Comparison Study between FPWM and NSVM Inverter in Neuro-Sliding Mode Control of Reactive and Active Power Control of a DFIG-based Wind Energy

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ABSTRACT:

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

KEYWORDS: Neural Space Vector Modulation; Fuzzy Pulse Width Modulation; Neuro-Sliding Mode Controller; Doubly Fed Induction Generator.

1. INTRODUCTION

The sliding mode control has a unique place in control theories. First, the exact mathematical treatment represents numerous interesting challenges for the mathematicians. Secondly, in many cases, it can be relatively easy to apply without a deeper understanding of its strong mathematical background and is therefore widely used in engineering practice.

The theory of variable structure system and sliding mode has been developed decades ago in the Soviet Union. The theory was mainly developed by Vadim I. Utkin and David K. Young. However, the main advantages of sliding mode control, including robustness, finite-time convergence, and reduced-order compensated dynamics, are demonstrated on numerous examples and simulation plots.

Recently the SMC technique has been widely used for robust control of nonlinear systems. SMC, based on the theory of variable structure systems, has attracted a lot of research on control systems [1]. This has been confirmed by a large number of research papers published over this period of time. The main basic principles of SMC are outlined in [2-4]. In [5], an integral sliding mode controller was designed to regulate stator reactive power and electromagnetic torque. A discrete SMC is designed to regulate the real and reactive power of doubly fed induction generator (DFIG) [6]. Sliding mode controller is proposed to control the reactive and active power under unbalanced and harmonically distorted grid voltage [7]. Fuzzy logic (FL) and SMC are combined to control DFIG based wind turbine systems (WTSs) [8]. On the hand, the SMC has an essential disadvantage, which is the chattering phenomenon caused by the discontinuous control action [9]. Chattering could be reduced or suppressed using the different technique such as :

- Non-linear gains.
- Dynamic extension.
- Higher order sliding mode control
- Hybrid sliding mode control (Neuro-sliding mode, Fuzzy sliding mode, ANFIS-sliding mode…).

Neural networks (NNs) is a technique based on engineering experience and observations. In NNs controller, an exact mathematical model is not necessary. This technique is simple and easy to implement.

On way to improve SMC performance is to combine it with NNs controllers to form a Neuro-sliding mode controller (NSMC). The design of an SMC incorporating neural control helps in achieving reduced chattering, simple control, and robustness against disturbances and nonlinearities.

Pulse width modulation (PWM) technique is widely used in command of the AC machine. This strategy is a simple control scheme and easy to implement. However, this strategy has the following drawbacks. This strategy gives more total harmonic distortion (THD) of stator current, this strategy gives more power ripples, this method does not smooth the progress of future development of vector control implementation of AC drive. To overcome these drawbacks lead to the development of a sophisticated PWM technique which is fuzzy PWM (FPWM) technique. This proposed technique reduced THD value of stator current and electromagnetic torque ripples compared to conventional PWM inverter. Furthermore, it minimizes the power ripples of DFIG-based wind energy conversion systems.

Space vector modulation (SVM) technique is generally urbanized as vector approach to PWM strategy for a three-phase inverter. The disadvantage of the SVM technique is obtainable in [10]. The details about this strategy can be established in [11-13]. In [14], the author proposes a new SVM technique based on NNs controllers to control stator reactive and active power of DFIG based WTSs. SVM and FL controller are combined to control doubly fed induction generator [15].

In this work, we apply the neuro-sliding mode controller to the wind energy conversion systems of doubly fed induction generator using two-level FPWM inverter and compared to the two-level NSVM technique.

2. FUZZY PULSE WIDTH MODULATION

Fig. 1 shows the principle of the pulse width modulation strategy of the two-level inverter. The main objective of this strategy is to command the inverter output voltage and to reduce the harmonic in the output voltage. Nevertheless, this technique gives more distortion harmonic of stator current and powers ripples of DFIG compared to SVM technique. In order to overcome the drawbacks of the PWM technique, fuzzy pulse width modulation has been presented [16]. In the fuzzy pulse width modulation (FPWM), the hysteresis comparators are replaced by FL controllers. Nevertheless, this technique reduces the powers ripples and electromagnetic torque of DFIG-based WECSs. The principal of FPWM technique is exposed in Fig. 2.

