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A novel Matlab/Simulink Model of DFIG Drive Using NSMC Method with NSVM Strategy

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ABSTRACT

In this article, we present a comparative study between pulse width modulation (PWM) and neural space vector modulation (NSVM) strategy in 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 which the chattering effect is created by the discontinuous part of command [2]. In order to minimize the chattering phenomenon, 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 to command doubly fed induction machines. Second order sliding mode controller and neural networks are combined to command active and reactive power of DFIG based wind turbine [4].

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

In this work, we apply the NSMC technique to the wind turbine systems of DFIG using the NSVM strategy and compared with the classical PWM strategy.

2. MODEL OF TURBINE

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

$$P_{\max} = 0.5\rho\pi\, R^2 V_{vent}^3 \tag{1}$$

The mechanical power is given by:

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

$$\lambda = \frac{R.\Omega_1}{V_1} \tag{3}$$

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

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

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 [9, 10] :

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

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

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

The torque is expressed as:

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

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

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

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

4. NEURAL SPACE VECTOR MODULATION

The disadvantage of the SVM strategy is obtainable in [11]. The details about this strategy can be established in [12-14]. The proposed SVM inverter as shown in Fig. 1. This modulation strategy is simple scheme and easy implementation, based on following steps:

- Calculates the minimum voltages (min (V_1, V_2, V_3))
- Calculates the maximum voltages (max (V_1, V_2, V_3))
- Add the maximum and minimum voltages (max (V_1, V_2, V_3) + min (V_1, V_2, V_3)).
- 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. Fig. 2 shows neural space vector modulation (NSVM) of the two-level inverter of 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.

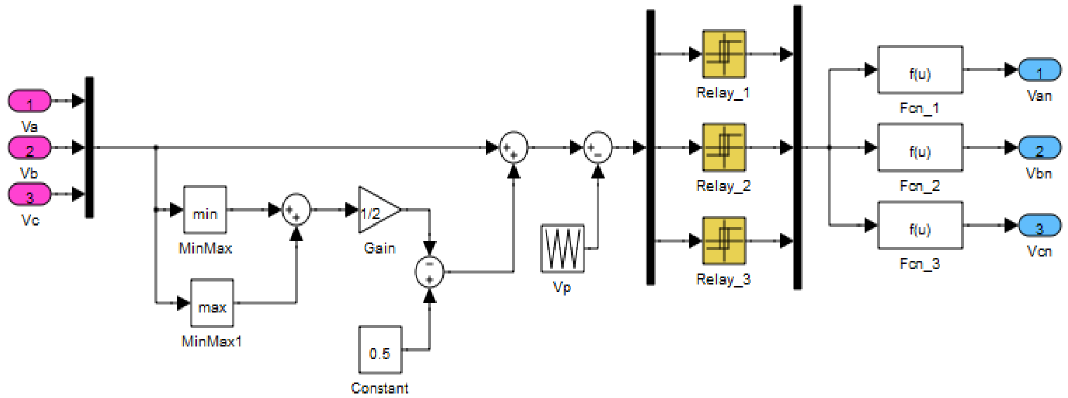

Fig. 1 Traditional SVM.

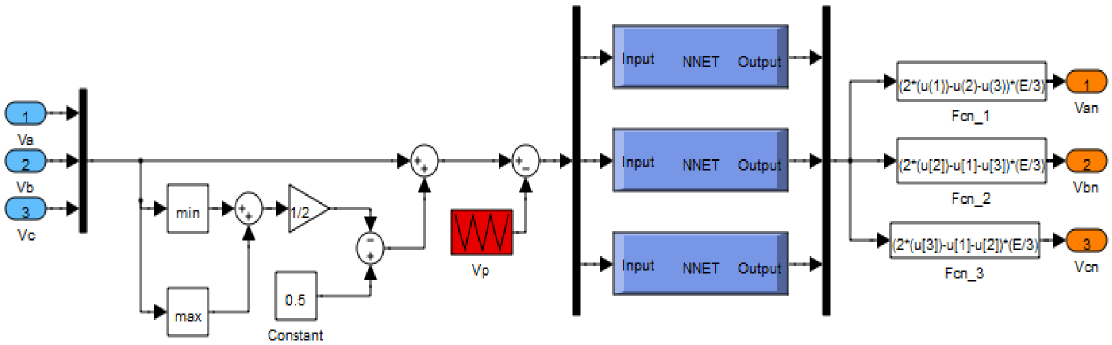

Fig. 2 NSVM strategy.

