International Journal of Applied Power Engineering (IJAPE)
Vol.8, No.3, December 2019, pp. 221~233
ISSN: 2252-8792 DOI: 10.11591/ijape.v8.i3.pp221-233

A novel matlab/simulink model of DFIG drive using NSMC method with NSVM strategy

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Article Info

Article history:

Received Dec 30, 2018
Revised Jan 22, 2019
Accepted Mar 6, 2019

Keywords:

DFIG
NSMC
NSVM
PWM

ABSTRACT

In this article, we present a comparative study between pulse width modulation (PWM) and neural space vector modulation (NSVM) strategy associated with a neuro-sliding mode control (NSMC) of stator reactive and stator active power command of a doubly fed induction generator (DFIG). The obtained results showed that, the proposed NSMC with NSVM strategy have rotor current with low harmonic distortion and low powers ripples than PWM strategy.

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1. INTRODUCTION

In recent years, sliding mode control (SMC) has drawn much attention from research groups and industry. The SMC theory was proposed by Utkin in 1977 [1]. The principle advantage of the SMC is that the robustness and simple control. On the other hand, the SMC has a major inconvenience called the chattering phenomenon created by the discontinuous part of command [2]. In order to minimize this effect, artificial intelligence strategies like fuzzy logic (FL) and artificial neural networks (ANN) are used to improve the performance of SMC technique. In [3], fuzzy sliding mode controller (FSMC) was designed for the doubly fed induction machines control. Second order sliding mode controller and neural networks are combined to command active and reactive power of DFIG based wind turbine systems [4].

Traditionally, the space vector modulation (SVM) technique is widely used in AC inverters. However, this strategy reduces the total harmonic distortion (THD) compared to pulse width modulation (PWM) technique. In addition, this strategy is difficult to implement. However, this technique has essential drawbacks such as the need of sector and angle calculatation [5] and important powers ripples. In [6], the authors propose a novel SVM technique based on FL controller (FSVM) to control active and reactive powers of a DFIG. In this paper, we use the neural space vector modulation (NSVM) to control the powers of a DFIG. These proposed strategies reduce the THD value of rotor current and powers ripples.

2. MODEL OF THE WIND TURBINE

In The wind turbine input power is given by [7, 8]:

$$P_{\max} = 0.5\rho\pi R^2 V_{vent}^3 \quad (1)$$

The mechanical power can be written as [9]:

$$P_m = 0.5.C_p(\lambda).\rho\pi R^2 V_{vent}^3 \quad (2)$$

$$\lambda = \frac{R.\Omega_1}{V_1} \quad (3)$$

$$C_p(\beta,\lambda) = C_1.(\frac{C_2}{\lambda_i} - C_3.\beta - C_4).\exp(\frac{-C_5}{\lambda_i}) + C_6.\lambda \quad (4)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{\beta^3 + 1} \quad (5)$$

Where, C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21, C_6=0.0068.
ρ: is air density.
V_{vent}: Wind speed (m/s).
P_{max}: Maximum power in (watts).
R: Radius of the turbine in (m).
C_p: The aerodynamic coefficient of power.
λ: The tip speed ratio.
β: The blade pitch angle in a pitch-controlled wind turbine.

3. MODELING OF THE DFIG

The mathematical models of three phases DFIG in the Park frame are written as [10-12]:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases} \quad (6)$$

The *dq* synchronous reference frame equations of the rotor flux and stator may be written also as:

$$\begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (7)$$

The torque is expressed as [13]:

$$T_e = pM(I_{dr}.I_{qs} - I_{qr}.I_{ds}) \quad (8)$$

$$T_e = T_r + J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \qquad (9)$$

The stator active and stator reactive powers can be expressed as:

$$\begin{cases} P_s = \frac{3}{2}(V_{ds} I_{ds} + V_{qs} I_{qs}) \\ Q_s = \frac{3}{2}(V_{qs} I_{ds} - V_{ds} I_{qs}) \end{cases} \qquad (10)$$

4. NEURAL SPACE VECTOR MODULATION

The disadvantage of the conventional SVM strategy are explained in [14]. The details about this strategy can be established in [15-17]. The proposed SVM inverter as shown in Figure 1. This modulation strategy is simple scheme and easy implementation, based on following steps [18]:

a. Calculates the minimum voltages (min (V_1, V_2, V_3))
b. Calculates the maximum voltages (max (V_1, V_2, V_3))
c. Add the maximum and minimum voltages (max (V_1, V_2, V_3) + min (V_1, V_2, V_3)).
d. The last step is to compare step-3 waveforms with Vp (VTriangle), and generates the pulses for that switch presents in the 3 phase voltage source converter circuit.

In this article, we propose new SVM strategy based on neural networks (NN) to get better the performances of DFIG machine. Figure 2 the simulation block of two-level inverter controlled by NSVM strategy for a DFIG-based wind turbine.

The theory of NSVM inverter is similar to traditional SVM strategy. However, the hysteresis controllers are replaced by NN regulators. This modulation method based on neural organization has advantage of reduce the harmonic distortion of rotor current and reduce the powers ripples. On the other hand, The NSVM technique is simple modulation and easy to implement.