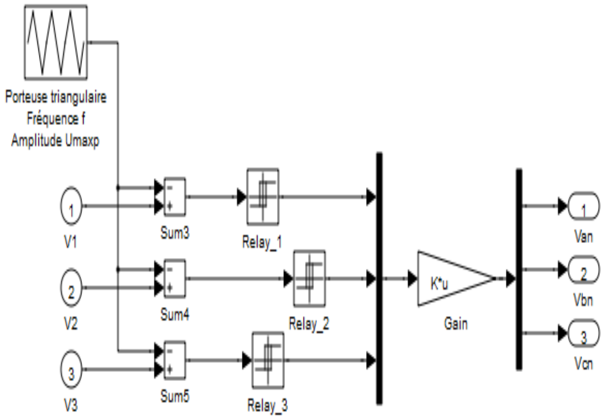


Fig. 1. Block diagram of PWM inverter.

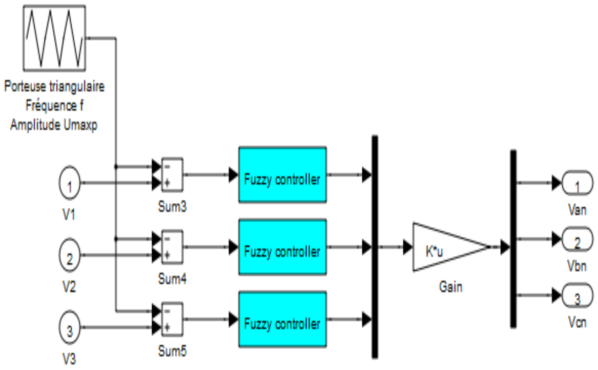


Fig. 2. Block diagram of FPWM inverter.

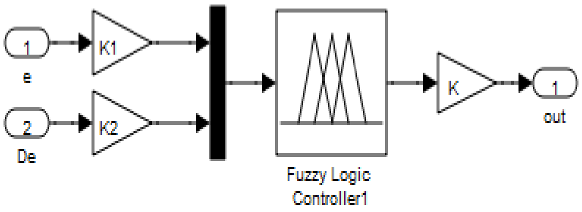


Fig. 3. Fuzzy command of FPWM technique.

The FL controller contains three blocks: fuzzification, fuzzy rule base and defuzzification. On the other hand, the FL rules are developed using linguistic changes that are formulated in the form of « IF THEN » rules. The Table 1 shows these rules [16, 17].

Table 1. Matrix of Inference.

e **Δe**	**NB**	**NM**	**NS**	**EZ**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	EZ
NM	NB	NB	NB	NM	NS	EZ	PS
NS	NB	NB	NM	NS	EZ	PS	PM
EZ	NB	NM	NS	EZ	PS	PM	PB
PS	NM	NS	EZ	PS	PM	PB	PB
PM	NS	EZ	PS	PM	PB	PB	PB
PB	EZ	PS	PM	PB	PB	PB	PB

Where, NB: Negative Big
NS: Negative Small
PM: Positive Middle
EZ: Equal Zero
PB: Positive Big
PS: Positive Small
NM: Negative Middle

The Table 2 shows the parameters of FL controller for FPWM technique.

Table 2. Parameters of Fuzzy Regulator

Fis type	Mamdani
And method	Min
Or method	Max
Implication	Min
Aggregation	Max
Defuzzification	Centroid

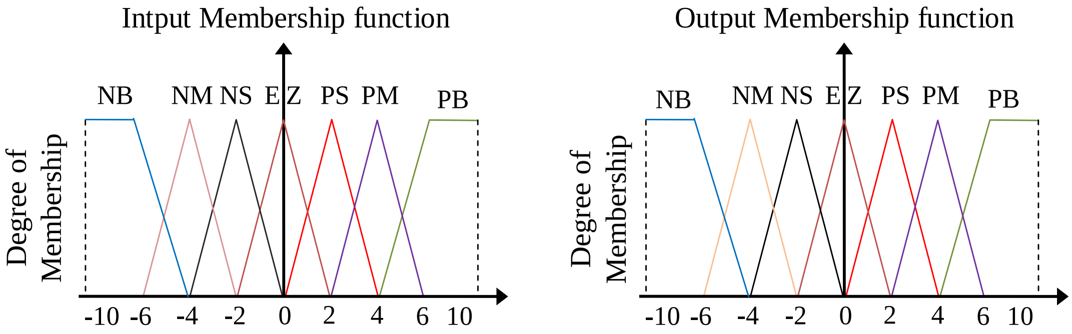


Fig. 4. Fuzzy sets and its memberships functions.