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 Fig. 3. The construction of Layer 1 and layer 2 is shown in Fig. 4 and Fig. 5 respectively.

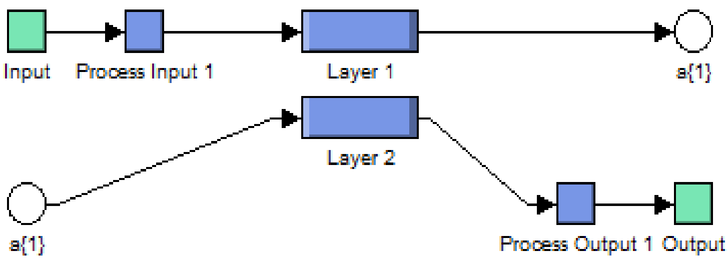

Fig. 3 Neural network structure for SVM inverter.

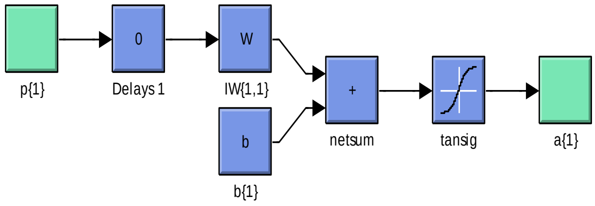

Fig. 4 Architecture of Layer 1.

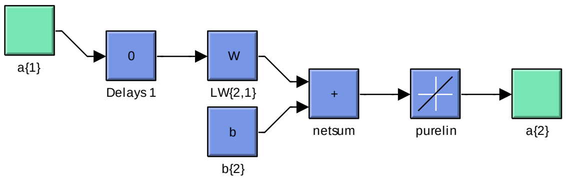

Fig. 5 Architecture of Layer 2.

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 machine: neuro-sliding mode control (NSMC). However, the SMC command is one of the most interesting nonlinear command approaches [15, 16]. 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 [17]. The SMC method goes through three stages, as follows:

- Choice of switching surface
- Convergence condition
- Control calculation

Many paper proposed SMC method to command the reactive and active powers of a DFIG-based wind turbine systems. In [18], the author proposes the design of a robust SMC based on nonlinear modeling of variable speed wind turbine system.

Yahdou et al. In 2016 [19] 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 [20] used robust command to command the DFIG machine. In [21], 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:

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

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

$$V_{dq} = V_{dq}^{eq} + V_{dq}^{n} \tag{15}$$

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

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

Where K determine the ability of overcoming the chattering.

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

$$S.\dot{S} \prec 0 \tag{17}$$

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.

