Comparison of Two Fractional-Order High-Order SMC Techniques for DFIG-Based Wind Turbines: Theory and Simulation Results

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ABSTRACT

Two new nonlinear techniques are proposed in this study for improving the performance and efficiency of the doubly-fed induction generator (DFIG)-based wind turbine systems. Direct torque control (DTC) is among the most widely used strategies for controlling DFIGs due to its many advantages, such as robustness, simplicity, and fast response dynamics. However, this control causes big ripples in both torque and flux. Furthermore, it has significant total harmonic distortion (THD). Several solutions are proposed to overcome these problems, including nonlinear techniques and intelligent strategies such as genetic algorithms. In this work, two different controllers are proposed to improve the performance of the DTC technique. Firstly, the second-order continuous sliding mode (SOCSM) based on fractional-order (FO) control, and secondly, the super twisting algorithm (STA) based on the FO technique. The biggest advantages of the proposed strategies are their durability and ease of execution. Based on the proposed controls, the DTC strategy can greatly improve generator performance in different operating conditions. This paper also provides a comparative analysis of DTC-FOSOCSMC, DTC, and DTC-FOSTA in terms of reference tracking, robustness, chattering reduction, and computational complexity, using mathematical theory and simulation carried out in Matlab/Simulink using a 1.5 MW DFIG-based wind turbine. The simulation results demonstrate the effectiveness and high performance of the proposed DTC techniques.

Keywords: Doubly-fed induction generators, Total harmonic distortion, Fractional calculus, Super twisting algorithms, Second-order continuous sliding mode, Wind turbine

1. INTRODUCTION

In recent years, electricity demand has increased significantly, and traditional sources alone are becoming insufficient. There are numerous and varied reasons for this rising demand, such as high temperatures and the widespread use of electric motors and electrical appliances. Technology has invaded our daily lives, with telephones and electronic media becoming necessities. Therefore, other sources of inexpensive and clean electricity generation must be found [1].

Several solutions have been proposed to compensate for the use of petroleum, including nuclear energy. However, despite the advantages and value of the electrical energy produced through this method, it remains harmful to human health and nature. In recent years, other sources not harmful to human health while also limiting the spread of toxic gases have been identified under the term renewable energy. It depends on the use of natural elements, such as wind and solar energy.

Wind energy is among the most widely used form of renewable energy in the world, with wind farms (wind stations) scattered around the world due to its low cost and ease of use compared to other sources [2]. To generate electricity from wind, electric generators powered by turbines are used. The latter converts wind energy into mechanical energy which is then used to rotate the generator. The rotation of the generator leads to the production of electrical energy.

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***Table 1**: A comparative study between the DTC and various published techniques.*

Published Techniques							
Criteria	DARPC	DVC	IVC	SMC	DTC	SOSMC	Backstepping
Controller	Hysteresis Components	PI	PI	-	Hysteresis Components	-	-
Implementation	Easy	Easy	Difficult	Difficult	Easy	Difficult	Easy
Robustness	++	+	+	+++	++	++++	++++
Response Dynamics	Good	Well	Good	Excellent	Good	Excellent	Excellent
Reference	+++	+	++	+++	+++	++++	++++
Tracking	Simple	Simple	Complicated	Complicated	Simple	Complicated	Complicated
Improvement in transient performance	Good	Weak	Weak	Good	Good	Excellent	Excellent