On the other hand, the two-level NSVM technique reduces the powers ripples, electromagnetic torque ripple and THD value of rotor current compared to traditional SVM technique.

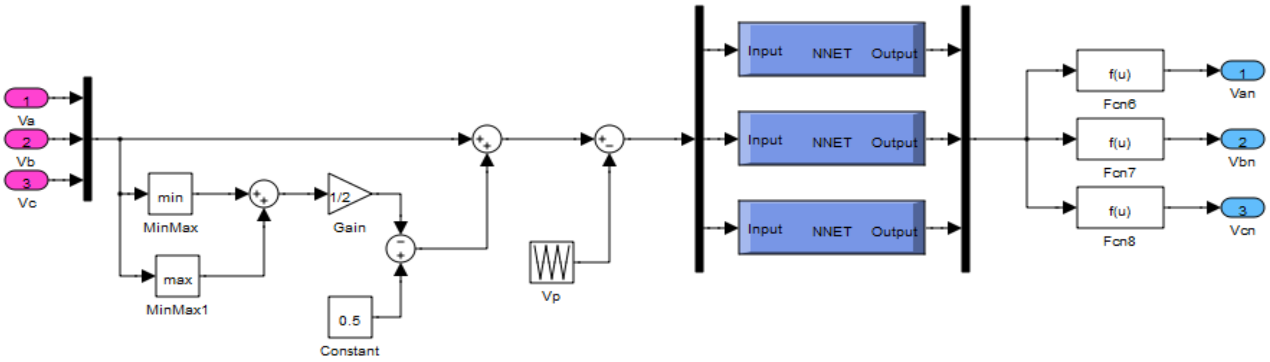


Fig. 5. Block diagram of two-level NSVM technique.

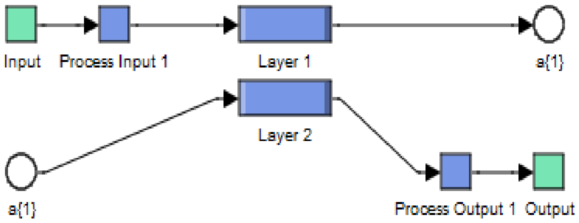


Fig. 6. The ANN controller of the hysteresis comparators.

3. NEURAL SPACE VECTOR MODULATION INVERTER

The principle of the two-level neural space vector modulation (NSVM) is similar to conventional SVM inverter. However, the hysteresis comparators are replaced by NN controllers and this technique based on neural classification has the advantage of simplicity and easy implementation.

The structure of SVM based on the NN controller is shown in Fig. 5. On the other hand, the artificial neural networks controllers for the model system are shown in Table 3. The artificial neural networks model structure of the system is shown in Fig. 6. The construction of Layer 1 and layer 2 is shown in Fig. 7 and Fig. 8 respectively.

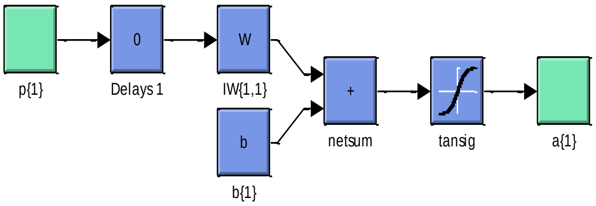


Fig. 7. Block diagram of Layer 1.

Table 3. Parameters of the LM 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

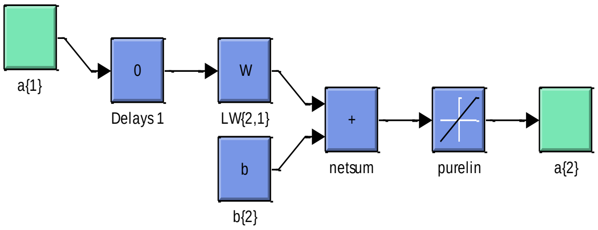


Fig. 8 Block diagram of Layer 2.