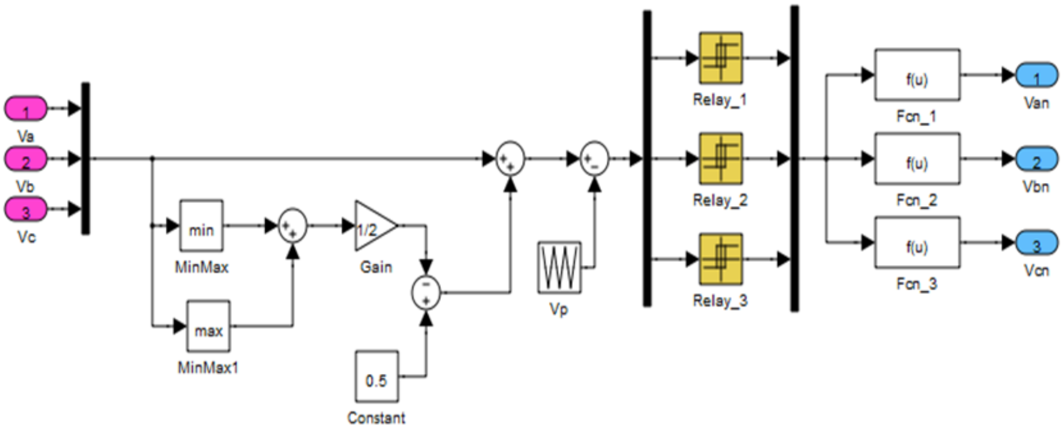


Figure 1. Traditional SVM strategy

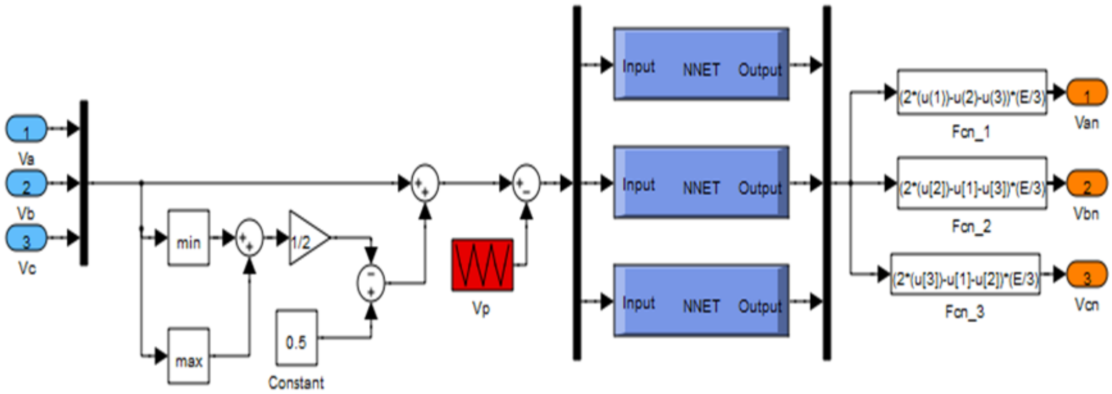


Figure 2. NSVM strategy

The NN regulators contain 3 layers: input layers, hidden layers and output layers. On the other hand, the number of the neurons in the output and input layers depends on the number of the selected output and input variables. This method based on NN control has the advantage of simplicity and easy implementation. The construction of the NN regulator to realize the SVM method applied to DFIG adequately was a NN with one linear input node, 8 neurons in the hidden layer, and one neurone in the output layer, as shown in Figure 3. The construction of Layer 1 and layer 2 is shown in Figure 4 and Figure 5 respectively.

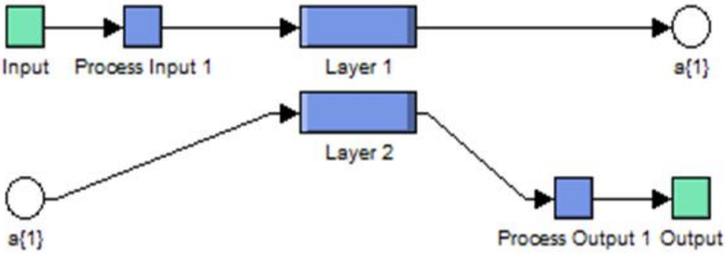


Figure 3. Neural network structure for SVM inverter

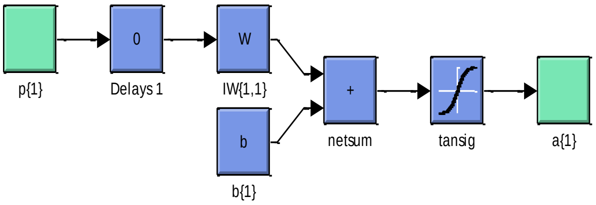


Figure 4. Architecture of layer 1

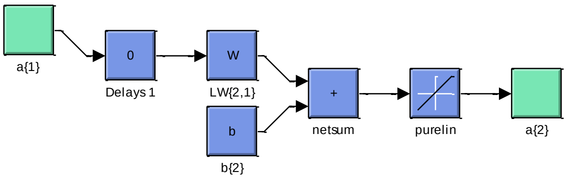


Figure 5. Architecture of layer 2

The convergence of the network in summer obtained by using the value of the parameters grouped in the Table 1.

