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Intelligent super twisting high order sliding mode controllers of dual-rotor wind power systems with a direct attack based on doubly-fed induction generators

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Abstract **– In this work, we present a robust method using an intelligent super twisting sliding mode (STSM) controller for a dual-rotor wind turbine (DRWT) with a direct attack based on a doubly-fed induction generator (DFIG) supplied by a two-level inverter. In the first place, we carried out briefly a study of modeling on the whole system (DRWT). To command the power flowing between the stator of the DFIG and the grid, a proposed command design uses direct power control (DPC) based intelligence STSM controllers (ISTSM-DPC) is applied for implementing to remove completely the active and reactive powers ripples on a traditional DPC method. The use of this technique provides very satisfactory performance for the DFIG command, and the power ripple effect is also more minimized by this method. The DFIG is tested in association with a DRWT system. Simulations results are presented and discussed for the whole system.**

Keywords- intelligent super twisting sliding mode, dual-rotor wind turbine, doubly-fed induction generator, direct power control

I. Introduction

Sliding mode control (SMC) is one of the most famous robust control and nonlinear techniques due to features such as simple design, robustness, minimized order, and ease of implementation [1]. Due to these suitable properties, it has been applied in many applications in various industries, e.g., robotic manipulations, spacecraft, and power systems.

The main idea of this method is to design a controller that drives the states of the system towards a defined sliding surface. In traditional SMCs through, since the sliding surface is defined to be linear, the asymptotic convergence cannot be achieved in finite time [2].

To solve this problem, a fuzzy SMC method is proposed [3]. This technique combines the advantage of the fuzzy logic method and SMC control so that power undulations can be reduced. The neuro-SMC method is proposed to control the power of DFIG [4]. Although NSMC has been able to offer better performance, it has reduced the torque and active power ripples compared to the traditional SMC method [5]. In [6], a new SMC technique based on ANFIS controller (Adaptive-network-based fuzzy inference system) has been presented to minimizes the current undulation by replacing a sign (U) term with an ANFIS controller. However, the performance of the technique highly depends on the generator model accuracy.

In recent years, the DPC method has been attracted more and more attention in wind power systems [7-10]. In this technique, two hysteresis comparators and a switching table were used to control the active and reactive powers. This strategy has advantages such as robust and easy to implementation. But this strategy gives more harmonic distortion in voltage and current. Therefore, some improved DPC strategy such as DPC with SVM technique and DPC with super-twisting SMC method (STSMC-DPC) have been proposed [11, 12].

STSMC-DPC strategy has been designed to achieve the advantages of both the direct control and nonlinear methods such as fast response dynamic, sample structure, and constant switching frequency. In [13], the STSMC-DPC strategy based on neural controllers has been used. Even though, an active power ripple is reduced compared to the DPC strategy with PI controllers. The ANFIS-STSMC controllers are used for DFIG in [14] and the inverter is controlled via the modified SVM strategy.

The main focus of this work is to design and implement an intelligent super-twisting SMC method to improve the performance of the DFIG controlled by the DPC strategy. In this work, two intelligent techniques were applied in super twisting SMC strategy to minimizes the torque and current ripples. The first technique is fuzzy logic and the second strategy is the ANFIS method. The Fuzzy logic technique is one of the most used strategies in AC machines due to advantages such as simplicity and robustness.

A comparison between the results obtained for the DPC with ANFIS-STSMC controllers and the DPC with STSMC based on fuzzy logic controllers validates the effectiveness of the designed strategy.

Lower active power ripple, higher dynamic response, and lower torque ripple are achieved by both strategies. Matlab software is used for simulation.

II. DRWP MODEL

In the DRWT system, the total aerodynamic power (P_T) is given by the auxiliary turbine power (P_A) together with the main turbine power (P_M) as shown by the following equation [15]:

$$P_T = P_M + P_A \tag{1}$$

The total torque of the DRWT system is given:

$$T_T = T_M + T_A \tag{2}$$

Where: T_M: Main turbine torque.
T_A: Auxiliary turbine torque.
T_T: Total aerodynamic torque.

The aerodynamic torque of the auxiliary and main turbines are given [16]:

$$T_A = \frac{1}{2\lambda_A^3} . \rho . \pi . R_A^5 . C_p . w_A^2 \tag{3}$$

$$T_M = \frac{1}{2\lambda_M^3} . \rho . \pi . R_A^5 . C_p . w_M^2 \tag{4}$$

With R_A, R_M: Blade radius of the main and auxiliary turbines, λ_A, λ_M: the tip speed ration of the main and auxiliary turbines, ρ: the air density and w_M, w_A the mechanical speed of the main and auxiliary turbines.

