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ANFIS-sliding mode control of a DFIG supplied by a two-level SVPWM technique for wind energy conversion system

Habib Benbouhenni
Department of Electrical Engineering, National Polytechnique School of Oran Maurice Audin, Algeria

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ABSTRACT

A modified adaptive neuro-fuzzy inference system sliding mode control (ANFIS-SMC) by using two-level space vector pulse width modulation (SVPWM) for doubly fed induction generator (DFIG) is proposed in this article. ANFIS-SMC with SVPWM strategy improves the basic SMC performances, which features low stator active and reactive power and also minimize the total distortion harmonic (THD) of stator current. The computer simulation results, in Matlab, demonstrate the effectiveness of the proposed control strategy which improves the performance of the DFIG.

Corresponding Author:

Habib Benbouhenni,
Department of Electrical Engineering,
National Polytechnique School of Oran Maurice Audin,
Oran, Algeria.
Email: habib0264@gmail.com

NOMENCLATURE

WTS	Wind turbine system
DFIG	Doubly fed induction generator
WECS	Wind energy conversion systems
ANFIS	Adaptive neuro-fuzzy inference system
SMC	Sliding mode control
THD	Total distortion harmonic
SVPWM	Space vector pulse width modulation
DTC	Direct vector control
DPC	Direct power control
SOSMC	Second order sliding mode controller
ANN	Artificial neural network
FL	Fuzzy logic
L_r, L_s	Stator and rotor self-inductances
L_m	Mutual inductance
R_r, R_s	Stator and rotor resistances
ψ_r, ψ_s	Rotor and Stator flux vectors
I_s, I_r	Rotor and stator current vectors
V_s, V_r	Rotor and stator voltage vectors
P_s, Q_s	Active and reactive powers.
r, s	Rotor, stator
d, q	Synchronous d-q axis

1. INTRODUCTION

Traditionally, DFIG based wind turbine systems (WTSs) are mainly installed in remote and rural areas [1]. Operation and control of DFIG has been the subject of intense research during last few years. The rotor of the DFIG is connected to AC-DC-AC converter and the stator is connected to the power grid [2]. The principal advantage of the DFIG is that the rotor side converter (RSC) is only sized for 30% of rated power compared to other generators used in variable speed WTSs. Various control strategies have been proposed for studying the behavior of DFIG-based wind energy conversion systems (WECSs) during normal operation. Indirect vector control [3] and a direct vector control [4] have been proposed for DFIG. In these techniques, the decoupling between q-axis and d-axis current is achieved with feedforward compensation, and thus the DFIG model becomes less difficult and PI controllers can be used [5].

In [6], direct vector control (DTC) was proposed to control DFIG. Similar to the DTC method, a direct power control (DPC) of DFIG based wind energy conversion system has proposed recently [7-9]. In [10], DPC control based on neural network (NNs) has been proposed. In [11], a modified DTC technique was proposed based on second order sliding mode controller (SOSMC) to regulate the electromagnetic torque and rotor flux. In [12], an reactive and active stator power proportional-integral controllers and space vector pulse width modulation (SVPWM) strategy were combined to replace the traditional hysteresis comparators. In [13], a modified DPC strategy was proposed based on SOSMC technique to regulate the reactive and active stator power of the DFIG-based WECS. SOSMC and fuzzy logic (FL) are combined to control the DFIG [14]. In [15], fuzzy sliding mode controller (FSMC) was designed to regulate the active and reactive power of the DFIG-based WTSs.

Neuro-sliding mode controller (NSMC) is proposed to control electromagnetic torque, reactive and active stator power of the DFIG [16]. Artificial neural networks (ANNs) and SOSMC are combined to control the stator reactive and active power of the DFIG [17]. Backstopping control was proposed to control DFIG [18]. In [19], LQR method was designed to control flux and electromagnetic torque of DFIG. In [20], neural space vector pulse width modulation (NSVPWM) and NSMC technique were combined to control DFIG. Fuzzy SVPWM strategy is proposed to reduce the total harmonic distortion (THD) of current and powers ripples of DFIG [21]. In literature [22], vector control (VC) is the most popular technique used in the DFIG based WECS. This control scheme is simple and easy to implement. On the other hand, this strategy gives more THD value of rotor current and powers ripples of DFIG.