Table 1. Parameters of the LR for Hysteresis Controllers

Parameters of the LM	Values
Number of hidden layer	12
TrainParam.Lr	0.005
TrainParam.show	50
TrainParam.eposh	1000
Coeff of acceleration of convergence (mc)	0.9
TrainParam.goal	0
TrainParam.mu	0.9
Functions of activation	Tensing, Purling, gensim

5. NEURO-SLIDING MODE CONTROL

In this section, we propose a novel robust control of the DFIG based on neural network and SMC which is NSMC. However, the SMC command is one of the most interesting nonlinear command approaches [19, 20]. The SMC technique based on the theory of variable structure systems (VSS). Since the robustness is the best advantage of the SMC command. On the other hand, the disadvantage of SMC controllers is the chattering effect.

The basic idea of SMC technique is first to draw the states of the system in an area properly and then design a law control that will always keep the system in this region [21]. The SMC method goes through three stages, as follows:

a. Choice of switching surface
b. Convergence condition
c. Control calculation

Many paper proposed SMC method to command the reactive and active powers of a DFIG-based wind turbine systems. In [22], the author proposes the design of a robust SMC based on nonlinear modeling of variable speed wind turbine system.

Yahdou et al., In 2016 [23] used second order sliding mode control to command stator reactive and stator active powers of a dual-rotor wind turbine system using a matrix converter. Boudjema et al. In 2012 [24] used robust command to command the DFIG machine. In [25], the high order SMC method was proposed by Levant.

$$\begin{cases} S_p = P_{sref} - P_s \\ S_q = Q_{sref} - Q_s \end{cases} \tag{11}$$

Where $P_{s\,ref}$ and $Q_{s\,ref}$ are the expected active and reactive power reference.

The first order derivate of (11), gives:

$$\begin{cases} \dot{S}_p = \dot{P}_{sref} - \dot{P}_s \\ \dot{S}_q = \dot{Q}_{sref} - \dot{Q}_s \end{cases} \tag{12}$$

$$\begin{cases} \dot{S}_p = \dot{P}_{sref} - \dfrac{V_s.M}{L_S}\dot{I}_{qr} + \dfrac{V_s^2}{R_s} - \dfrac{w_s^2\psi_s^2}{R_s} \\ \dot{S}_q = \dot{Q}_{sref} + \dfrac{V_s M}{L_s}\dot{I}_{dr} - \dfrac{w_s\psi_s^2}{L_s} \end{cases} \tag{13}$$

The equivalent command vector V^{eq} can express by:

$$\begin{cases} V_{dr}^{eq} = R_r \cdot I_{dr} - L_s \dfrac{(L_r - \frac{M^2}{L_s})}{M\,\psi_s\, w_s}\dot{Q}_{sref} - g.w_s.(L_r - \dfrac{M^2}{L_s}).I_{qr} + \dfrac{(L_r - \frac{M^2}{L_s})}{M} w_s \\ V_{qr}^{eq} = R_r \cdot I_{qr} + \dfrac{L_s}{V_s M}\dot{P}_{sref} - g.w_s.(L_r - \dfrac{M^2}{L_s}).I_{dr} + g.\dfrac{M.V_s}{L_s} \end{cases} \quad (14)$$

To obtain good performances, dynamic and a commutation around the surface, the command vector is imposed as follows:

$$V_{dq} = V_{dq}^{eq} + V_{dq}^{n} \quad (15)$$

V_{dq}^{n} is the saturation function defined by :

$$V_{dq}^{n} = -K.sat(S_{dq}) \quad (16)$$

Where K determine the ability of overcoming the chattering.

The SM will exist only if the following condition is met:

$$S.\dot{S} \prec 0 \quad (17)$$

The disadvantage of SMC strategy is that the discontinuous command signal produces chattering. In order to improve the SMC command and eliminate the chattering phenomenon, we propose to use the NN regulators. The Neuro-Sliding Mode Controllers (NSMC) is a modification of the SMC technique, where the switching regulator term sat(S(x)), has been replaced by NN regulator input as given below.

$$V_{dq}^{com} = V_{dq}^{eq} + V_{dq}^{Neural} \quad (18)$$

The proposed NSMC strategy, which is designed to command the stator reactive and stator active powers of the DFIG machine, is shown in Figure 6.

