of DFIG

To overcome the chattering effect that causes by the attractive section of SMC a hybrid SM-ANN control was selected, to design a new controller of stator power (active/reactive) of DFIG, where the switching section of SMC is calculated using a strategy of artificial neural networks (ANN) as shown in Figure 1. Nevertheless, the ANN strategy can be considered as a calculation of distributed processing which resembles biological neural networks in their behavior. It is made up of numerous nonlinear computational elements (neurons), functioning parallelly and connected by forces expressed by numerical values named weights [34], [35]. The SMC law becomes as (20):

$$\begin{cases} V_{qr} = v_{qr}^{eq} + v_{qr}^{nurl} \\ V_{dr} = v_{dr}^{eq} + v_{dr}^{nurl} \end{cases} \quad (20)$$

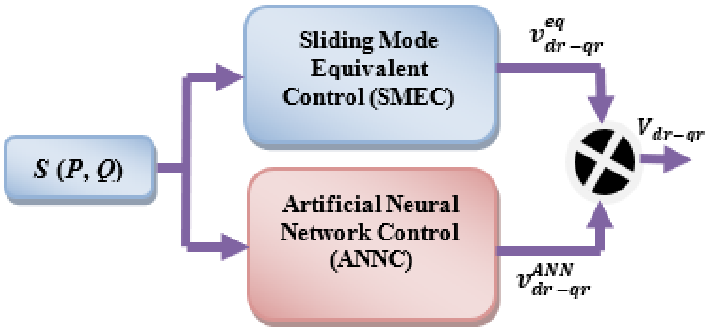


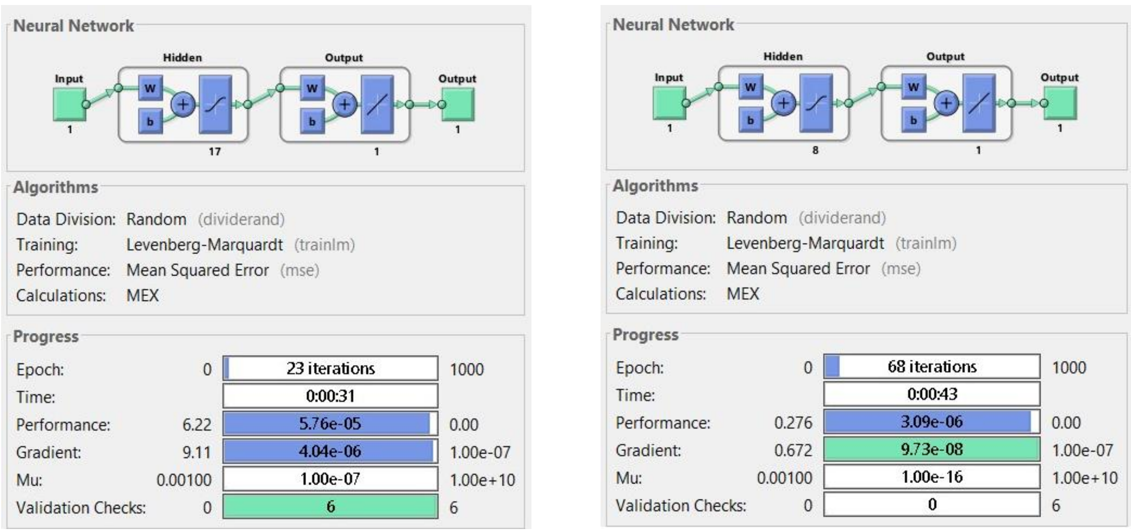
Figure 1. Hybrid SM-ANN controller

The mathematical model of the neuron is given by:

$$y_j = k(\sum_{i=1}^{n} w_i x_i + b_j) \quad (21)$$

where; w_i, x_i, and b_j are the corresponding input-signal synaptic weight, the input signals and, the bias input often takes the values -1 or 1, respectively. The function k can be a simple threshold function, a hyperbolic tangent, a sigmoid function, or a radial basis function.

In our case, the training process used is that of the Levenberge-Marquardt algorithm, in order to determine the optimal synaptic weights. It's an excellent optimization method due to its quick convergence properties and robustness. the structure of the ANN controller designed to replace the switching section of the SM regulator, for controlling the stator active power, consists of one linear input, 17 nodes in the hidden layer and, one neuron in the output layer as depicted in Figure 2(a), besides that, the stator reactive power loop controlled by an ANN controller with one linear input, 8 nodes in the hidden layer, and one neuron in the output layer showing in Figure 2(b), the curve of training, test and validation of the controller ANN of stator active power and stator reactive power are depicted in Figure 3(a) and Figure 3(b) respectively.