To obtain high performance VC, a simple and robust ANFIS-SMC controller is designed to control the RSC and regulate the stator reactive and active stator power. The ANFIS-SMC controller is designed to avoid the reaching phase stability problem. The proposed scheme preserves the advantages of the conventional SMC such as simplicity, less parameters dependence and fast response. In addition, axes transformation of the stator voltage or current is not required. The stability of the ANFIS-SMC controller is proven using lyapunov stability theorem. Finally, the proposed and conventional SMC techniques performance is verified by the simulation study on 1.5 MW DFIG systems under variation parameters, harmonic distortion of stator current and reference tracking.

2. MATHEMATICAL MODEL OF DFIG

The general electrical state model of the DFIG obtained using Park transformation is given by (1) [23, 24]:

Rotor and stator flux:

$$\begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \tag{1}$$

where, L_r is the inductance of the rotor, L_s is the inductance of the rotor, M is the mutual inductance, R_r is the resistances of the rotor windings, R_s is the resistances of the stator windings, ψ_{dr} and ψ_{qr} are the two-phase rotor fluxes, ψ_{ds} and ψ_{qs} are the two-phase stator fluxes.

Rotor and stator voltages:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases} \quad (2)$$

where, V_{dr}, and V_{qr} are the rotor voltages, V_{qs} and V_{ds} are the two-phase stator voltages, I_{dr}, and I_{qr} are the two-phase rotor currents, I_{ds} and I_{qs} are the two-phase stator currents.

Reactive and stator active powers:

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

where, P_s is the stator active power, Q_s is the stator reactive power.

Electromagnetic torque is done as:

$$T_e = pM(I_{dr}.I_{qs} - I_{qr}.I_{ds}) \quad (4)$$

where, T_e is the electromagnetic torque, p is the number of pole pairs.

And its associated motion equation is:

$$T_e = T_r + J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \quad (5)$$

where, T_r is the load torque, Ω is the mechanical rotor speed, J is the inertia, f is the viscous friction coefficient.

3. SVPWM TECHNIQUE

Space vector modulation strategy is widely used in variable speed drive of AC machine. This technique gives 15% more voltage output compare to conventional pulse width modulation (PWM). On the other hand, this strategy minimizes the THD of voltage and powers ripples this technique based on the principal of space vectors and need to calculate of angle and zone [25]. This strategy is detailed in [26]. However, this method of modulation is difficult to implement compared to PWM strategy. To avoid the disadvantages of the SMC technique, a new SVPWM scheme has been discussed in this paper [27]. This proposed strategy based on calculation of maximum (Max) and minimum (Min) of three-phase voltages [28].

The advantages of the proposed SVPWM strategy is not needed to calculate the zone and angle, simple scheme and easy to implement compared to classical SVPWM method. This proposed technique is detailed in [29]. The proposed SVPWM algorithm, which is designed to control the two-level inverter, is shown in Figure 1.

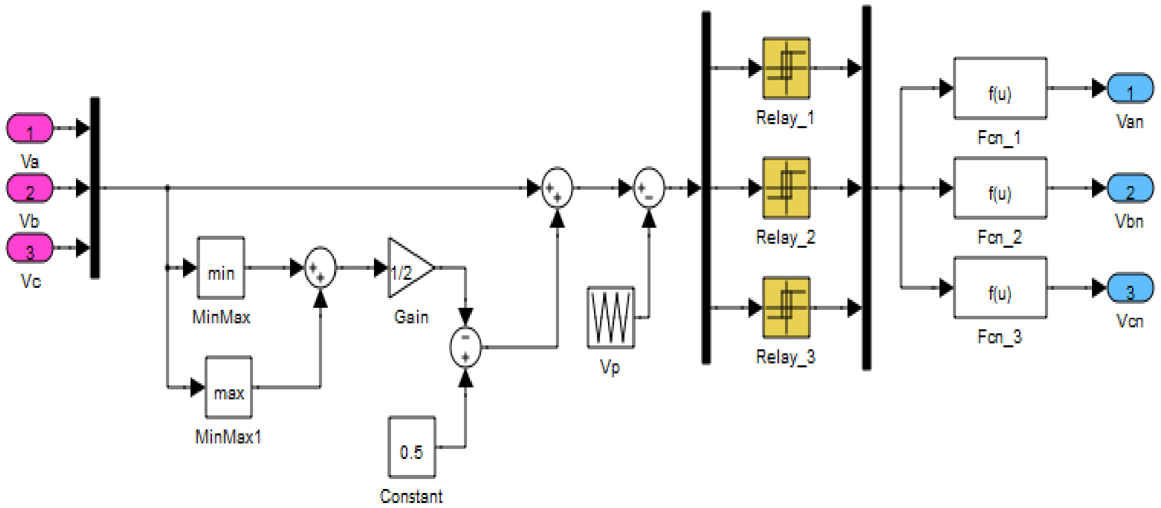

Figure 1. Simulation block of proposed SVPWM technique

4. ANFIS-SMC CONTROL

In control system, SMC control is a type of variable structure control (VSV). It is a nonlinear control technique. The SMC method was proposed by Utkin in 1977 [30]. However, this technique is simple control scheme and easy to implement compared to traditional control techniques. Since the robustness is the best advantage of an SMC strategy [31]. But, this strategy has an essential disadvantage, which is the chattering phenomenon caused by the discontinuous control action [32]. This strategy gives more distortion harmonic of rotor voltage, electromagnetic torque ripple and powers ripples.