$$V_{dq}^{com} = V_{dq}^{eq} + V_{dq}^{Neural} \tag{18}$$

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

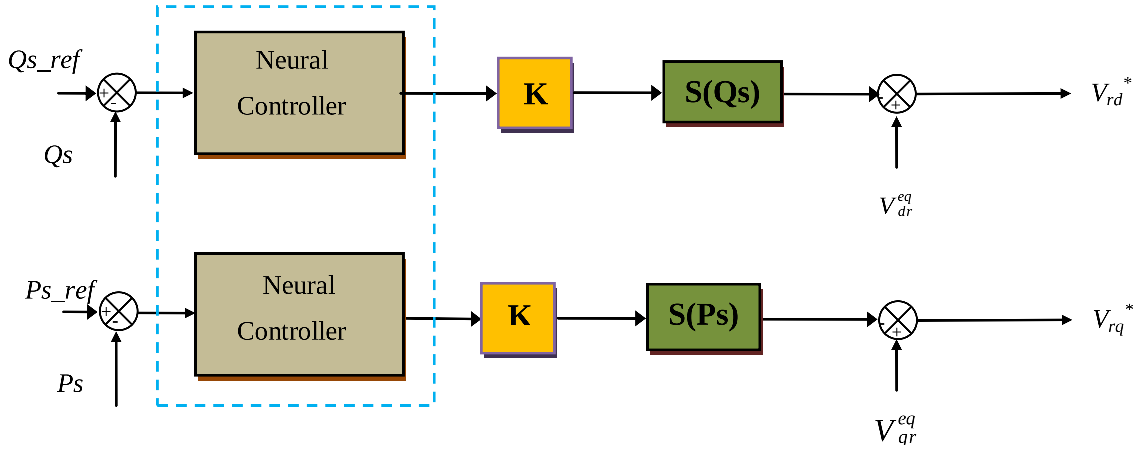

Fig. 6 Block diagram of the DFIG control with NSMC strategy.

For the two proposed neuro-sliding mode controllers in Fig. 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.

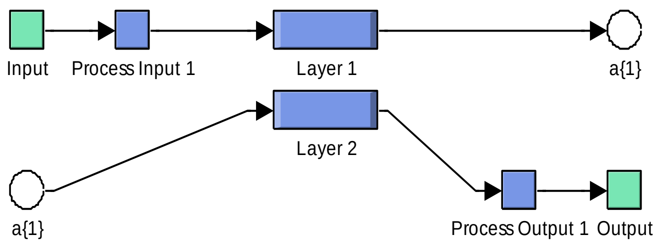

Fig. 7 Neural network structure for reactive and active powers.

Fig. 8 represents the SMC strategy of DFIG driven by a two-level NSVM inverter.

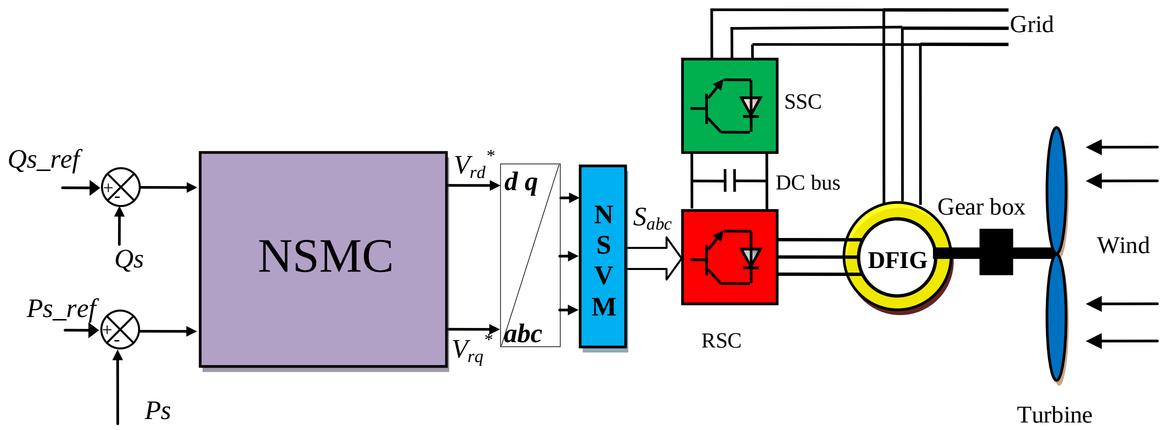

Fig. 8 NSMC control of a DFIG using NSVM strategy.

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 1. The proposed command schemes will be tested and compared in two different configurations: robustness against parameters variations and reference tracking.

Table. 1 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

A. Reference tracking test

Figs. 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 (See Figs. 11-12). On the other hand, Figs. 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%**).

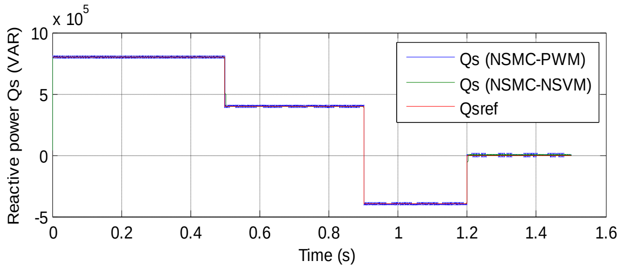

Fig. 9 Reactive power (reference tracking test).