4. MODEL OF TURBINE

The WT input power usually is [18, 19]:

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

Where, R: Radius of the turbine in (m).
ρ: is air density.
V_{vent}: Wind speed (m/s).
P_{max}: Maximum power in (watts).
The mechanical power is given by:

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

Where, λ: The tip speed ratio.
C_p: The aerodynamic coefficient of power.

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

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

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

Where, C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21, C_6=0.0068.

β: The blade pitch angle in a pitch-controlled wind turbine.

5. THE DFIG MODEL

The conventional electrical equations of the DFIG in the Park frame are written as follows [20, 21]:

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

Where, R_r : is the resistances of the rotor windings.
R_s : is the resistances of the stator windings.
V_{dr}, and V_{qr} : is the rotor voltages.
V_{qs} and V_{ds} : is the stator voltages.
I_{dr}, and I_{qr} : is the rotor currents.
I_{ds} and I_{qs} : is the stator currents.

The rotor and stator flux can be expressed as:

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

Where, L_r : is the inductance own rotor
L_s : is the inductance own rotor
M : is the mutual inductance.
ψ_{dr} and ψ_{qr} : is the rotor fluxes.
ψ_{ds} and ψ_{qs} : is the stator fluxes.

The reactive and active powers can be expressed as:

$$\begin{cases} P_s = \frac{3}{2}(V_{ds}I_{ds} + V_{qs}I_{qs}) \\ Q_s = \frac{3}{2}(V_{qs}I_{ds} - V_{ds}I_{qs}) \end{cases} \tag{8}$$

Where, P_s : is the stator active power.
Q_s : is the stator reactive power.

The torque is expressed as:

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

Where, T_r : is the load torque.
T_e : is the electromagnetic torque.
Ω : is the mechanical rotor speed.
J : is the inertia.
f : is the viscous friction coefficient.

6. NEURO-SLIDING MODE CONTROLLER

Sliding mode control (SMC) has been an important theoretical research field. Today, it is becoming a good source of solutions to real-world problem. The advantage of SMC is their insensitivity to parameter variations and disturbances once in the sliding mode, thereby eliminating the necessity of exact modelling. SMC is a type of variable structure control (VSC) that possess robust characteristics to system disturbances and parameter uncertainties. This technique is a nonlinear control method that alters the dynamics of a nonlinear system by application of a high-frequency switching control.

Sliding mode control is a nonlinear control method featuring remarkable properties of accuracy, robustness, and easy tuning and implementation. The SMC-FPWM goal is to control the stator active and the reactive power of the DFIG based WECSs. In the SMC control, stator reactive is controlled by means of the direct axis voltage V_{dr}, while the torque is controlled by means of the quadrature axis voltage V_{qr}. This technique is detailed in [22], [23].

$$V_{dq}^{com} = V_{dq}^{eq} + V_{dq}^{Neural} \tag{10}$$

The proposed NSMC control scheme, which is designed to regulate the stator active and reactive powers of the DFIG based WECSs, is shown in Fig. 9.

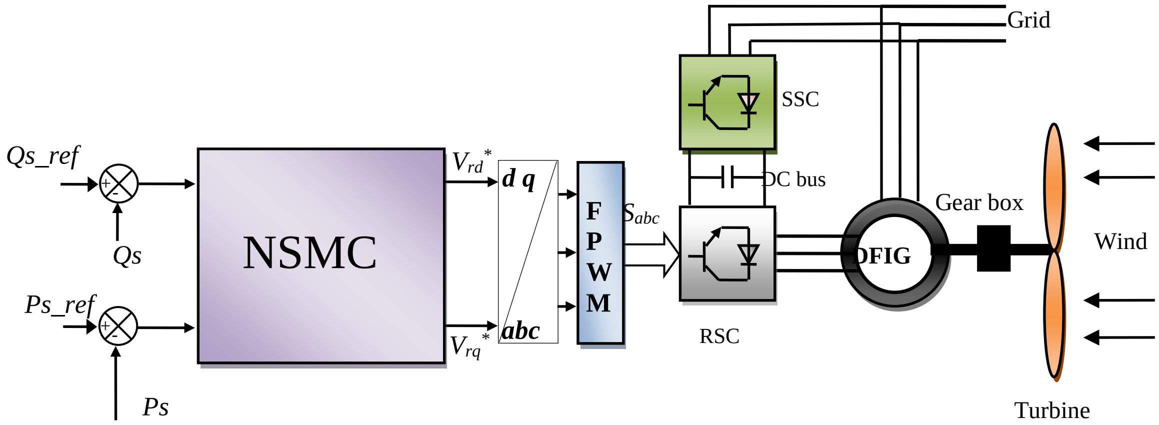


Fig. 9. NSMC control of a DFIG using NSVM strategy.