The tip speed ratios of the auxiliary and main turbines are given:

$$\lambda_A = \frac{w_A . R_A}{V_1} \tag{5}$$

$$\lambda_M = \frac{w_M . R_M}{V_M} \tag{6}$$

Where V_1 is the wind speed on an auxiliary turbine and V_M is the speed of the unified wind on main turbine.

The wind speed at any point between the auxiliary and main blades is given:

$$V_x = V_1 \left(1 - \frac{1 - \sqrt{(1 - C_T)}}{2} \left(1 + \frac{2.x}{\sqrt{1 + 4.x^2}}\right)\right) \tag{7}$$

With x: the non-dimensional distance from the auxiliary rotor disk, Vx the velocity of the disturbed wind between rotors at point x and C_T the trust coefficient, which is chosen to be 0.9. [17].

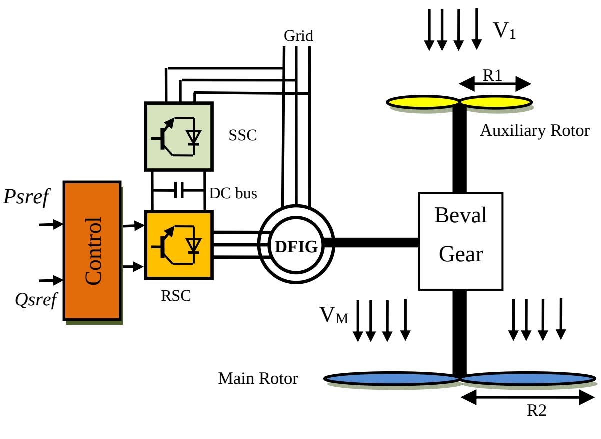

Figure 1. Block diagram of DRWT with a DFIG.

Equation (8) shows the power coefficient function, β is pitch angle

$$C_p(\lambda, \beta) = 0.517\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \tag{8}$$

With:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{9}$$

The mathematical model of the DFIG using Park transformations is detailed in [18-20].

III. SPUER TWISTING SMC METHOD

To overcome the chattering problems. Super twisting SMC methods have been presented [21]. This technique gives a fast response dynamic and minimizing the harmonic distortion of voltage. The structure of the super twisting SMC method is depicted in Figure 2. This controller is easy to apply in control. This technique is expressed as the following equation:

$$\begin{cases} u = K_p |S|^r \operatorname{sgn}(S) + u_1 \\ \dfrac{d u_1}{dt} = K_i \operatorname{sgn}(S) \end{cases} \tag{10}$$

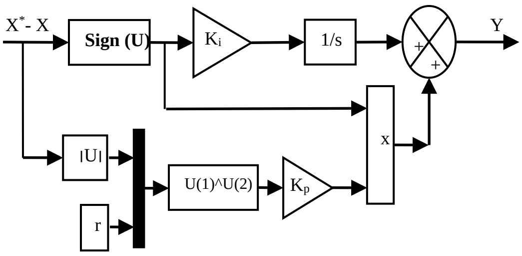

Figure 2. Block diagram of the STSM strategy.

In super twisting SMC method, we use two Sign(U) term, two constant gain (Ki and Kp) and one integral.

IV. DPC-PI CONTROL

The DPC method based on integral-proportional (PI) controllers has some advantages such as robust control, simple structure, and minimizing the harmonic distortion of current compared to the classical DPC method with hysteresis controllers. The DPC control with PI controller uses the SVM to control the inverter. In this work, we use a modified SVM technique to control the rotor inverter of DFIG. Figure 3 shows the structure of the DPC control with PI controllers. In this strategy, the DRWP is connected to the DFIG using Beval Gear. A grid side converter and generator side converter are connected back to back through a DC link. On the other hand, we use the two-level converter in the generator side converter and control by using the modified SVM technique. In [22], a neural DPC control has been presented to reduce the active power ripple and response time.

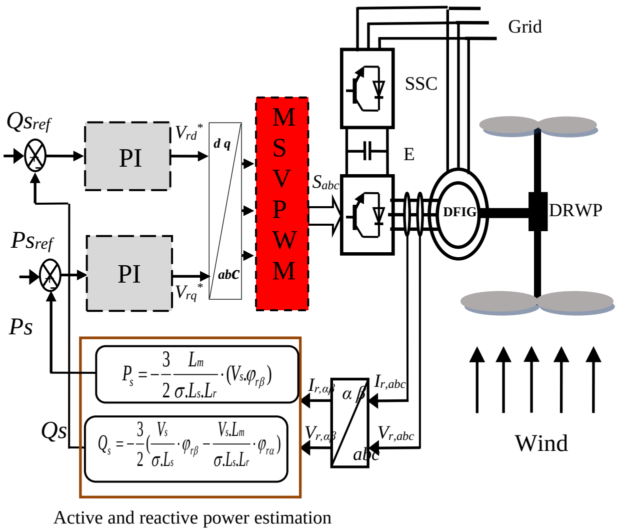

Figure 3. Block diagram of DPC with PI controllers.