(a) (b)

Figure 2. ANN structure of stator power controller and its progression (a) active power and (b) reactive power

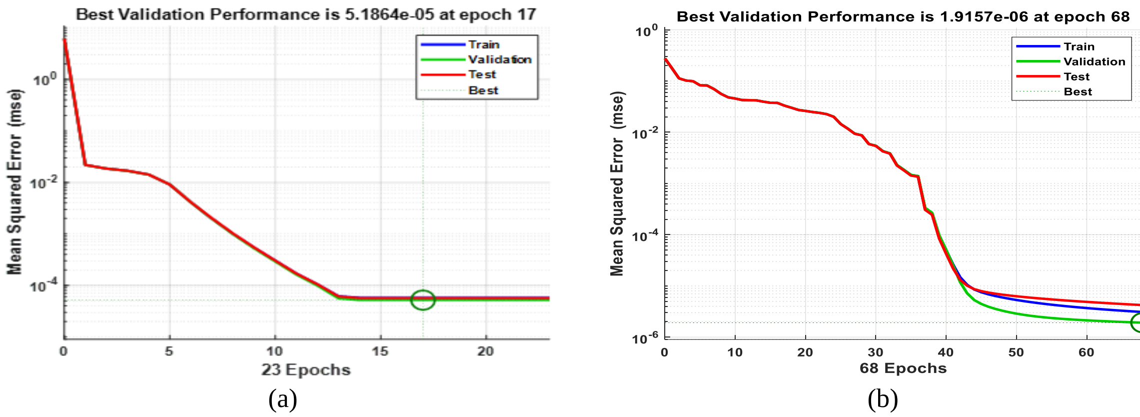


Figure 3. Performance curve of training (a) stator active power and (b) stator reactive power

4. WIND PROFILE AND DATA

The data used in this work are data from April 2020 taken from measurements of the weather stations called new energy Algeria (NEAL) as shown in Figure 4, placed in research unit in renewable energies in saharan medium (URER/MS), in Adrar region, which is a section of renewable energy development center (CDER), in Algeria capital. Knowing that the Adrar area in south Algeria has even greater potential for wind power. The yearly average wind speed is over 6 m/s [36]. The curve of average daily wind speed for April 2020 at Adrar zone. are displayed in Figure 5.

Figure 4. NEAL station in URER/MS Adrar

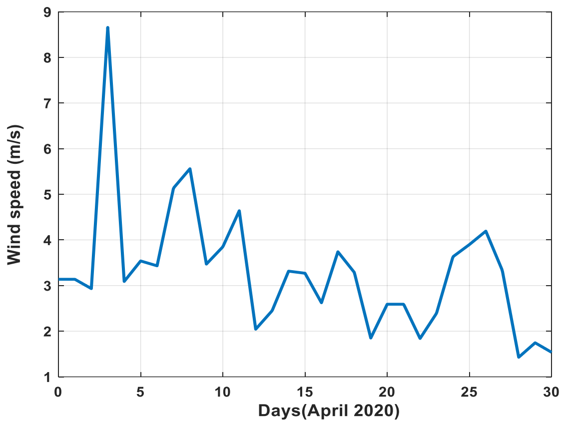


Figure 5. Average daily wind speed values (April 2020)

5. RESULTS AND DISCUSSION

In the real wind speed scenario, the SM-ANN controller proposed for the stator power (reactive/active) of the DFIG based on the vertical axis wind system is verified by MATLAB/Simulink software. Besides that, Simulink models are developed to compare the effectiveness of the suggested controller SM-ANN with conventional SM and PI controllers, taking into account reference tracking, stator current total harmonic distortion (THD), reduction of chattering phenomena, and robustness to machine parameter changes. The main parameters of the wind turbine power system are presented in Table 1. The suggested SM-ANN controller is developed to control the stator power (reactive/active) of a DFIG system is displays in Figure 6.