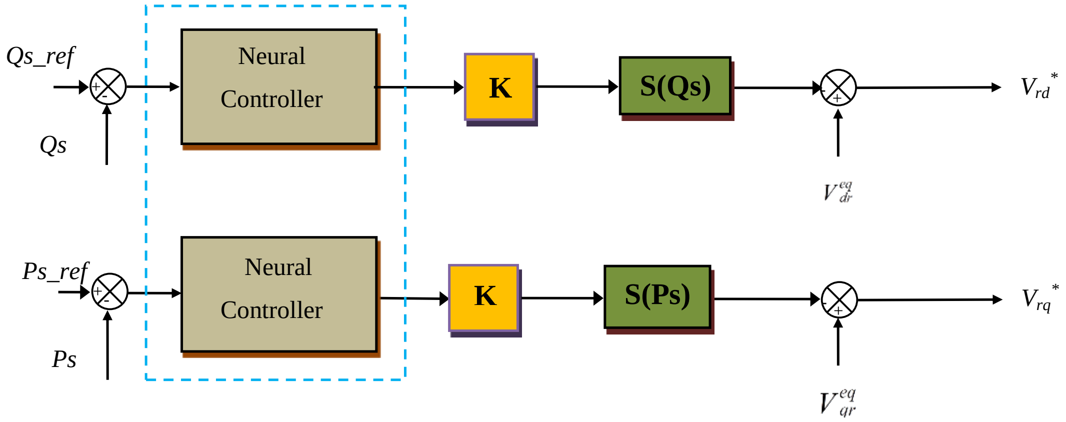


Figure 6. Block diagram of the DFIG control with NSMC strategy

For the two proposed neuro-sliding mode controllers in Figure 7, the structure of the NN with one linear input node, 8 neurons in the hidden layer and one neuron in the output layer.

The training used is that of the algorithm, Gradiant descent with momentum & Adaptive LR. The number of iteration count maximum 2000 with an iteration step of 50. Figure 8 represents the SMC strategy of DFIG driven by a two-level NSVM inverter.

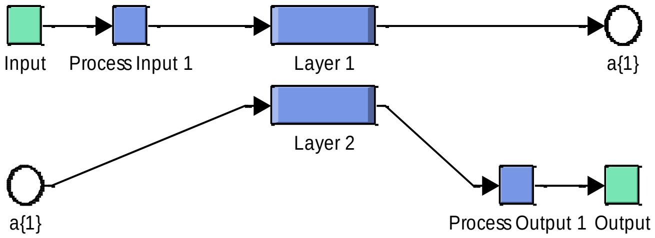


Figure 7. Neural network structure for reactive and active powers

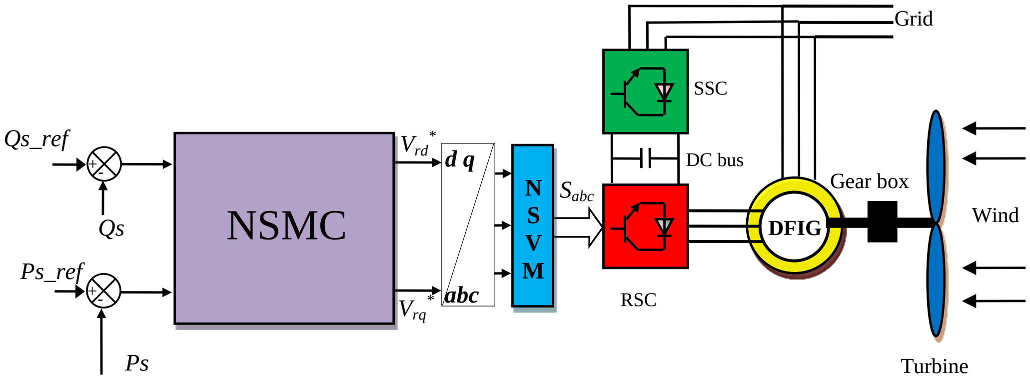


Figure 8. NSMC control of a DFIG using NSVM strategy

6. SIMULATION RESULTS

In this section, simulations are investigated with a 1.5MW DFIG connected to a 398V/50Hz grid. The DFIG parameters are presented in the Table 2. The proposed command schemes will be tested and compared in two different configurations: robustness against parameters variations and reference tracking.

Table 2. The DFIG Parameters

Parameters	Rated Value	Unity
Nominal power	1.5	MW
Stator voltage	398/690	V
Stator frequency	50	Hz
Number of pairs poles	2	
Stator resistance	0.012	Ω
Rotor resistance	0.021	Ω
Stator inductance	0.0137	H
Rotor inductance	0.0136	H
Mutual inductance	0.0135	H
Inertia	1000	Kg m^2
Viscous friction	0.0024	Nm/s

6.1. Reference tracking test

Figures 9-14 show the obtained simulation results. For the proposed command strategies, the stator reactive and active power tracks almost perfectly their references values. Moreover, the NSMC-NSVM control strategy reduced the powers ripples compared to the NSMC-PWM control scheme as shown in Figures 11-12. On the other hand, Figures 13-14 shows the harmonic spectrums of one phase rotor current of the DFIG obtained using Fast Fourier Transform method for NSMC-PWM and

NSMC-NSVM one respectively. It can be clear observed that the THD is reduced for NSMC-NSVM control method (THD=0.82%) when compared to NSMC-PWM (THD=**0.17%**).