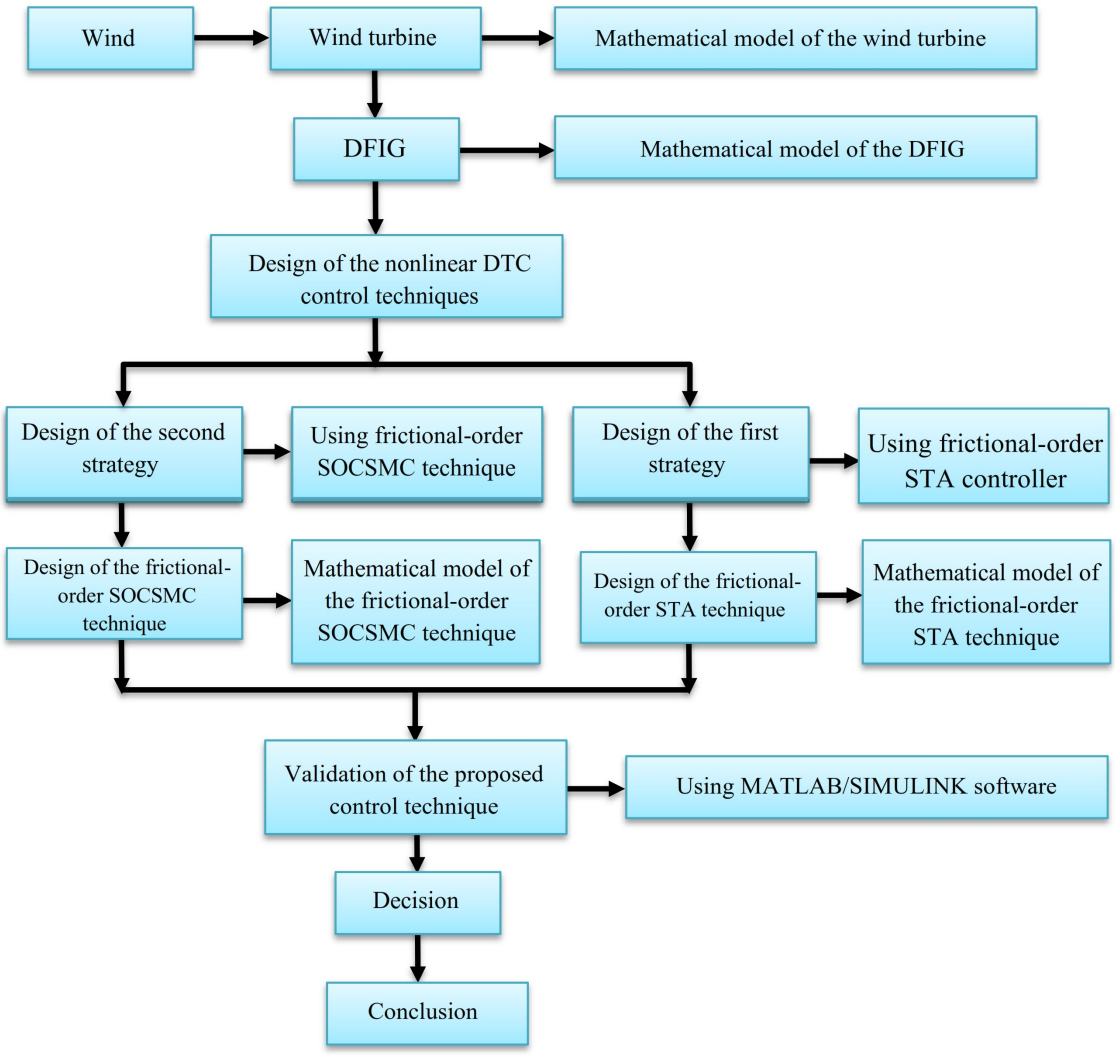

***Fig. 1**: Diagram for proposed nonlinear DTC control techniques.*

Several generator types can be used in wind stations (farms), such as the squirrel cage asynchronous generator (SCAG), synchronous generator (SG), DC generator, doubly-fed induction generator (DFIG), etc. However, the DFIG remains the most widely used in this field due to its simplicity of control, robustness, and low cost. The DFIG also requires little maintenance and compares favorably to its counterparts in both characteristics and advantages [3]. Among the most widely used methods for controlling the DFIG are direct torque control (DTC) [4], synergetic control (SC) [5], backstepping control [6], sliding mode control (SMC) [7], direct power control (DPC) [8], field-oriented control (FOC) [9], and hybrid control [10–13].

Traditionally, the DTC technique is one of the most widely used strategies for controlling electric generators, such as the DFIG, induction motor (IM), and SGs, due to the characteristics and advantages it has over other methods. This control uses the same principle as the DPC technique, with a switching table and hysteresis comparators to control the torque and flux. In [9], the IM was controlled by the DTC technique. The results showed the effectiveness of this control in improving the performance and efficiency of the IM drive. In [14], DTC strategies were applied to control the dual open-end winding IM drive. On the other hand, the DTC control has previously been proposed to control both permanent magnet synchronous motors (PMSM) [15], brushless DC motor [16], SGs [17], DFIG [18], six-phase IM [19], five-phase IM [20], and six-phase synchronous motor [21].

A comparison can be made between this control and the various known strategies published in scientific papers such as FOC and DPC in terms of ease of implementation, robustness, and speed of response. Table 1 presents a comparative study between the DTC technique and the various strategies currently known to control electrical machines. In this control, the switching table is used to control the inverter rather than using the pulse width modulation (PWM) technique, as in the case of the FOC. The DTC technique is among the best and most robust and offers a very fast dynamic response compared to many other methods such as the FOC, direct vector control (DVC), and indirect vector control (IVC). However, this control has many drawbacks, including torque ripples, rotor flux ripples, and harmonic distortion of the stator current. Several recently published scientific works have suggested solutions for improving the performance of the DTC technique, such as the use of fuzzy logic, neural networks, a genetic algorithm, neuro-fuzzy algorithm, super twisting algorithm (STA), fractional-order control (FOC), second-order continuous sliding mode control (SOCSMC), etc. Table 2 presents most of the works carried out to improve the performance and effectiveness of the DTC technique using nonlinear controllers and artificial intelligence. The controller used for improvement is mentioned in the table along with the results and type of study, whether experimental or simulated [3].