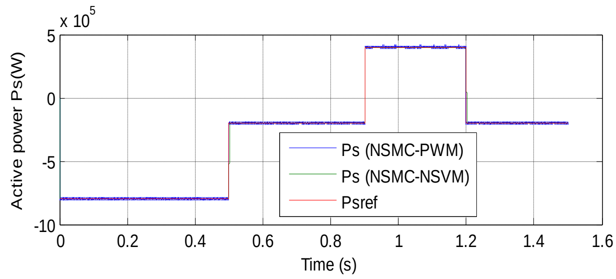

Fig.10 Active power (reference tracking test).

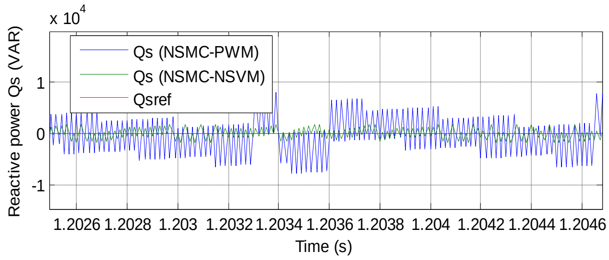

Fig. 11 Zoom in the reactive power (reference tracking test).

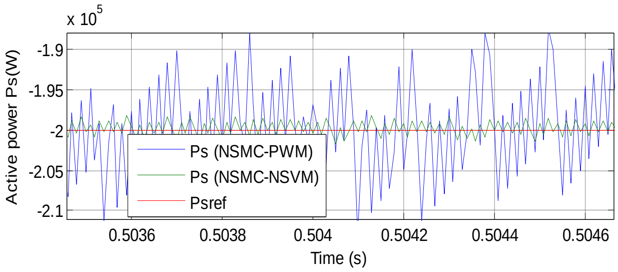

Fig. 12 Zoom in the active power (reference tracking test).

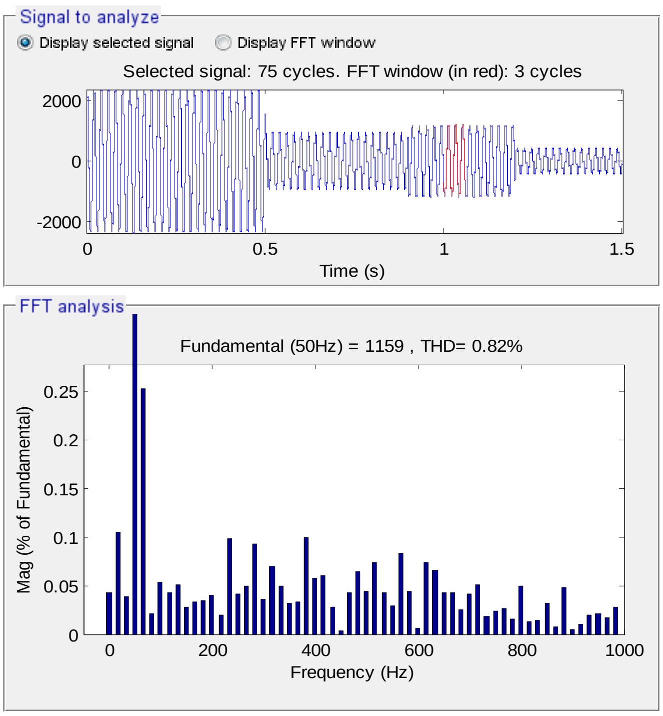

Fig. 13 THD of one phase rotor current for NSMC-PWM control (reference tracking test).