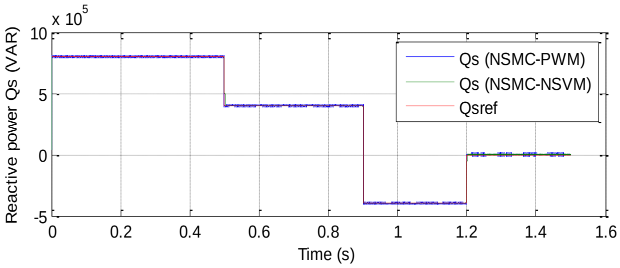


Figure 9. Reactive power (reference tracking test)

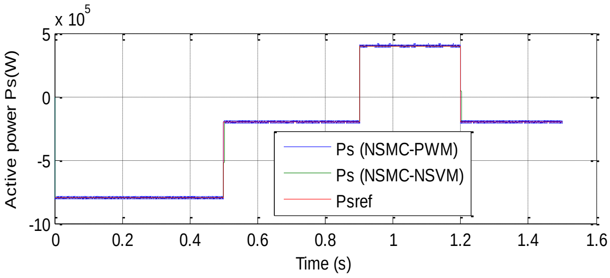


Figure 10. Active power (reference tracking test)

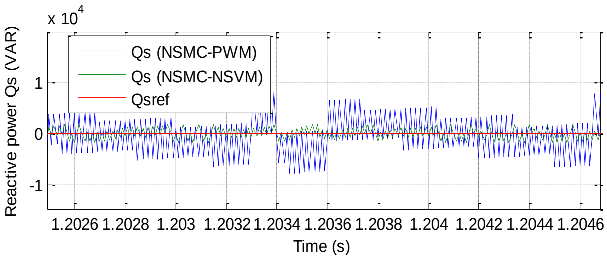


Figure 11. Zoom in the reactive power (reference tracking test)

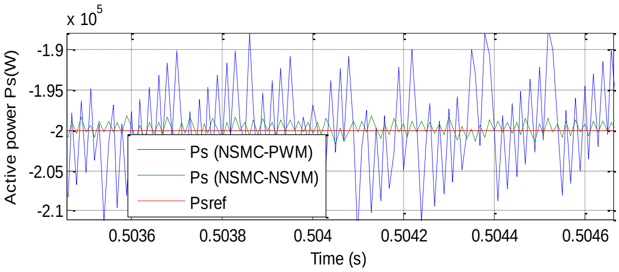


Figure 12. Zoom in the active power (reference tracking test)

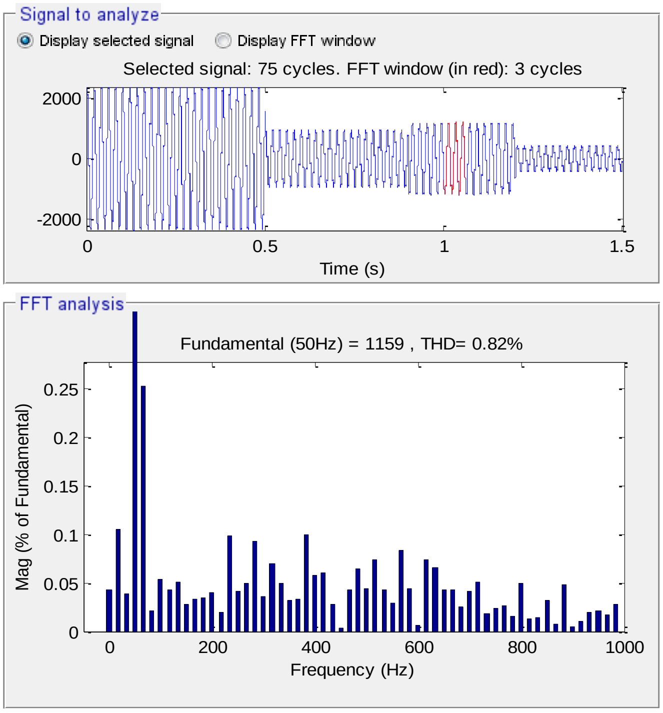


Figure 13. THD of one phase rotor current for NSMC-PWM control (reference tracking test)