The estimated reactive and active powers are given as:

$$Q_s = -\frac{3}{2}\left(\frac{V_s}{\sigma.L_s}\cdot\varphi_{r\beta} - \frac{V_s.L_m}{\sigma.L_s.L_r}\cdot\varphi_{r\alpha}\right) \quad (14)$$

$$P_s = -\frac{3}{2}\frac{L_m}{\sigma.L_s.L_r}\cdot(V_s.\varphi_{r\beta}) \quad (15)$$

Where:

$$\Psi_{s\alpha} = \sigma L_r I_{r\alpha} + \frac{M}{L_s}\Psi_s \quad (17)$$

$$\sigma = 1 - \frac{M^2}{L_r L_s} \quad (18)$$

$$\Psi_{s\beta} = \sigma L_r I_{r\beta} \quad (16)$$

In order to reduce the reactive and active powers, we need to use the intelligent nonlinear control strategies.

V. DPC CONTROL WITH INTELLIGENT SUPER TWISTING SMC METHOD

Nonlinear active and reactive powers control is used in many strategies that require DPC strategy [23]. In this technique, the active and reactive power was regulated using PI controllers or a lookup table. However, the algorithm of these strategies, which uses hysteresis comparators, PI controllers and lookup table, gives more and more the THD of voltage and minimizes the life of the system due to the need for maintenance. In the nonlinear DPC method, by using intelligent super twisting SMC method (ISTSMC), a novel DPC control scheme is obtained, which can be reduce the reactive power undulation, THD of voltage, and torque ripple. DPC-ISTSMC works like a DPC with PI controllers so it can be minimized the response time of active and reactive powers and improve the performances of the DFIG-based DRWP systems. In DPC-ISTSMC control, two ISTSMC controllers have been used to regulate and control the active and reactive powers as shown in Figure 4. Furthermore, to improve the performance of the DFIG-based DRWP systems, fuzzy logic controller and ANFIS algorithms have been used. A more detailed description of the proposed strategies for the DFIG is given in [24, 25].

The developed system in Figure 4 is used for reducing the torque, current, reactive and active power ripples.

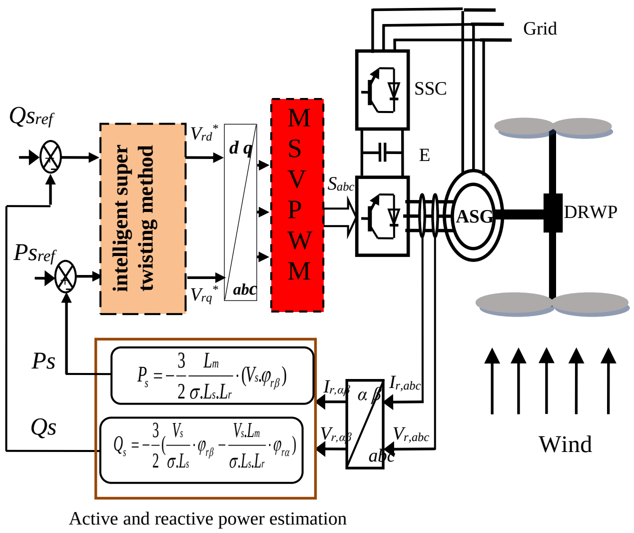

Figure 4. DPC control with intelligent super twisting SMC method.

A. *Fuzzy*-super twisting SMC method *reactive and active power controllers design*

In SVM-DPC control is well known to use a traditional PI controller in the outer active power loop to generate reference V_{qr}^* and V_{dr}^*. In this section, we designed a new nonlinear method design basing on the fuzzy-super twisting SMC method (FSTSMC). The main idea of this controller is to combine an STSMC controller with a fuzzy technique. Although FSTSMC has been able to offer better performance and reduces active power and torque ripple compared to the classical STSMC method. The proposed intelligent super-twisting SMC method is shown in Figure 5.