In order to improve the conventional SMC, a complimentary use of adaptive neuro-fuzzy inference system (ANFIS) controller is proposed. The ANFIS controller has been used in many application and this method is simple scheme and easy to implement. This strategy was proposed by Jang in 1995 [33]. This strategy based on observation and engineering experience. In ANFIS control, does not need a mathematical model of system [34]. On the other hand, the ANFIS controller structure consiste of four blocks that are defuzzification, fuzzification, knowledge base and neural network. One way to improve SMC technique performance is to combine it with ANFIS to form a ANFIS-SMC. The design of a sliding mode controller incorporating ANFIS control helps in achieving reduced chattering, simple control scheme, reduced harmonic distortion of voltage and robustness against disturbances and nonlinearities.

4.1. Sliding mode controller

The SMC technique goes through three stages, as follows:

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

The sliding mode reactive and active stator powers controllers are designed to respectively change the *d* and *q*-axis voltages (V^*_{qr} and V^*_{dr}) as in (6) [27].

$$\begin{cases} V^{eq}_{dr} = R_r \cdot I_{dr} - L_s \dfrac{(L_r - \dfrac{M^2}{L_s})}{M\,\psi_s\,w_s}\dot{Q}_{sref} - g \cdot w_s \cdot (L_r - \dfrac{M^2}{L_s}) \cdot I_{qr} + \dfrac{(L_r - \dfrac{M^2}{L_s})}{M} w_s \\ V^{eq}_{qr} = R_r \cdot I_{qr} + \dfrac{L_s}{V_s M}\dot{P}_{sref} - g \cdot w_s \cdot (L_r - \dfrac{M^2}{L_s}) \cdot I_{dr} + g \cdot \dfrac{M \cdot V_s}{L_s} \end{cases} \tag{6}$$

To obtain good performances, dynamic and a commutation around the surface, the command vector is imposed as follows [35]:

$$V_{dq} = V^{eq}_{dq} + V^{n}_{dq} \tag{7}$$

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

$$V_{dq}^{n} = -K.sat(S_{dq}) \tag{8}$$

where K determine the ability of overcoming the chattering.

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

$$S.\dot{S} \prec 0 \tag{9}$$

Conventional SMC technique as shown in Figure 2.