5.1. Test of reference tracking

The target of this test is to guarantee the effectiveness and to verify the effectiveness of the suggested controller when the stator active power reference of DFIG is chosen as the real power extracted from the direct-drive turbine trajectory. According to the results obtained, it seems clear that the high decoupling between stator active power and reactive power is maintained. Also, all controllers track their reference correctly with the major advantages of the SM-ANN controller in terms of error static, is very low and the chattering phenomenon is significantly reduced compared to SMC, as seen in Figure 7(a), that leads to an improvement in the quality of energy provided to the grid is a better. Besides that, the desired reference of the stator reactive power is kept null to get the value of the power factor equal to one (Figure 7(b)).

Table 1. Characteristics of the wind turbine system

Parameters	Value
Power coefficient (C_p)	0.27
Radius of wind turbine (R)	4.45 m
Turbine height (h)	7.4 m
Air density (ρ)	1.225 Kg/m^3
Moment of total inertia (J)	30.5 Kg/m^2
Tip speed ratio (λ)	2.8
Nominal power	10 kW
Stator frequency (f)	50 Hz
Viscous friction f_r	0.024 Nm
Resistance of stator R_s	1.518 Ω
Resistance of rotor R_r	1.247 Ω
Inductance of stator L_s	0.0921 H
Mutual inductance L_m	0.0696 H
Inductance of rotor L_r	0.0640 H

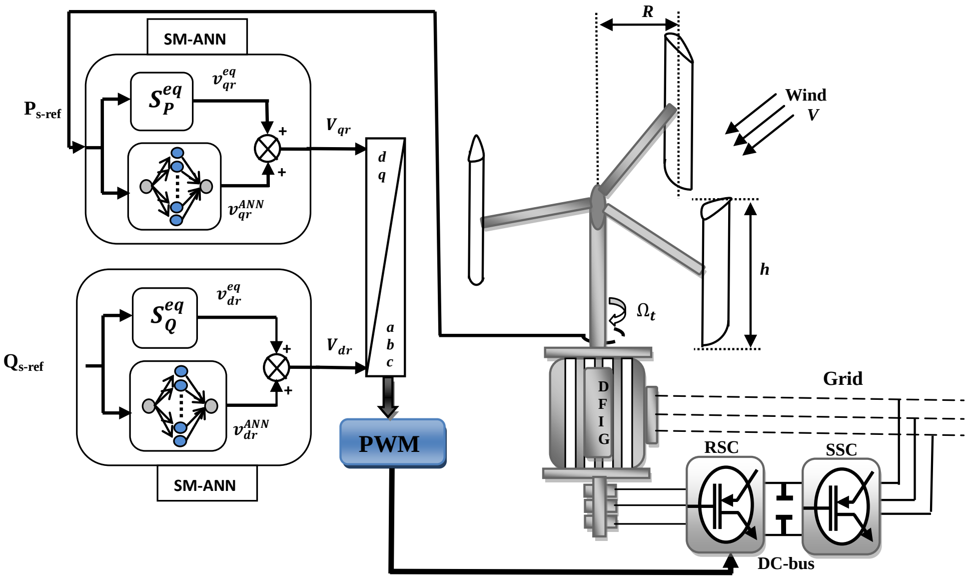
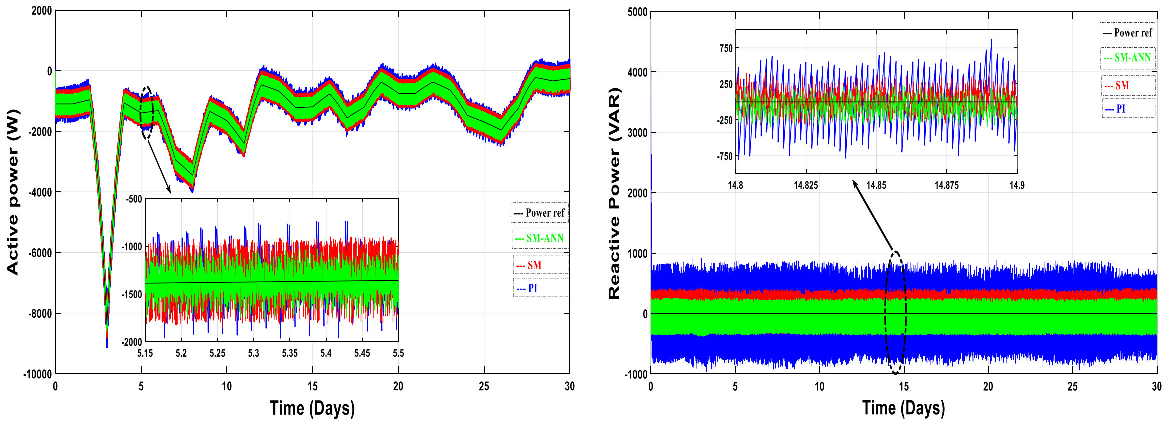