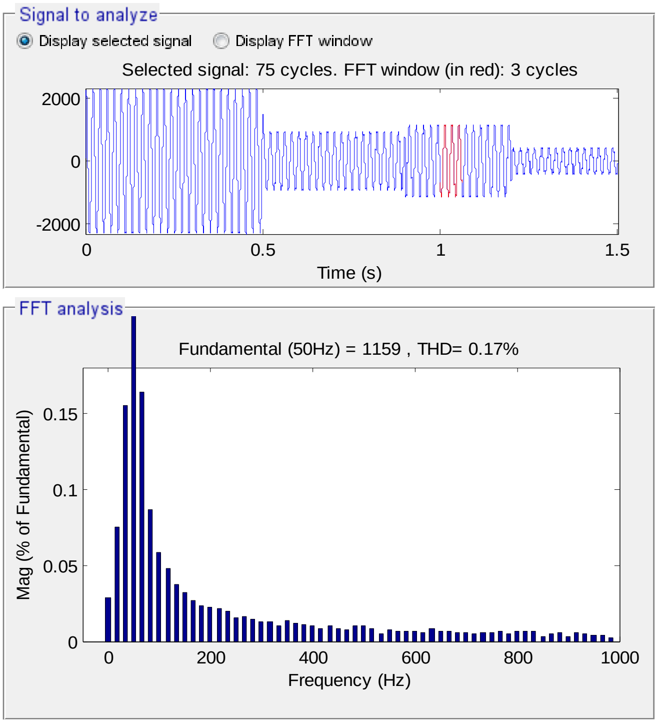

Fig. 14 THD of one phase rotor current for NSMC-NSVM control (reference tracking test).

B. 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 Figs. 15-16 and Figs. 19-20. 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 (see Figs. 17-18). On the other hand, the THD value of rotor current in the NSMC-NSVM has been minimized significantly. Table 2 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.

Table 2. Comparative analysis of THD value

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

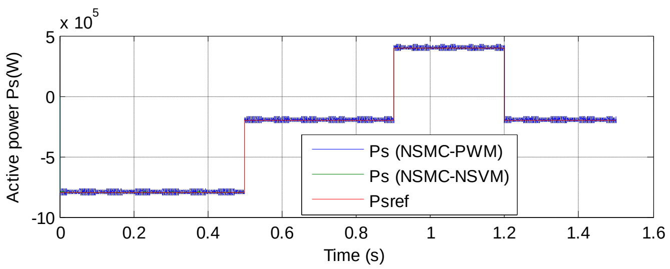

Fig. 15 Active power (robustness test).

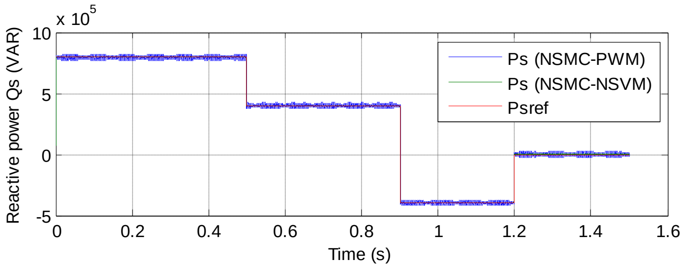

Fig. 16 Reactive power (robustness test).

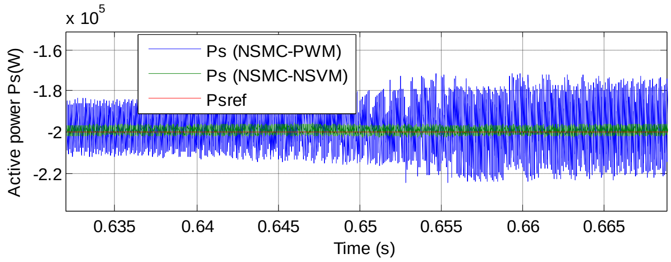

Fig. 17 Zoom in the active power (robustness test).

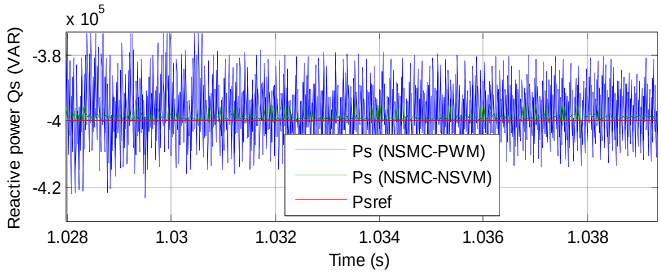

Fig. 18 Zoom in the reactive power (robustness test).