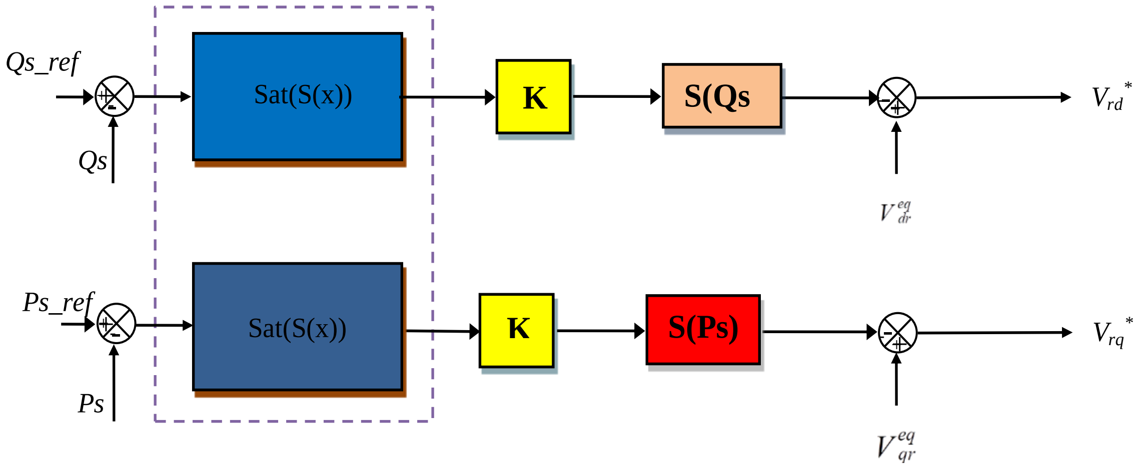

Figure 2. Conventional SMC technique

4.2. Anfis-sliding mode controller

The ANFIS-SMC goal is to control the reactive and active stator powers of the DFIG-based WTS. The ANFIS-SMC is similar to a conventional SMC strategy. However, the switching regulators term sat(S(x)), has been replaced by ANFIS controller as given by Figure 3. On the other hand, the ANFIS-SMC control gives more and more minimum THD value of rotor current compared to classical SMC method. Fuzzy system has 49 roles. This roles for the proposed system are given in Table 1 [23]. The membership function definition is shown in Figure 4. We use the next designations for membership functions:

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

Table 1. Fuzzy logic rols

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

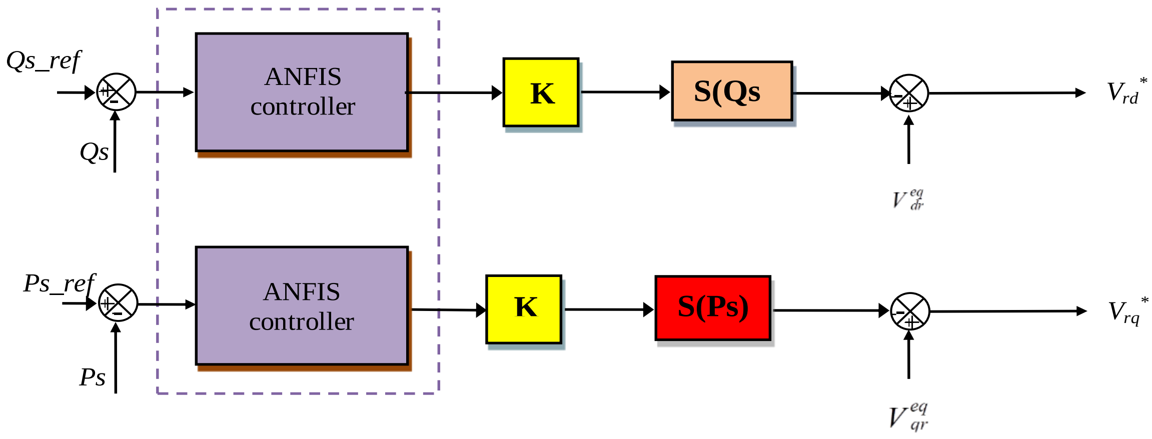

Figure 3. ANFIS-SMC technique

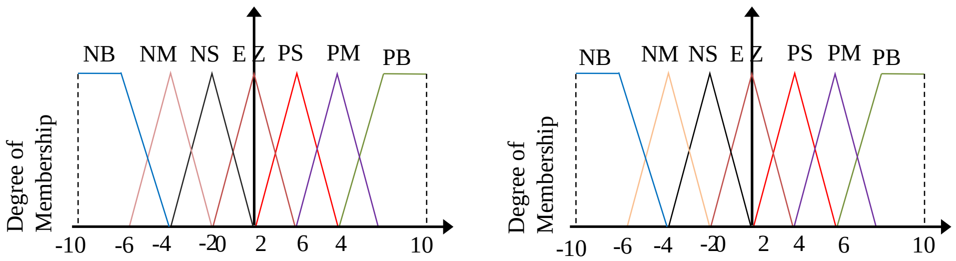

Figure 4. FL sets and its memberships functions

The training used is that of the algorithm, Gradiant descent with momentum & Adaptive LR. The convergence of the network in summer obtained by using the value of the parameters grouped in Table 2. For the two proposed ANFIS-sliding mode controllers in Figure 3, the structure of the ANFIS controller is shown in Figure 5. The proposed ANFIS-SMC with SVPWM strategy, which is designed to control reactive stator power and active power of the DFIG-based WTS, is shown in Figure 6.

Table 2. Parameters of the LR

Parameters of the LM	Values
Number of hidden layer	12
TrainParam.Lr	0.002
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