Figure 6. Schematic diagram of direct-drive vertical axis wind system based SM-ANN



(a) (b)

Figure 7. DFIG stator power with PI, SMC and SM-ANN controllers (a) active power and (b) reactive power

Furthermore, using the fast fourier transform (FFT) approach, the THD of stator currents are presented in Figure 8 and 9, as shown, the SM-ANN controller reduces THD down to 2.05% (Figure 9(b)), compared to SMC, where THD is 4.40% (Figure 8(b)), which helps to reduce the chattering phenomenon effect. The stator current signal quality of the SM-ANN controller has a good sinusoidal shape and, is less corrugated (Figure 9(a)) compared to SM controllers (Figure 8(a)).

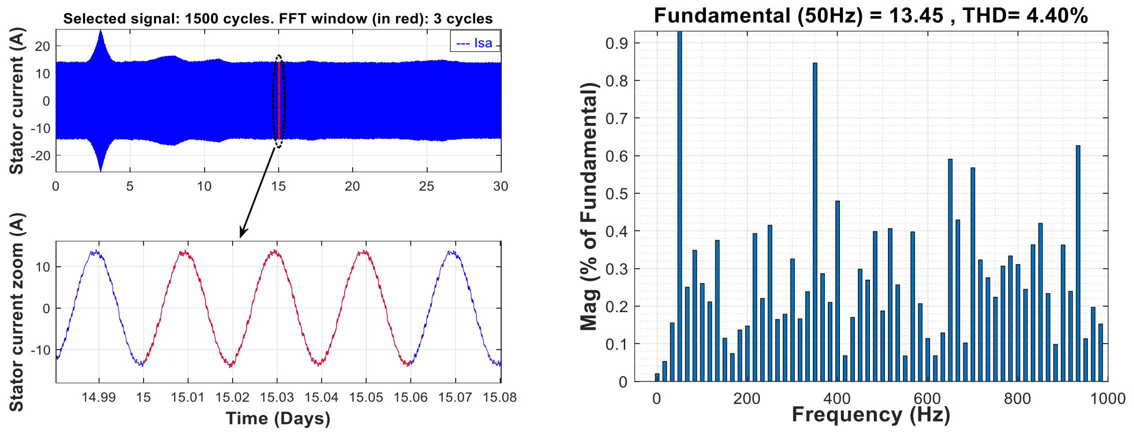


Figure 8. DFIG one-phase stator current (a) I_{sa} of SMC and (b) THD of SMC

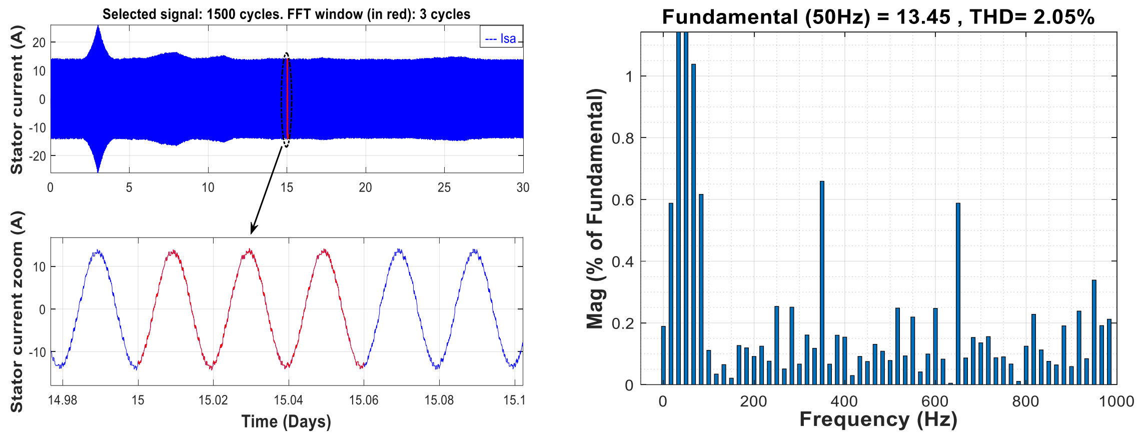
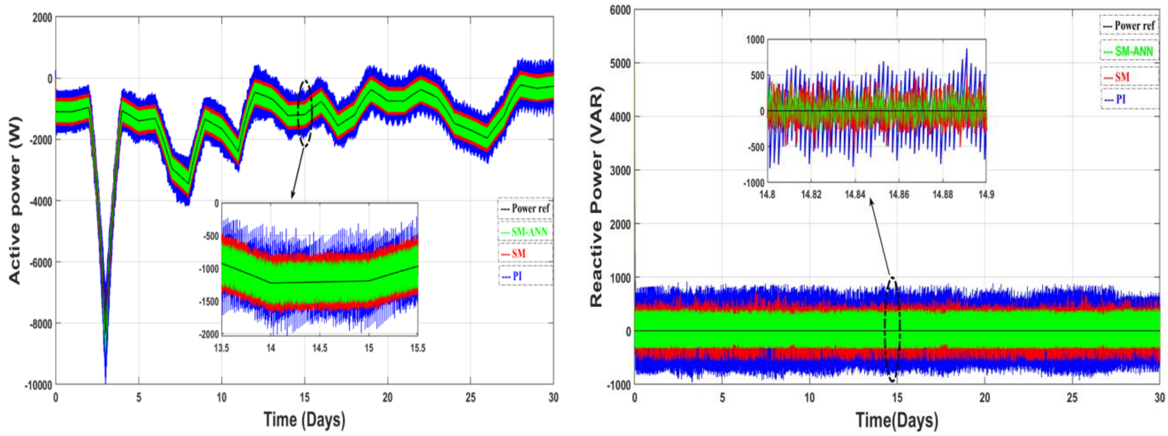