Several techniques have been used to improve the efficiency and properties of the traditional DTC strategy. However, their effectiveness differs from one controller to another. Researchers who relied on the use of nonlinear techniques only, and some combined nonlinear techniques with artificial intelligence to obtain a more robust control were able to improve the DTC technique [30].

This work proposes two nonlinear DTC techniques to control the DFIG-based wind power generation system. Two new nonlinear controllers are proposed to improve the performance and characteristics of the DTC strategy in the DFIG-based wind turbine. The two proposed nonlinear controllers consist of the fractional-order STA (FOSTA) controller and the fractional-order SOCSMC (FOSOSMC) controller. These two new nonlinear controllers are proposed to minimize torque and flux ripples, as well as reducing the THD value of the stator current.

Two different DTC strategies are proposed to control the DFIG-based wind turbine, the first of which is the DTC-FOSTA technique and the second the DTC-FOSOCSMC. The results obtained from these proposed DTC techniques were compared with those of the classical DTC strategy, in terms of electric current quality, ratio of torque and flux ripples, and degree of durability. The work carried out in this study is illustrated in Fig. 1. A diagram of the proposed nonlinear DTC techniques is also shown in Fig. 1, with two different conceptual approaches proposed for generator control. The obtained results were compared with the classical method.

Consequently, the novelty and main contributions of this paper are as follows:

- A two nonlinear controller is designed and applied in the DTC strategy of the DFIG.
- Two nonlinear DTC strategies of the DFIG-based wind power system are proposed since they have more favorable characteristics than the DTC strategy while retaining the merits of its ease of execution and simplicity.
- The ripples of the flux and torque are reduced, and the inverter switching frequency mastered to limit the different problems of DFIG-based wind power systems.
- The proposed FOSTA and FOSOCSMC controllers are used to reduce the THD value of the stator current.
- The characteristics of the DFIG controlled by the two proposed nonlinear DTC strategies are compared to those of the DFIG controlled by the DTC strategy to demonstrate performance improvement.

The comparative results confirm the good performance of the two proposed nonlinear DTC techniques, where the rotor flux, current and electromagnetic ripples, and the THD of the generated currents were significantly minimized, especially under a change in system parameters. Moreover, the simulation results indicate that the DTC-FOSTA technique is better in terms of ripple ratio and the THD current value than the DTC-FOSOCSMC technique.

***Table 2**: Different methods for improving the DTC technique.*

References	Study Type	Electric Machine Type	The Type of Method Used	Torque Ripple	Flux Ripple	Ratio of THD	Robustness	Simplicity
[22]	Simulation	DFIG	Third-order SMC technique	Low	Low	Low	High	Simple
[23]	Simulation	Induction Motor	Three-level inverter	Medium	Medium	Medium	Low	Simple
[24]	Experimental	PMSM	Space vector modulation	Medium	Medium	Medium	Low	Simple
[25]	Simulation	PMSM	Sliding mode control	Medium	Medium	Medium	Medium	Complicated
[26]	Experimental	PMSM	Modified finite set model predictive strategy	Medium	Medium	Medium	Medium	Complicated
[27]	Simulation	DFIG	Fuzzy logic	Medium	Medium	Medium	Medium	Complicated
[28]	Simulation	Multi-phase PMSM	Feedforward neural network	Medium	Medium	Medium	Medium	Simple
[29]	Simulation	Multi-phase IPMSM	Fuzzy logic and SVM technique	Medium	Medium	Medium	High	Complicated
[30]	Simulation	DFIG	ANFIS-STA and SVM	Medium	Medium	Low	High	Complicated
[31]	Simulation	DFIG	Neural PI and modified SVM	Medium	Medium	Low	High	Simple
[32]	Simulation	DFIG	Second-order continuous sliding mode control	Medium	Medium	Low	High	Simple