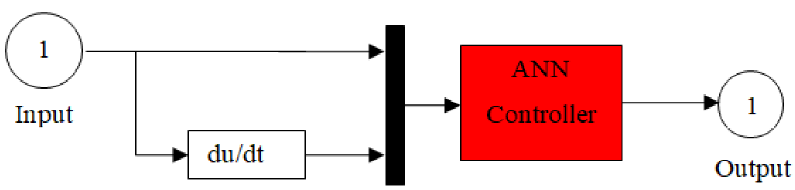

Figure 5. Architecture of ANFIS controller

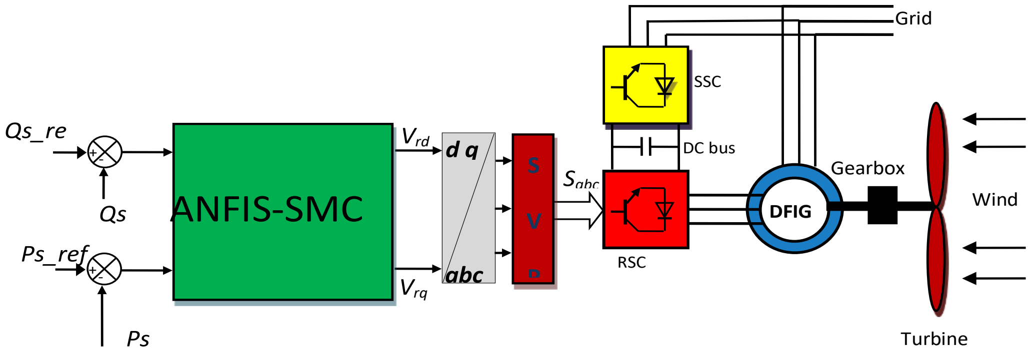

Figure 6. Block diagram of the ANFIS-SMC with SVPWM technique

5. RESULTS

The ANFIS-SMC control of a DFIG-based WTS is implemented with simulation tools of MATLAB/Simulink. The DFIG attached to a 398 V/50 Hz grid. Both control techniques ANFIS-SMC using SVPWM and conventional SMC using SVPWM technique are simulated and compared regarding reference tracking, rotor current harmonics distortion, and robustness against doubly fed induction generator parameter variations. 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.

5.1. Reference tracking test (RTT)

Figures 7 and 8 shows the THD of rotor current of the DFIG-based WTS obtained using FFT (Fast Fourier Transform) method for ANFIS-SMC control with SVM (ANFIS-SMC-SVPWM) and conventional SMC with SVPWM one respectively. It can be clearly observed that the THD is minimized for ANFIS-SMC control when compared to conventional SMC with SVPWM technique. Table 3 shows the comparative analysis of THD value.

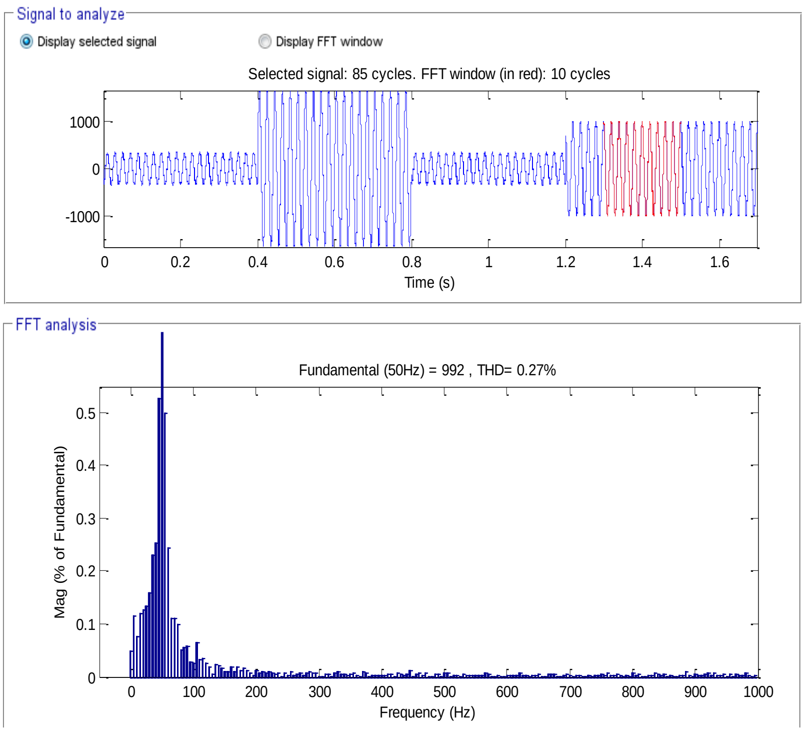

Figure 7. Spectrum harmonic of rotor current (SMC)