The active and reactive power regulator generates the reference voltage V_{qr}^* and V_{dr}^*. The sliding surfaces will be chosen as :

$$S_{P_s} = P_{sref} - P_s \quad (17)$$

$$S_{Q_s} = Q_{sref} - Q_s \quad (18)$$

Then the derivative of it is given by:

$$\dot{S}_{P_s} = \dot{P}_{sref} - \dot{P}_s \quad (19)$$

$$\dot{S}_{Q_s} = \dot{Q}_{sref} - \dot{Q}_s \quad (20)$$

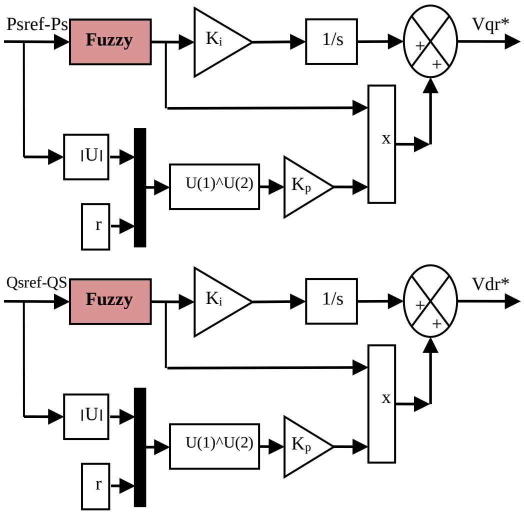

Figure 5. Block diagram of the FSTSMC of active and reactive power controllers.

Table 1 shows the proposed rule bases for the FSTSMC algorithms [25]. Membership functions are shown in Figure 6 and Figure 7 respectively.

TABLE I. FSTSMC RULES

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

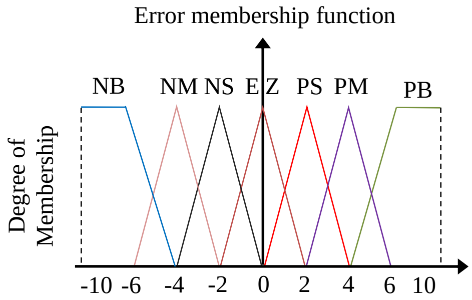

Figure 6. Membership functions for sliding surface.

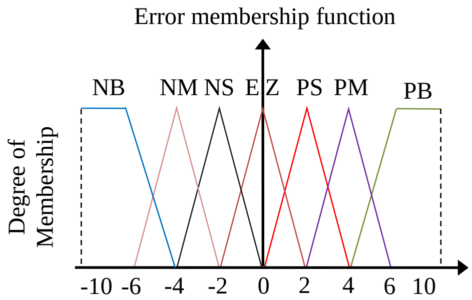

Figure 7. Membership functions for output variables.

B. *ANFIS*-super twisting SMC method *active and reactive power controllers design*

In this part, a super twisting SMC controller based on ANFIS algorithms are designed to control the active and reactive power. This strategy is detailed in [14]. The ANFIS-super twisting SMC technique is shown in Figure 8. In this control system, the stator reactive and stator active powers are controlled by the ANFIS-STSM algorithms.

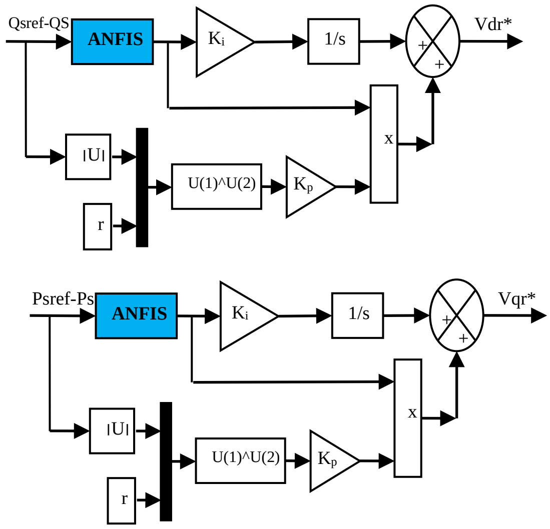

Figure 8. Block diagram of the ANFIS-STSMC of active and reactive power controllers.

ANFIS controller is a method based on the advantages of the fuzzy logic and neural algorithm. This controller was proposed by Jang [26] in 1993. ANFIS controller was used for complex and nonlinear systems.

The STSM-ANFIS controller is a modification of the classical STSMC controller, where the sgn(U) term, has been replaced by an ANFIS controller. This proposed controller does not need the mathematical model of systems. The DPC with STSM-ANFIS controllers goal is to reduce the active and the reactive powers of the DFIG. The rules of ANFIS controllers are shown in Table 1.

The structure of the ANFIS algorithm is given in Figure 9.