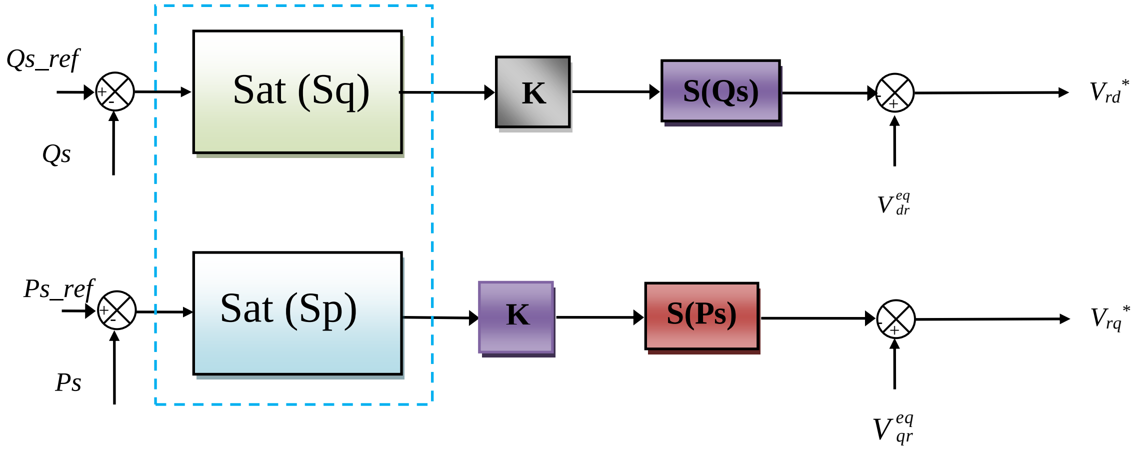


Fig. 10. Block diagram of the SMC strategy.

The proposed SMC-FPWM, which is designed to control the reactive and active powers of the DFIG, is shown in Fig. 9. The internal structure of the SMC technique is shown in Fig. 10.

The disadvantage of the SMC control scheme of the DFIG-based WTSs is that the discontinuous command signal produces chattering and powers ripples. In order to improve the SMC method and eliminate the chattering phenomenon and minimize the powers ripples of the DFIG, we propose to use the NNs controllers. The neuro-sliding mode controllers (NSMC) is a modification of the SMC control, where the switching controllers term sat(S(x)), has been replaced by NNs controllers input as given below.

This technique reduced the powers ripples, electromagnetic torque ripple and THD value of rotor current of the DFIG.

For the two proposed neuro-sliding mode controllers in Fig. 11, the structure of the NN with one linear input node, 8 neurons in the hidden layer and one neuron in the output layer.