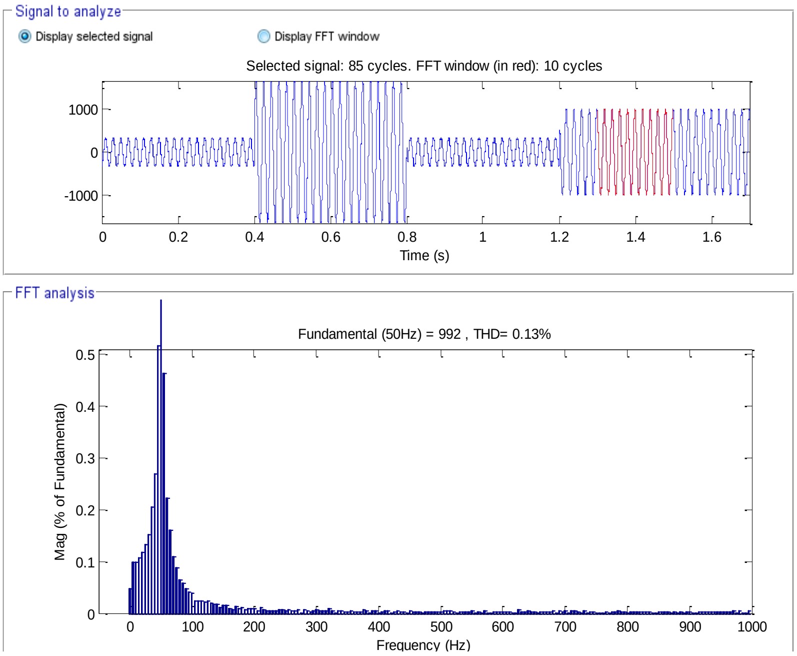

Figure 8. Spectrum harmonic of rotor current (ANFIS-SMC)

Table 3. Comparative analysis of THD value (RTT)

	THD (%)	
	SMC	ANFIS-SMC
Rotor current	0.27	0.13

For the ANFIS-SMC and SMC control scheme, the active stator power (Ps) and reactive stator power (Qs) tracks almost perfectly their references values (Ps_{ref} and Qs_{ref}), see Figures 9 and 10. Figure 11 shows the electromagnetic torque of the both strategies. The simulation result validates the torque ripple is reduced in the proposed control scheme based DFIG drive (See Figure 14).On the other hand, the ANFIS-SMC control scheme using the two-level SVPWM strategy minimized the reactive stator power ripples, electromagnetic ripples and active stator power ripples compared to the traditional SMC using two-level SVPWM technique, see Figures 12-14.

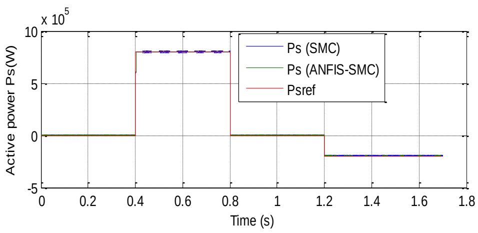

Figure 9. Active stator power (RTT)

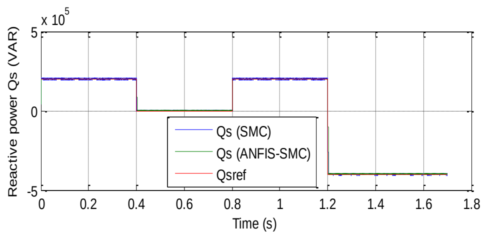

Figure 10. Reactive stator power (RTT)

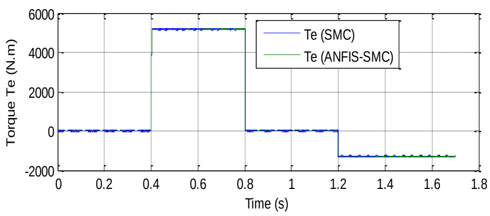

Figure 11. Electromagnetic torque (RTT)

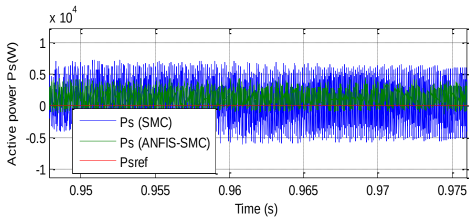

Figure 12. Zoom in the active stator power (RTT)

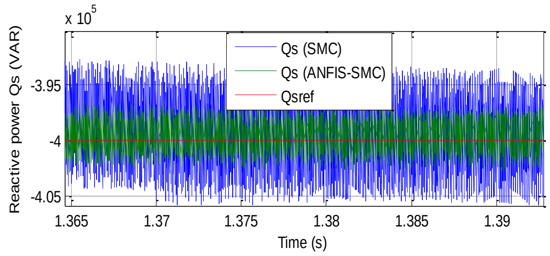

Figure 13. Zoom in the reactive stator power (RTT)