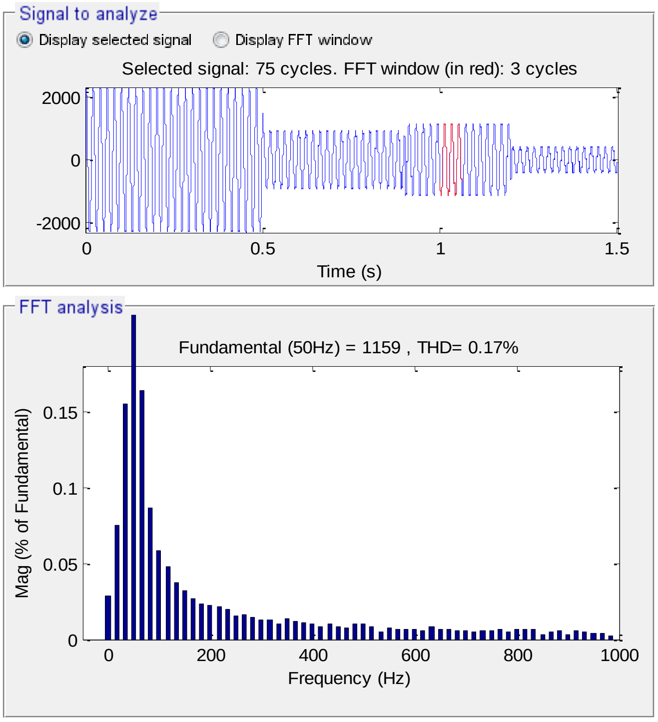


Figure 14. THD of one phase rotor current for NSMC-NSVM control (reference tracking test)

6.2. Robustness test

In order to examine the robustness of the proposed commands schemes, the nominal value of the R_r and R_s is multiplied by 2, the values of inductances L_s, M, and L_r are multiplied by 0.5. Simulation results are presented in Figures 15-16 and Figures 17-18. As it's shown by these Figures, these variations present a clear effect on the reactive power and active powers. However the effect appears more important for the

NSMC-PWM command scheme compared to NSMC-NSVM command as shown in Figures 19-20. On the other hand, the THD value of rotor current in the NSMC-NSVM has been minimized significantly. Table 3 shows the comparative analysis of THD value. Thus it can be concluded that the NSMC-NSVM command scheme is more robust than the NSMC-PWM command.

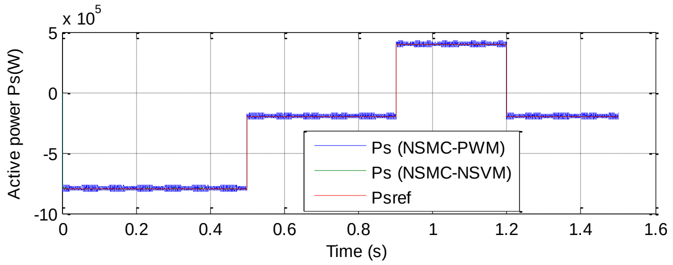


Figure 15. Active power (robustness test)

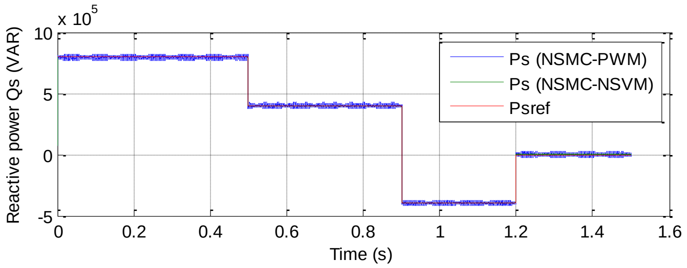


Figure 16. Reactive power (robustness test)

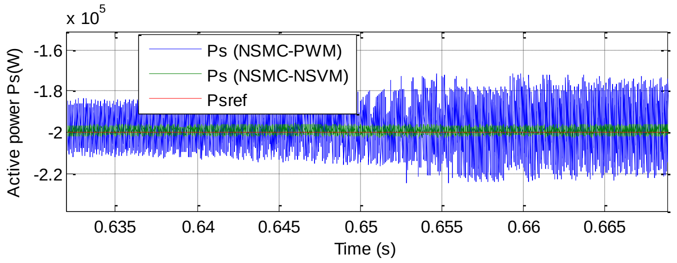


Figure 17. Zoom in the active power (robustness test)

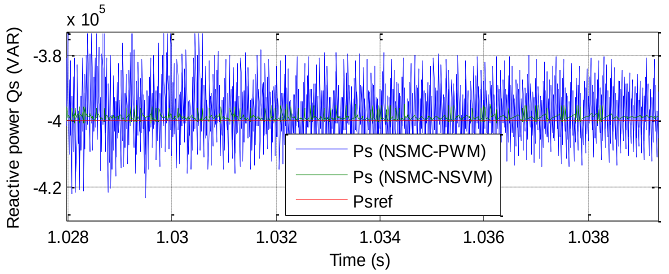
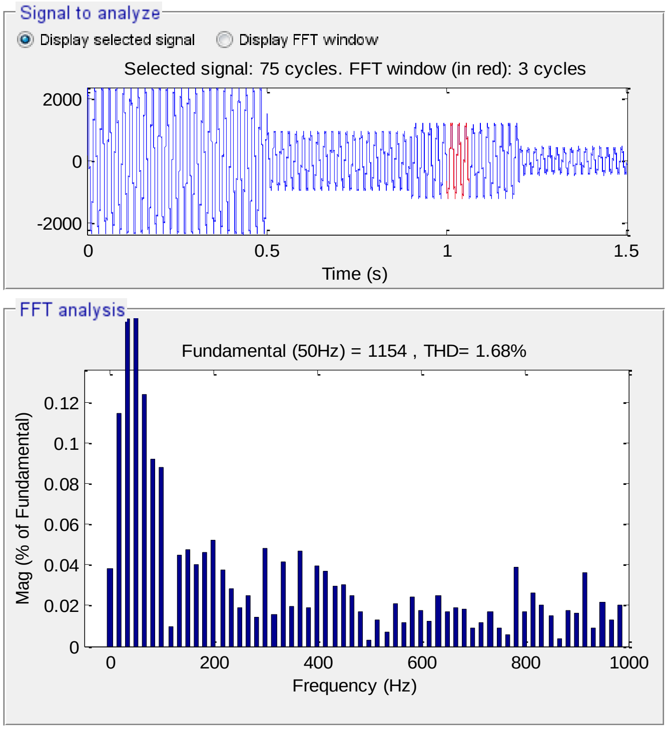