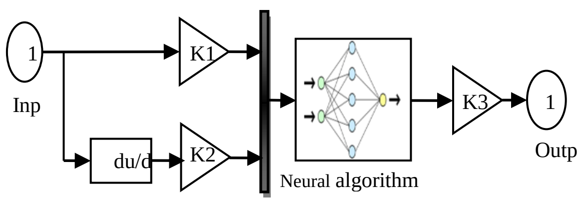

Figure 9. Structure of the ANFIS algorithm.

VI. RESULTS AND ANALYSIS

In this part, two control strategies were proposed and simulated by using Matlab software. This technique is a DPC control with FSTSMC controllers and DPC control with STSMC-ANFIS controllers. These strategies were tested in two different tests: reference tracking and robustness tests.

The parameters of the DFIG are given: 50Hz, 380/696V, R_r = 0.021 Ω, P_{sn}=1.5 MW, p=2, R_s = 0.012 Ω, L_m = 0.0135H, L_s = 0.0137H, J = 1000 kg.m^2, L_r = 0.0136H and f_r = 0.0024 Nm/s.

A. First Test

The simulation waveforms of the reference and measured reactive and active powers are shown in Figure 10 and Figure 11, respectively. It can be seen that the reactive and active powers track almost perfectly their reference values (Q_{sref}, $P_{s\text{-}ref}$). The waveforms of the current and electromagnetic torque of both control schemes are shown in Figure 12 and Figure 13, respectively. The amplitudes of the current and electromagnetic torque depending on the state of the drive system and the value of the load active power.

Figure 18 and Figure 19 show the THD value of both techniques. It can be seen that the THD value is minimized for the ANFIS-STSMC-DPC strategy (THD = 0.29%) when compared to the DARPC with PI controllers (THD =0.56%). On the other hand, the ANFIS-STSMC-DPC strategy reduced the current, active power, torque, and reactive power ripples compared to the FSTSMC-DPC strategy (see Figures 14-17).

The ANFIS-STSMC-DPC strategy reduced more the response time of the reactive power, torque, and active powers compared to the FSTSMC-DPC strategy (see Table 2).

TABLE II. COMPARATIVE ANALYSIS OF RESPONSE TIME

	Response time		
	Torque	**Active power**	**Reactive power**
FSTSMC-DPC	0.56ms	0.56ms	0.77ms
ANFIS-STSMC-DPC	0.23ms	0.23ms	0.37ms

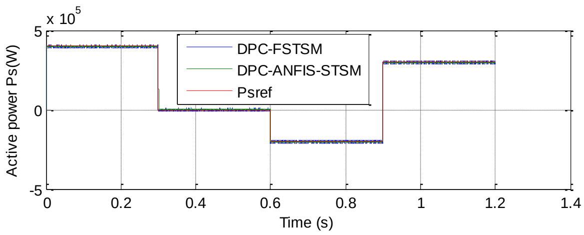

Figure 10. Active power

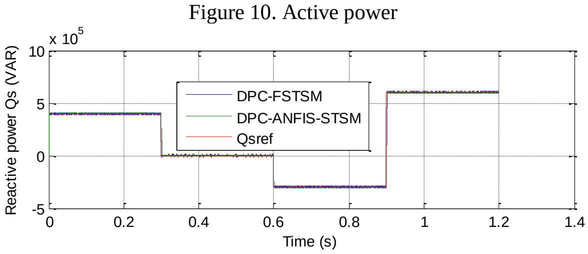

Figure 11. Reactive power

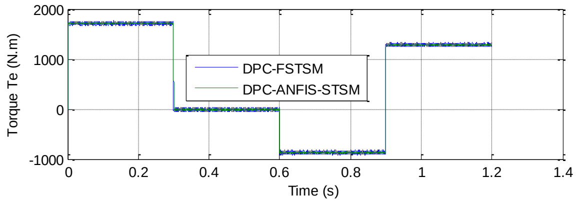

Figure 12. Torque.