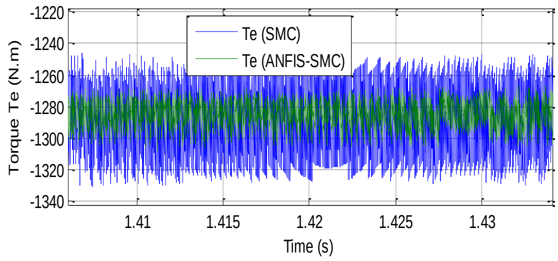

Figure 14. Zoom in the torque (RTT)

5.2. Robustness test (RT)

In this section, 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 15-19. As it's shown by these figures, these variations present an apparent effect on the active stator power, reactive stator power and electromagnetic torque curves and that the effect appears more significant for the SMC control with SVPWM strategy compared to ANFIS-SMC control with SVPWM, see Figures 20-22. The THD value of rotor current in the ANFIS-SMC control scheme has been minimized significantly, see Figures 15-16. Table 4 shows the comparative analysis of THD value. Thus it can be concluded that the proposed ANFIS-SMC control with SVPWM strategy is more robust than the conventional SMC with SVPWM strategy.

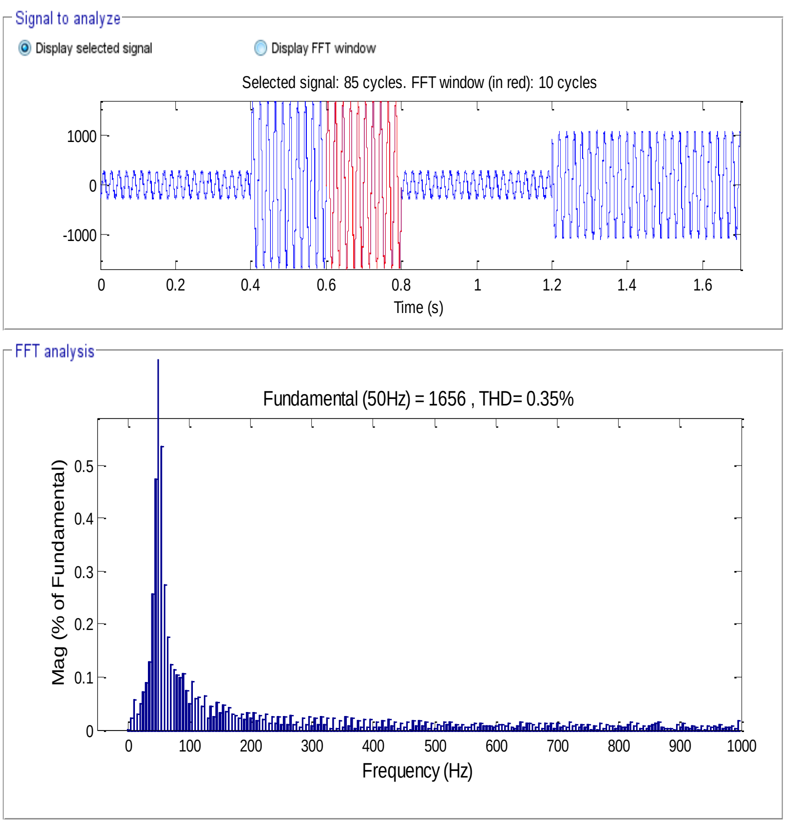

Figure 15. Spectrum harmonic of rotor current (SMC)

Table 4. Comparative analysis of THD value (RT)