Figure 9. DFIG one-phase stator current (a) I_{sa} of SM-ANN and (b) THD of SM-ANN

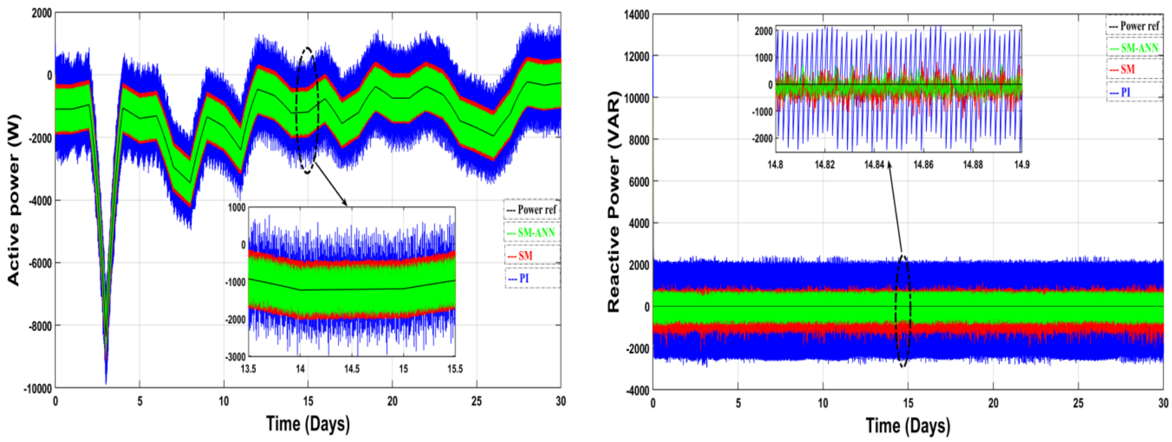
5.2. Test of robustness

This test aims to investigate and evaluate the impact of parametric changes on the SM-ANN controller, in order to assess the robustness of the suggested controller compared to SM and PI controllers, to achieve this objective, the resistances *Rs*, *Rr* of DFIG, increased by 50% more than its nominal value and the inductances *Ls*, *Lr* and Lm reduced by 30% of its nominal value. As seen in Figure 10(a) and Figure 10(b), the SM-ANN controller has better robustness against the variation of stator and rotor resistance of DFIG, there is hardly any change in terms of chattering phenomenon and reference tracking at the level of the power. Contrary, the other controllers have high error static and numerous oscillations at the level of the power. Nevertheless, it keeps the decoupling between the powers. According to Figure 11(a), SM-ANN controller was observed with a slight effect at the level of the active power, but it still has solid robustness and high performance compared to SM and PI controllers. Nevertheless, there is no effect at the level of the reactive power for the proposed controller when the variation of inductances, while, the SM and PI controllers witness a significant rise of the corrugate at the level of reactive power as shown in the Figure 11(b), which influences on the power quality supply to the network.