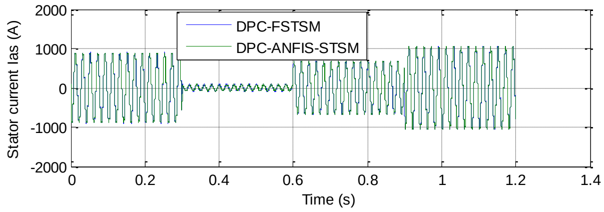

Figure 13. Stator current

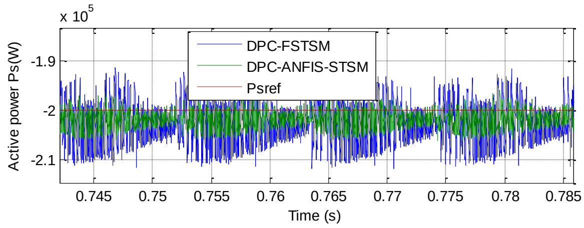

Figure 14. Zoom in the active power

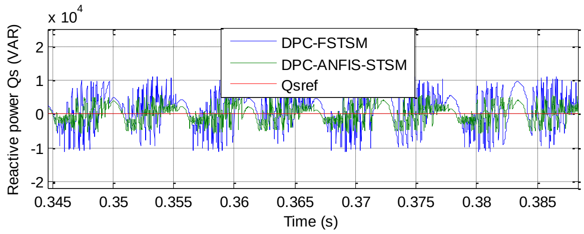

Figure 15. Zoom in the reactive power

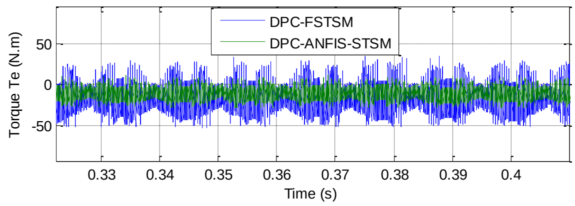

Figure 16. Zoom in the torque

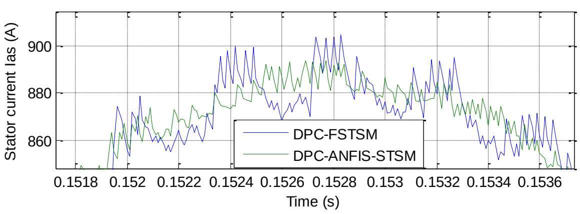

Figure 17. Zoom in the current

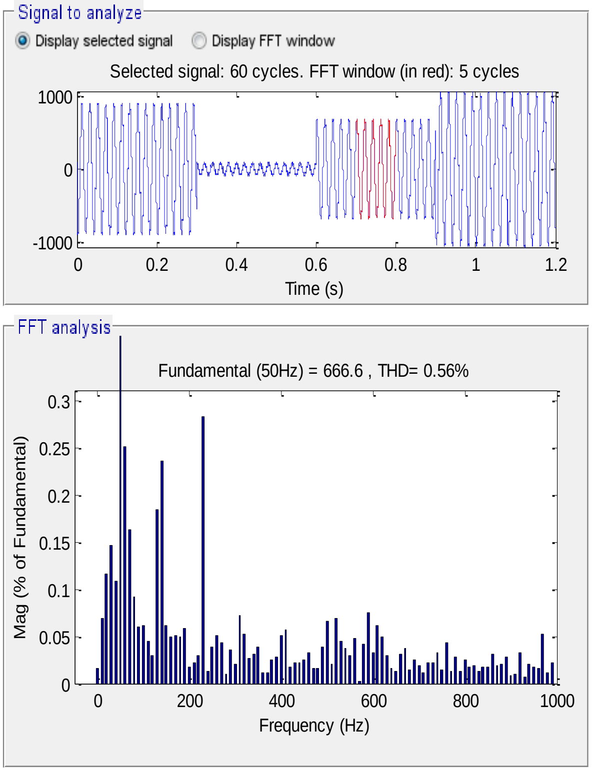

Figure 18. THD value of stator current (FSTSMC-DPC)

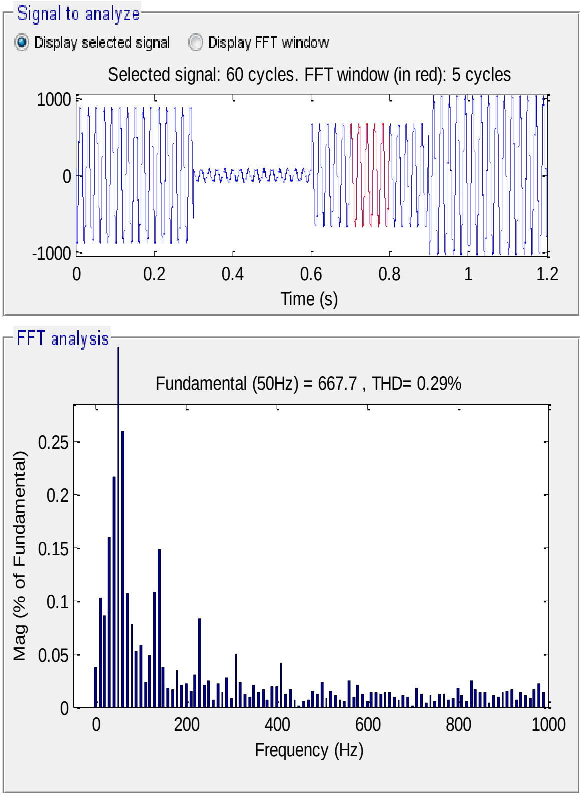

Figure 19. THD value of stator current (ANFIS-STSMC-DPC)