	THD (%)	
	SMC	ANFIS-SMC
Rotor current	0.35	0.18

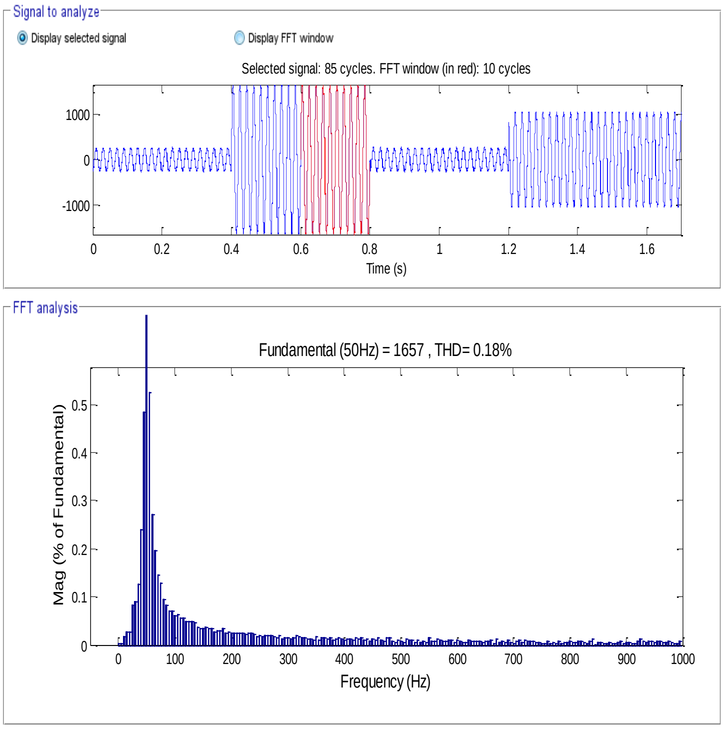

Figure 16. Spectrum harmonic of rotor current (ANFIS-SMC)

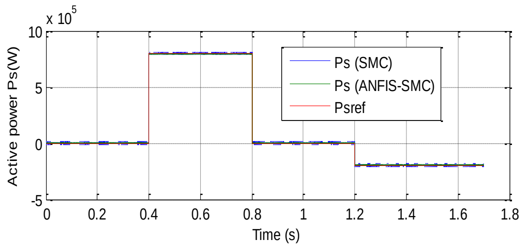

Figure 17. Active stator power (RT)

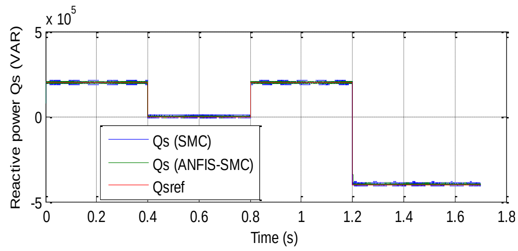

Figure 18. Reactive stator power (RT)

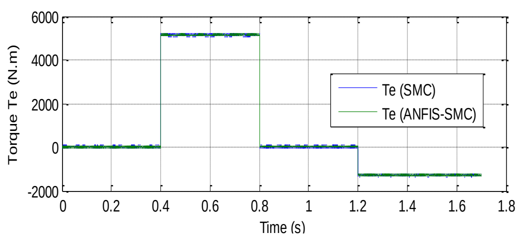

Figure 19. Electromagnetic torque (RT)

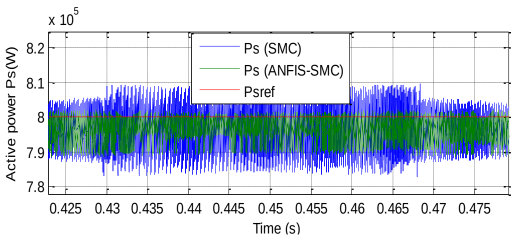

Figure 20. Zoom in the active stator power (RT)

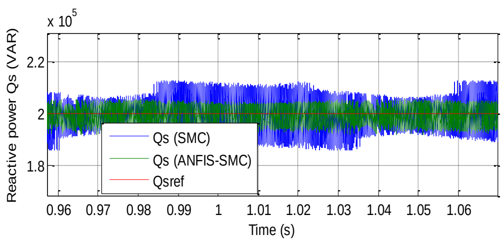

Figure 21. Zoom in the reactive stator power (RT)

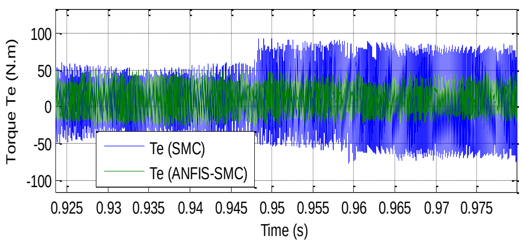

Figure 22. Zoom in the torque (RT)

6. CONCLUSION

In this paper, the ANFIS-SMC principle is presented and it is shown that with SVPWM technique for a two-level inverter. The simulation results obtained for the ANFIS-SMC with SVPWM technique illustrate a considerable reduction in reactive power ripple, active stator power ripple, electromagnetic torque ripple and THD value of rotor current compared to the conventional SMC utilizing two-level SVPWM strategy.

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BIOGRAPHY OF AUTHOR

H. Benbouhenni was born in chlef, Algeria. He is a PhD student in the Departement of electrical engineering at the ENPO-MA, Oran, Algeria. He received a M.A. degree in Automatic and informatique industrial in 2017. His research activities include the application of robust control in the wind turbine power systems.
E-mail: habib0264@gmail.com ; habib_benbouhenni@yahoo.com