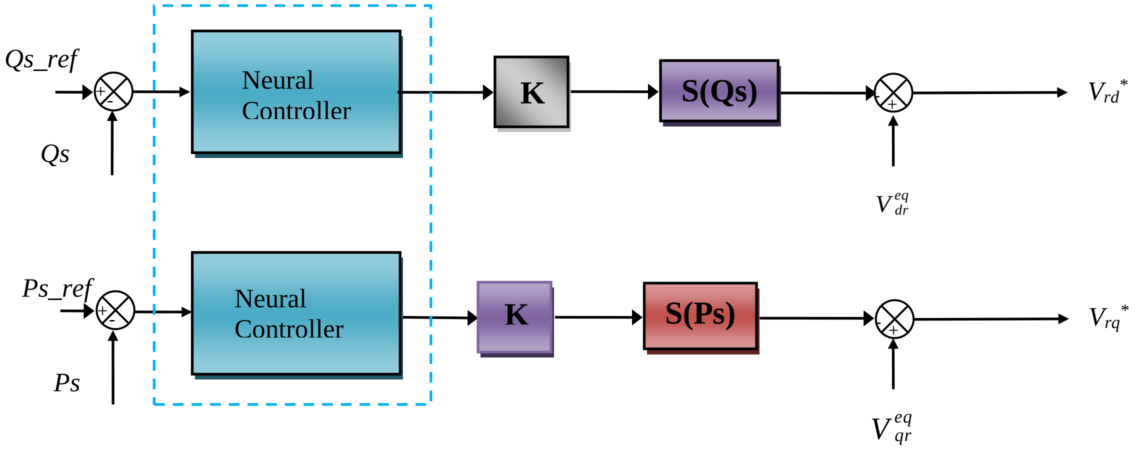


Fig. 11 Block diagram of the NSMC technique.

7. SIMULATION RESULTS

The simulation results of three-level NSMC with FPWM technique of the DFIG are compared with NSMC control scheme with NSVM inverter. The performance analysis is done with THD value, electromagnetic torque, stator active power and stator reactive power.

The DFIG used in this case study is a 1.5MW, 380/696V, two poles, 50Hz; with the following parameters: Rs = 0.012Ω, Rr = 0.021Ω, Ls = 0.0137H, Lr = 0.0136H and Lm = 0.0135H.

The system has the following mechanical parameters: J = 1000 kg.m2, fr = 0.0024 Nm.s/rad.

Figs 9-13 show the obtained simulation results. As it’s shown in Figs 9-11, for the two NSMC control techniques, the stator reactive and stator active powers track almost perfectly their references values. Moreover, the NSMC-FPWM command reduced the electromagnetic torque and powers ripples compared to the NSMC-NSVM (see Figs 14-16). On the other hand, Figs. 12-13 show the total harmonic distortion of stator current of the DFIG for two NSMC control schemes. It can be clearly observed that the total harmonic distortion value is minimized for NSMC-FPWM (THD = **0.09%**) when compared to SMC control using NSVM inverter (THD = 0.20%).

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.

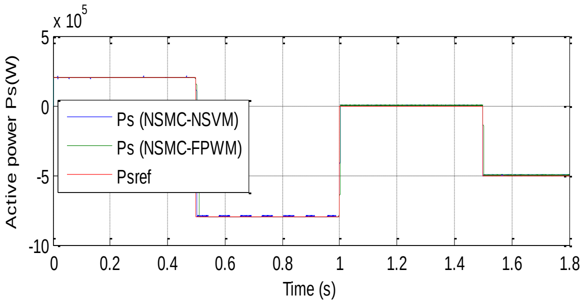


Fig. 12. Stator active power.

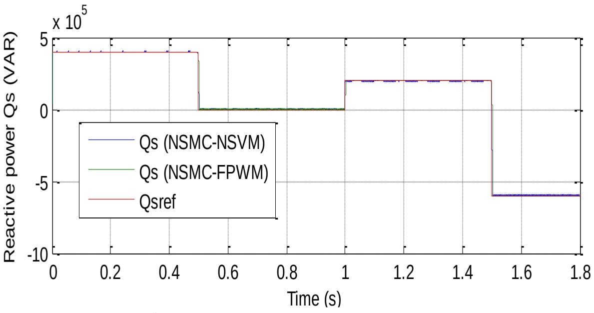


Fig. 13. Stator reactive power.

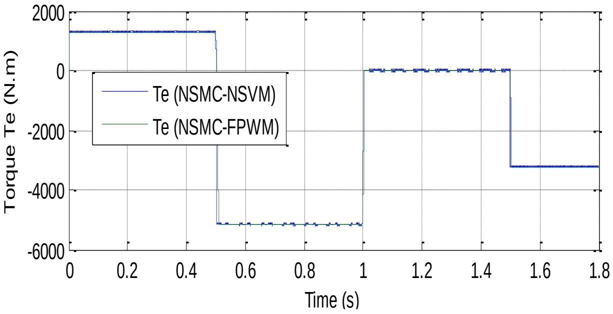
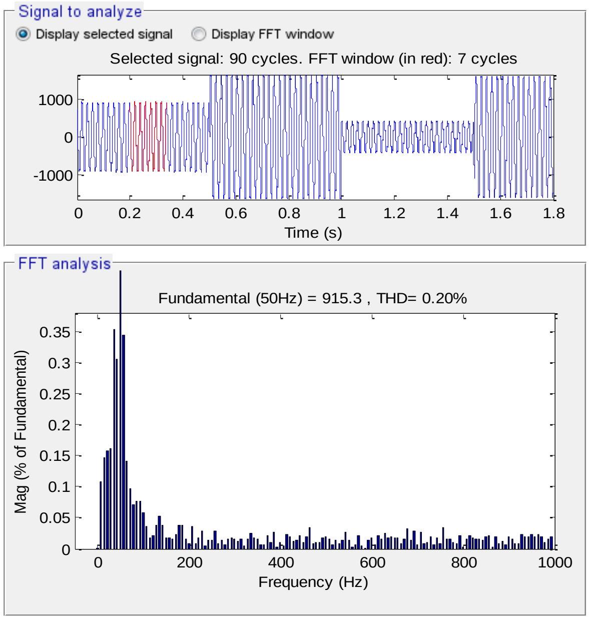