Figure 18. Zoom in the reactive power (robustness test)

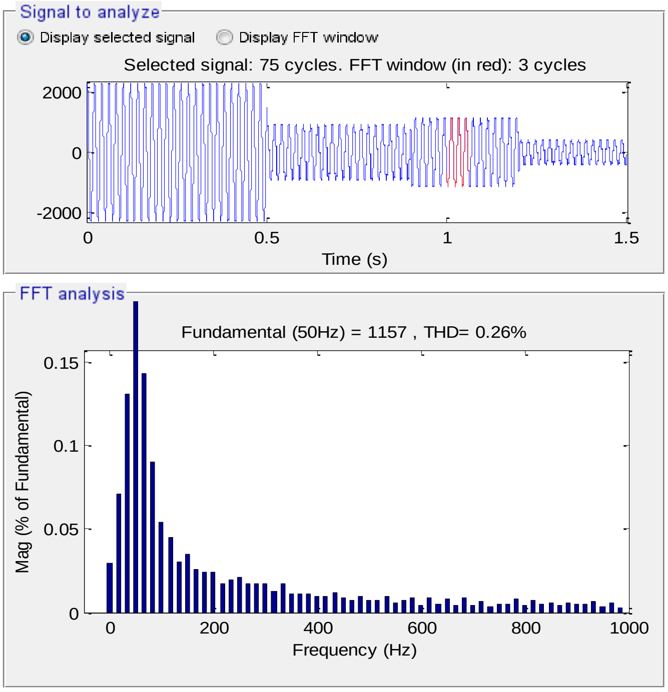


● Display selected signal ○ Display FFT window

Selected signal: 75 cycles. FFT window (in red): 3 cycles

Fundamental (50Hz) = 1154 , THD= 1.68%

Figure 19. THD of one phase rotor current for NSMC-PWM control (robustness test)



● Display selected signal ○ Display FFT window

Selected signal: 75 cycles. FFT window (in red): 3 cycles

Fundamental (50Hz) = 1157 , THD= 0.26%

Figure 20. THD of one phase rotor current for NSMC-NSVM control (robustness test)

Table 3. Comparative analysis of THD value

	THD (%)	
	NSMC-PWM	NSMC-NSVM
Rotor current	1.68	0.26

7. CONCLUSION

This article presents interesting simulation results of an advanced control scheme using NSMC and NSVM strategy for a DFIG-based wind turbine system. These simulation results show clearlly that for the same operation conditions, the DFIG stator active and reactive powers control presents good performances with NSMC using NSVM technique with fewer ripples compared to the conventional PWM and SVM strategies.

REFERENCES

[1] Y. Bekakra, D. Ben Attous, « Comparison study between SVM and PWM inverter in sliding mode control of active and reactive power control of a DFIG for variable speed wind energy, » *International Journal of Renewable Energy Research*, Vol. 2, No. 3, pp. 471-476, 2012.

[2] Z. Boudjema, R. Taleb, Y. Djerriri, A. Yahdou, « A novel direct torque control using second order continuous sliding mode of a doubly fed induction generator for a wind energy conversion system, » *Turkish Journal of Electrical Engineering & Computer Sciences*, Vol. 25, pp. 965-975, 2017.

[3] S. Z. Chen, N. C. Cheung, K. C. Wong, J. Wu, «Integral variable structure direct torque control of doubly fed induction generator, » *IET Renew. Power Gener*, Vol. 5, No. 1, pp. 18-25, 2011.

[4] H. Benbouhenni, Z. Boudjema, A. Belaidi, «Neuro-second order sliding mode control of a DFIG supplied by a two-level NSVM inverter for wind turbine system, » *Iranian Journal of Electrical & Electronic Engineering*, Vol. 14, No. 4, pp.362-373, 2018.

[5] H. Obdan, M. C. Ozkilic, « Performance comparison of 2-level and 3-level converters in a wind energy conversion system, » *Rev. Roum. Sci. Techn.-Electrotechn. Et Energ*, Vol. 61, No. 4, pp. 388-393, 2016.

[6] H. Benbouhenni, Z. Boudjema, A. Belaidi, «Direct vector control of a DFIG supplied by an intelligent SVM inverter for wind turbine system, » *Iranian Journal of Electrical & Electronic Engineering*, Vol. 15, No.1, pp. 45-55, 2019.