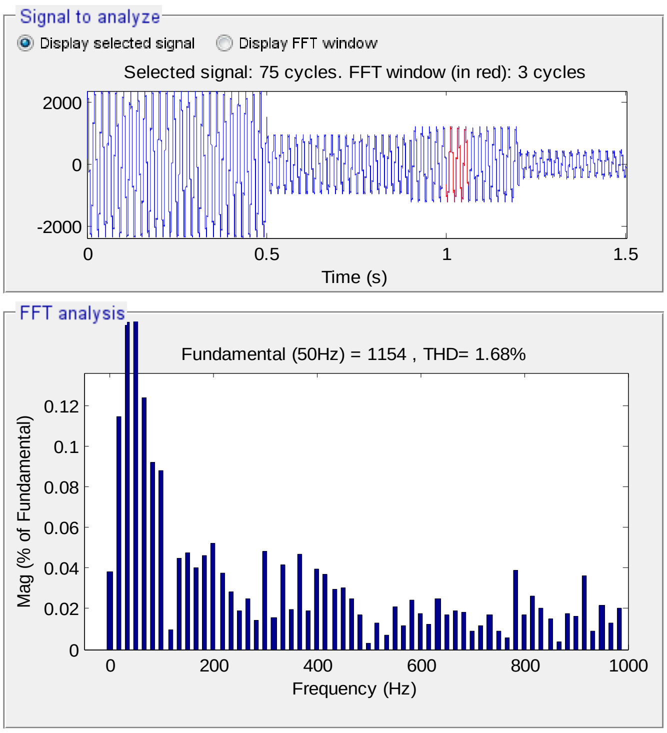

Fig. 19 THD of one phase rotor current for NSMC-PWM control (robustness test).

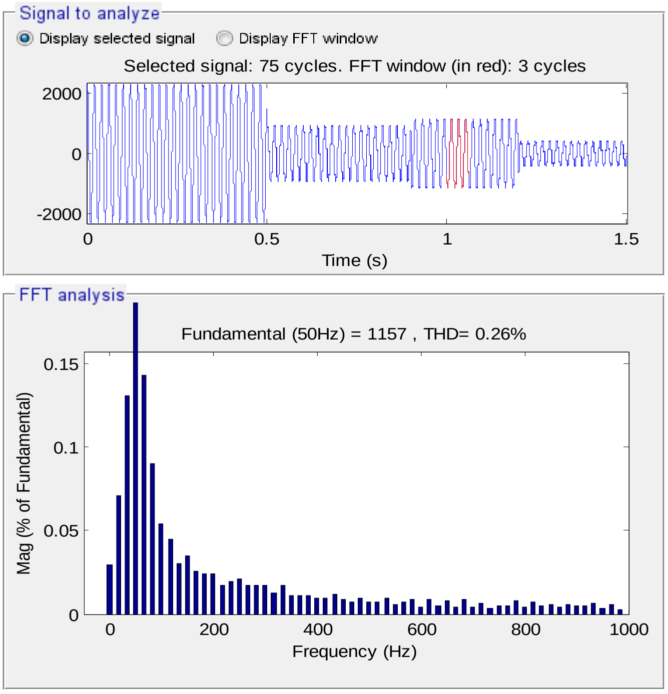

Fig. 20 THD of one phase rotor current for NSMC-NSVM control (robustness test).

7. CONCLUSION

This article presents simulation results of neuro-sliding mode control for stator reactive and stator active power command of a DFIG, using the modulation strategies of the PWM and NSVM strategy. With results obtained from simulation, it is clear that for the same operation condition, the DFIG stator reactive and stator active power command with NSMC using NSVM technique had better performance than the PWM strategy and that is clear in the spectrum of phase rotor current harmonics which the use of the NSVM strategy, it is minimized of harmonics more than PWM strategy.

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