(a) (b)

Figure 10. Impact of resistances variation R_s, R_r: (a) active stator power and (b) reactive stator power



(a) (b)

Figure 11. Impact of inductances variation L_s, $L_r$and L_m: (a) active power and (b) reactive power

6. CONCLUSION

A hybrid SM-ANN controller for stator power (active/reactive) of a direct drive vertical axis wind system based on a DFIG, linked to the grid, has been proposed in this study. The control scheme will be implemented on a 10 kW wind turbine doubly-fed system under a real wind speed scenario. The theory of SMC and its application to the DFIG have been presented in this study. To cope with the chattering phenomenon, the ANN method is briefly presented and developed to replace the attractive control part of SMC. Simulations are performed to verify the effectiveness of the suggested controller controller. Moreover, the SM-ANN controller is compared with the conventional SM) and PI controller. According to the findings, it can be concluded that the robust SM-ANN controller can be a very appealing approach for enhancing the SMC in terms of robustness face to the machine parameters variation, chattering phenomenon reduction, and the control axes were.

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BIOGRAPHIES OF AUTHORS

Youcef Bakou was born in Adrar, Algeria, 1986, he is currently Researcher Master at the Research Unit in Renewable Energies in the Saharan Medium (URER-MS) in Adrar Algeria. He received a Magister degree in Electrical engineering from the University of Sidi Bel Abbes-Algeria in 2012. He is currently working towards his Ph.D degree. His research interests are mainly in the areas of wind power and photovoltaic power, electrical machines drives, process control, sensorless control of electrical machine, robust, and nonlinear control. He can be contacted at email: youcefbakou@gmail.com.

Mohamed Abid is a professor of electrical engineering at University of Sidi Bel Abbes, Algeria. He received his BS degree in 1990, the MS degree in 1997, the PhD degree in 2005 from the Electrical Engineering Institute of Djilali Liabes University of Sidi Bel Abbes (Algeria). He is the director of IRECOM (Interaction Réseaux Electriques-Convertisseurs Machines). His current research interest includes power electronics, control of electrical machines, artificial intelligence and renewable energies. He can be contacted at email: irecom_abid@yahoo.fr.

Lakhdar Saihi was born in Naama, Algeria, on Mai 23, 1987. He received the Engineer degree in Instrumentation from University of Oran (Algeria) in (2010) and the M.sc degree in Automatic, from the Polytechnic national school (Oran, Algeria), in (2014). Currently, he is S.D student in Automatic at University of Bechar, Algeria. He received the Doctorate degree in Electrical Engineering from University of Bechar (Algeria) in (2021). He is a permanent researcher of Renewable Energy in Renewable Energy Research Unit in Saharan Environment, Adrar (Algeria). His areas research of interest is focused on renewable energy systems control and, robust and nonlinear control. He can be contacted at email: saihi_lakhdar@urerms.dz.

Abdel Ghani Aissaoui is a full professor of electrical engineering at University of Bechar (Algeria). He was born in 1969 in Naama, Algeria. He received his BS degree in 1993, the MS degree in 1997, the PhD degree in 2007 from the Electrical Engineering Institute of Djilali Liabes University of Sidi Bel Abbes (Algeria). He is an active member of IRECOM (Interaction Réseaux Electriques-Convertisseurs Machines) Laboratory and IEEE senior member. He is an editor member for many international journals (IJET, RSE, MER, IJECE, etc.), he serves as a reviewer in international journals (IJAC, ECPS, and COMPEL). He serves as member in technical committee (TPC) and reviewer in international conferences. His current research interest includes power electronics, control of electrical machines, artificial intelligence, and renewable energies. He can be contacted at email: irecom_aissaoui@yahoo.fr.

Youcef Hammaoui was born in Adrar, Algeria, 1985. He is currently Researcher Master at the Research Unit in Renewable Energies in the Saharan Medium (URER-MS) in Adrar Algeria. He received a Magister degree in Electrical engineering from the University of Sidi Bel Abbes-Algeria in 2012. He is currently working towards his Ph.D degree. His research interests are mainly in the areas of wind power and photovoltaic power, electrical machines drives, process control, sensorless control of electrical machine, robust, and nonlinear control. He can be contacted at email: youcef.hammaoui@gmail.com.