[7] A. Medjber, A. Moualdia, A. Mellit, M. A. Guessoum, « Comparative study between direct and indirect vector control applied to a wind turbine equipped with a double-fed asynchronous machine Article, » *International Journal of Renewable Energy Research*, Vol. 3, No. 1, pp. 88-93, 2013.

[8] N. Khemiri, A. Khedher, M. F. Mimouni, « Wind energy conversion system using DFIG controlled by backstepping and sliding mode strategies, » *International Journal of Renewable Energy Research*, Vol. 2, No. 3, pp. 422-435, 2012.

[9] H. Benbouhenni, Z. Boudjema, A. Belaidi, «Indirect vector control of a DFIG supplied by a two-level FSVM inverter for wind turbine system, » *Majlesi Journal of Electrical Engineering*, Vol. 13, No. 1, 2019.

[10] A. Nazari, H. Heydari, «Direct power control topologies for DFIG-based wind plants, » *International Journal of Computer and Electrical Engineering*, Vol. 4, No.4, pp. 475-479, 2012.

[11] A. Fekik, H. Denoun, N. Benamrouche, N. Benyahia, M. Zaouia, « A Fuzzy –Logic Based Controller For Three Phase PWM Rectifier With Voltage Oriented Control Strategy, » *International Journal Of Circuits, Systems And Signal Processing*, Vol. 9, pp. 412-419, 2015.

[12] H. Benbouhenni, Z. Boudjema, A. Belaidi, «Using three-level Fuzzy space vector modulation method to improve indirect vector control strategy of a DFIG based wind energy conversion systems, » *International Journal Of Smart Grid*, Vol.2, No.3, pp.155-171, 2018.

[13] H. Benbouhenni, Z. Boudjema, A. Belaidi, «DFIG-based wind turbine system using three-level neural space vector modulation technique, » *Majlesi Journal of Mechatronic Systems*, Vol. 7, No. 2, pp. 35-45, 2018.

[14] F. Bishuang, T. Guanzheng, F. Shaosheng, « Comparison of three different 2-D space vector PWM algorithms and their FPGA implementations, » *Journal of Power Technologies*, Vol. 94, No. 3, pp. 176-189, 2014.

[15] S. Krim, S. Gdaim, A. Mtibaa, M. F. Mimouni, « FPGA contribution in photovoltaic pumping systems : models of MPPT and DTC-SVM algorithms, » *International Journal of Renewable Research*, Vol. 6, No. 3, pp. 866-879, 2016.

[16] B. Allaoua, A. Laoufi, « A novel sliding mode fuzzy control based on SVM for electric vehicles propulsion system, » *Energy Procedia, Science Direct*, Vol. 36, pp. 120-129, 2013.

[17] M. Gaballah, M. El-Bardini, «Low cost digital signal generation for driving space vector PWM inverter, » *Ain Shams Engineering Journal*, Vol. 4, pp. 763-774, 2013.

[18] H. Benbouhenni, «Comparative study between different vector control methods applied to DFIG wind turbines, » *Majlesi Journal of Mechatronic Systems*, Vol. 7, No. 4, pp. 15-23, 2018.

[19] E. Bounadja, A. Djahbar, Z. Boudjema, «Variable structure control of a doubly fed induction generator for wind energy conversion systems, » *Energy Procedia*, Vol. 50, pp. 999-1007, 2014.

[20] H. Amoutaghi, S. Shojaeian, E. S. Naeini, « Enhancing low frequency oscillations danping of a power system by a TCSC controlled with sliding mode method, » *Majlesi Journal of Electrical Engineering*, Vol. 12, No. 1, pp. 31-37, 2018.

[21] A. Sid Ahmed EL Mehdi, M. Abid, «Fuzzy sliding mode control applied to a doubly fed induction generator for wind turbines, » *Turkish Journal of Electrical Engineering & Computer Sciences*, Vol. 23, pp. 1673-1686, 2015.

[22] S. M. M. Moghadam, A. Khosravi, S. M. R. Rostami, « Design of a robust sliding mode controller based on nonlinear modeling of variable speed wind turbine, » *Majlesi Journal of Electrical Engineering*, Vol. 11, No. 4, pp. 1-9, 2017.

[23] A. Yahdou, B. Hemici, Z. Boudjema, « Second order sliding mode control of a dual-rotor wind turbine system by employing a matrix converter, » *Journal of Electrical Engineering*, Vol. 16, No.4, pp.1-11, 2016.

[24] Z. Boudjema, A. Meroufel, A. Amari, « Robust control of a Doubly fed induction generator (DFIG) fed by a direct AC-AC converter, » *Przegląd Elektrotechniczny*, Vol. 11, pp. 213-221, 2012.

[25] F. Saeedizadeh, N. Pariz, S. A. Hosseini, « High-order sliding mode control of a bioreactor model through non-commensurate fractional equations, » *Majlesi Journal of Electrical Engineering*, Vol. 12, No. 1, pp. 1-12, 2018.

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