B. Second Test

In this second test, the nominal values of L_r and L_s are multiplied by 0.5, R_r and R_s are multiplied by 2. The results obtained are shown in Figures 20-29. As it's shown by these figures, these variations present an apparent effect on current, reactive power, torque, and active power such as the effect appears more significant for the FSTSMC-DPC strategy compared to the ANFIS-STSMC-DPC strategy (Figures 24-27). On the other hand, the ANFIS-STSMC-DPC strategy reduced more the THD value of current compared to the FSTSMC-DPC strategy (Figures 28-29). It can be concluded that the ANFIS-STSMC-DPC strategy is more robust than the FSTSMC-DPC strategy.

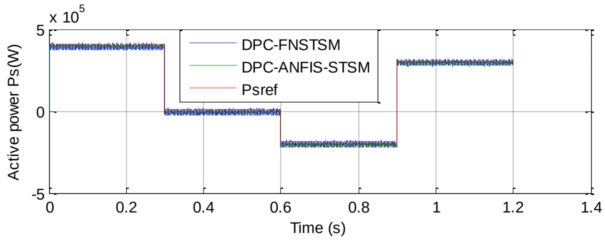

Figure 20. Active power

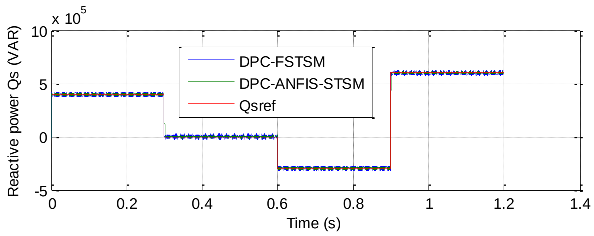

Figure 21. Reactive power

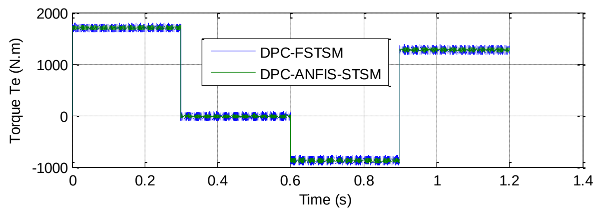

Figure 22. Torque

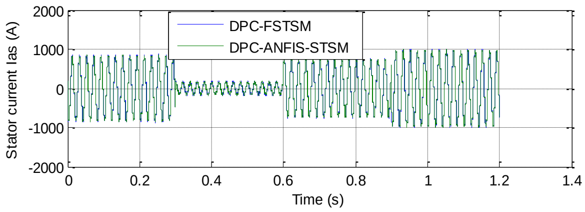

Figure 23. Stator currant

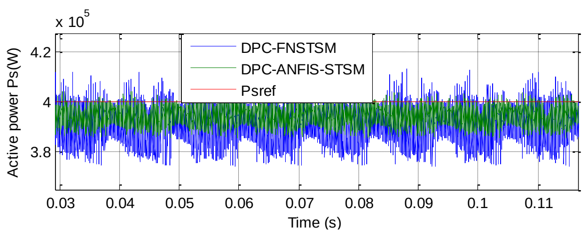

Figure 24. Zoom in the active power

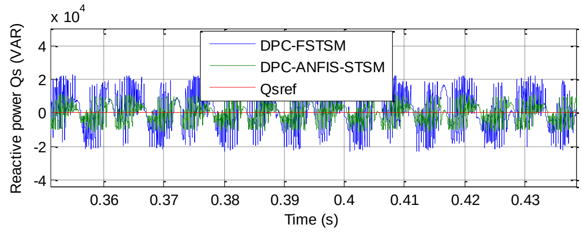

Figure 25. Zoom in the reactive power

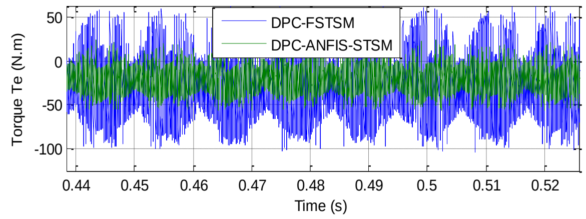

Figure 26. Zoom in the torque.