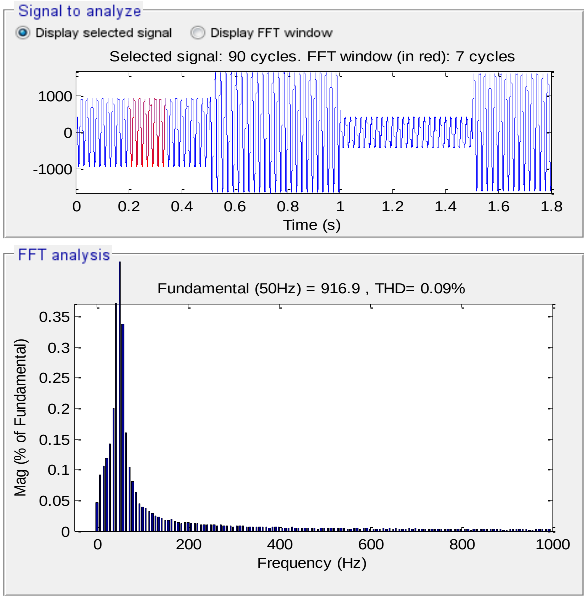
Fig. 14. Electromagnetic torque.



Selected signal: 90 cycles. FFT window (in red): 7 cycles

Fundamental (50Hz) = 915.3 , THD= 0.20%

Fig. 15. THD of one phase stator current for NSMC-NSVM control.



Selected signal: 90 cycles. FFT window (in red): 7 cycles

Fundamental (50Hz) = 916.9 , THD= 0.09%

Fig. 16. THD of one phase stator current for NSMC-FPWM-NSVM control.

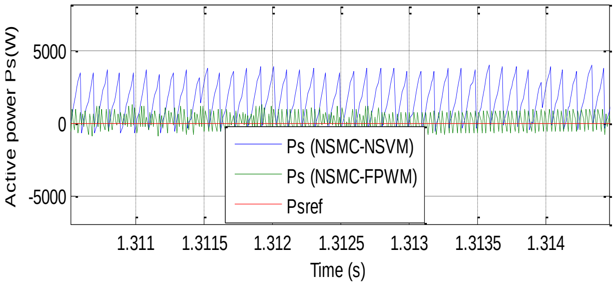


Fig. 17. Zoom in the active power.

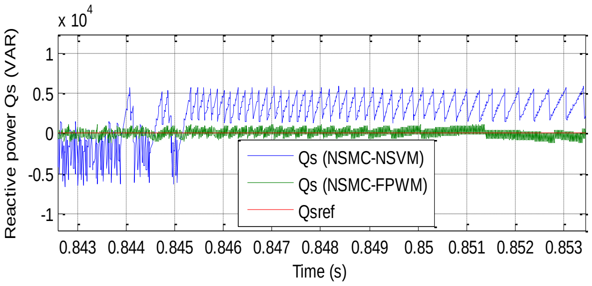


Fig. 18. Zoom in the reactive power.

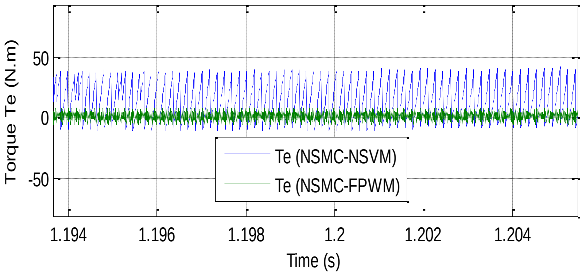


Fig. 19. Zoom in the torque.