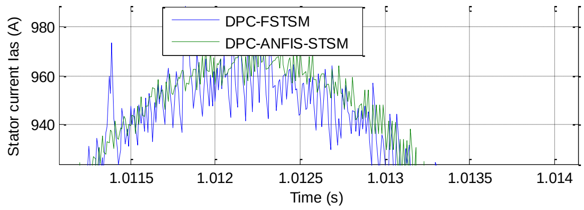

Figure 27. Zoom in the current

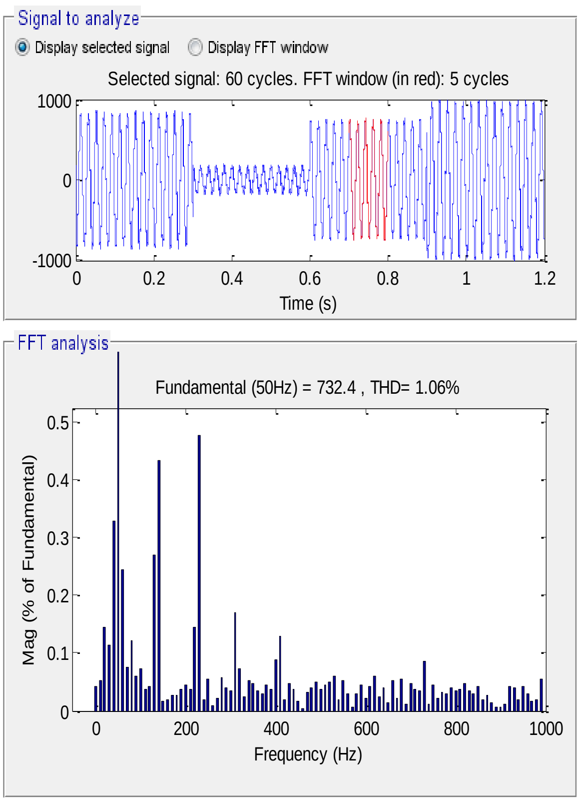

Figure 28. THD value of stator current (FSTSMC-DPC)

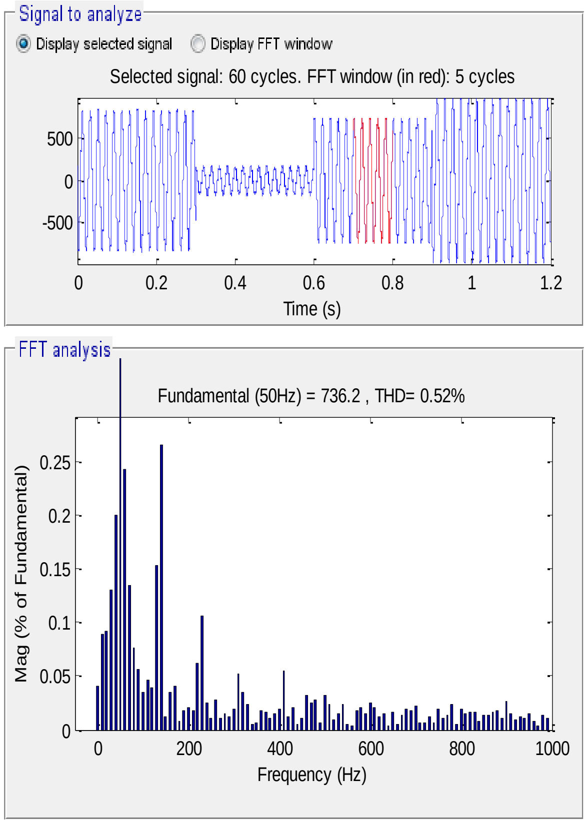

Figure 29. THD value of stator current (ANFIS-STSMC-DPC)

CONCLUSION

In this article, based on the nonlinear control, a new robust controller is proposed to improve the DPC control in dual-rotor wind farms with DFIGs. The proposed control scheme is proposed for a DFIG with variable speed in which the converter of the DFIG is controlled by the modified SVM technique.

A simple nonlinear controller is used for the analysis of active power undulation, reactive power undulations, and controller synthesis. Although the proposed nonlinear controllers of the DPC are represented with ANFIS and fuzzy logic techniques, the intelligent STSMC controllers are also considered to preserve the overall active and reactive power control structure inside the wind farm.

The performance of the designed DPC method is validated through Matlab software. Two different strategies of DPC were proposed in this work. The DPC method with FSTA controllers and DPC method with STSMC-ANFIS controllers. The DPC method with STSMC-ANFIS controllers is achieved by limiting the active and reactive power undulations. On the other hand, the DPC method with STSMC-ANFIS controllers is a simple model used in DFIG control.

The DPC simulation results confirm the performance of the designed DPC method for a DFIG-based DRWP system. The numerical simulation results also confirm the superiority of the proposed DPC method.

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