8. CONCLUSION

This work presents neuro-sliding mode control of a doubly fed induction generator using a two-level fuzzy pulse width modulation compared with the two-level neural space vector modulation. With results obtained from the simulation, it was clear that for the same operation conditions, the neuro-sliding mode control technique with two-level FPWM inverter presents good performance compared to the neuro-sliding mode control one using neural space vector modulation and that was clear in the THD of stator current which the use of the two-level fuzzy pulse width modulation minimize the THD more than the neural space vector modulation technique.

REFERENCES

[1] Boudjema Z., Taleb R., Djerriri Y., Yahdou A., "**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.

[2] Utkin V. I., "**Variable Structure systems with Sliding Modes**," *lIEEE Transaction on Automatic Contro*, 22, 2, 212-222, 1977.

[3] DeCarlo R. A., Zak S. H., Mathews G., "**Variable structure control of nonlinear multivariable systems: A Tutorial**," *Proceedings of the IEEE*, Vol. 76, No. 3, 1988.

[4] Hung J. Y., Gao W., Hung J. C., "**Variable Structure Control: A Survey**," *IEEE Trans. on Industrial Electronics*, Vol. 40, No. 1, 1993.

[5] Utkin V. I., "**Sliding mode control design principles and applications to electric drives**," *IEEE Trans. Ind. Electron*, Vol. 40, No. 1, pp. 23-36, 1993.

[6] Karous D., Wamkeue R., "**DFIG-based fuzzy sliding-mode control pf WECS with a flywheel energy storage**," *Electr. Power Syst. Res*, Vol. 93, pp. 16-23, 2012.

[7] Martinez M. I., Tapia G., Susperregui A., Camblong H., "**Sliding mode control for DFIG rotor and grid side converter under balanced and harmonically distorted grid voltage**," *IEEE Trans. Energy Convers*, Vol. 27, No. 2, pp. 328-339, 2012.

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

[9] Boudjema Z., Meroufel A., Djerriri Y., Bounadja E., "**Fuzzy sliding mode control of a doubly fed induction generator for wind energy conversion**," *Carpathian Journal of Electronic and Computer Engineering*, Vol. 6, No. 2, pp. 7-14, 2013.

[10] Bishuang F., Guanzheng T., Shaosheng F., "**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.

[11] Krim S., Gdaim S., Mtibaa A., Mimouni M. F., "**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.

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

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

[14] Benbouhenni H., Boudjema Z., Belaidi A., "**Neuro-second order sliding mode control of a DFIG supplied by a two-level NSVM inverter for wind turbine system**," *Iranian Journal of Electrical and Electronic Engineering*, In Press, 2018.

[15] Benbouhenni H., Boudjema Z., Belaidi A., "**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 , 2018, pp. 155-171.

[16] Boudjema Z., Taleb R., Yahdou A., Bouyekni A., "**Fuzzy second order sliding mode control of a doubly-fed induction machine supplied by to matrix converters**," *Journal of Electrical Engineering*, Vol. 15, No.3, pp. 1-10, 2015.

[17] Bakouri A., Mahmoudi H., Abbou A., "**Intelligent control for doubly fed induction generator connected to the electrical network**," *International Journal of Power Electronics and Drive System*, Vol. 7, No. 3, pp. 688-700, 2016.

[18] Fekik A., Denoun H., Benamrouche N., Benyahia N., Zaouia M., "**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.

[19] Massoum S., Meroufel A., Youcefa B. E., Massoum A., Wira P., "**Three-level NPC converter-based neuronal**

direct active and reactive power control of the doubly fed induction machine for wind energy generation," *Majlesi Journal of Electrical Engineering*, Vol. 11, No. 3, pp. 25-32, 2017.

[20] Khemiri N., Khedher A., Mimouni M. F., "**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.

[21] Djerriri Y., Meroufel A., Belabbas B., Massoum A., "**Three-level NPC voltage source converter based direct power control of the doubly fed induction generator at low constant switching frequency**," *Revue des Energies Renouvelables*, Vol. 16, No. 1, pp. 91-103, 2013.