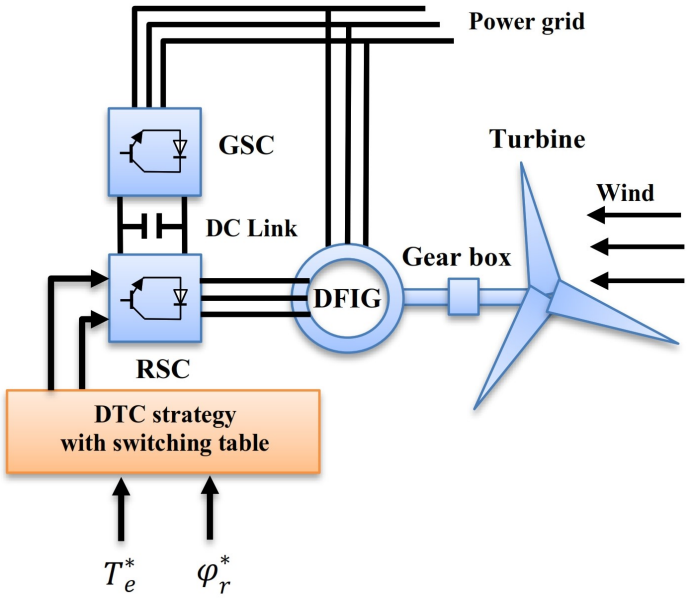

***Fig. 2**: Block diagram of a wind power system with a DFIG controlled by the DTC technique [33].*

2. WIND POWER SYSTEM

Fig. 2 shows the electric power generation system using wind energy. This system requires a turbine to convert wind energy into mechanical energy to rotate the DFIG. A generator is also needed to convert mechanical energy into electrical energy. This system uses two inverters; one to convert AC to DC, and another for converting from DC to AC [33]. The system is very simple and easy to implement and can be easily controlled.

2.1 Model of the Wind Turbine

The mechanical energy obtained by the turbine is represented by Eq. (1). This energy is related to each of the wind speeds (v), tip speed ratio (λ), air density (ρ), radius of the turbine (R), blade pitch angle (β), and power coefficient (C_P) [34].

$$P_t = \frac{1}{2} R^2 \cdot V^3 C_p(\beta,\ \lambda) \tag{1}$$

Eq. (2) represents the power coefficient of the wind turbine.

$$C_p(\lambda,\beta) = (\beta-2)(0.5-0.167)\sin\left(\frac{\pi(\lambda+0.1)}{18.5-0.3(\beta-2)}\right) - 0.0018\times(\beta-2)(\lambda-3) \tag{2}$$

The tip speed ratio is represented by Eq. (3).

$$\lambda = \frac{\Omega_t \cdot R}{V} \tag{3}$$

where Ω_t is the rotational speed of the wind turbine.

2.2 The Mathematic Model of the DFIG

To study this system, the mathematical form of the turbine and DFIG must be given. Eqs. (4)-(8) represent the mathematical model of the DFIG used in this work [35, 36].

$$\begin{cases} V_{dr} = R_r I_{dr} - w_r \Psi_{qr} + \frac{d}{dt}\Psi_{dr} \\ V_{qr} = R_r I_{qr} + w_r \Psi_{dr} + \frac{d}{dt}\Psi_{qr} \\ V_{qs} = R_s I_{qs} + w_s \Psi_{ds} + \frac{d}{dt}\Psi_{qs} \\ V_{ds} = R_s I_{ds} - w_s \Psi_{qs} + \frac{d}{dt}\Psi_{ds} \end{cases} \tag{4}$$

The following equation interconnects the rotor and stator pulsations and rotor speed: $w_s = w_r + w$. Where w_r and w_s are the rotor and stator electrical pulsations, respectively, while w is the mechanical one.

The rotor and stator flux can be written as follows:

$$\begin{cases} \Psi_{dr} = M I_{ds} + L_r I_{dr} \\ \Psi_{qr} = M I_{qs} + L_r I_{qr} \\ \Psi_{ds} = M I_{dr} + L_s I_{ds} \\ \Psi_{qs} = M I_{qr} + L_s I_{qs} \end{cases} \tag{5}$$

$(V_{dr}, V_{qr}, V_{ds}, V_{qs}), (\Psi_{dr}, \Psi_{ds}, \Psi_{qs}, \Psi_{ds}), (I_{dr}, I_{qr}, I_{ds}, I_{qs})$, are the stator and rotor voltages, fluxes, and currents, respectively; R_r and R_s are the resistances of the stator and rotor windings, respectively, while L_r, L_s, and M are the inductance rotor, stator, and mutual inductance between two coils, respectively.

The mechanical equation of the DFIG is given as:

$$T_e = T_r + J \cdot \frac{d\Omega}{dt} + F_r \cdot \Omega \tag{6}$$

The electromagnetic torque established by the DFIG can be written in terms of flux and current by Equation (7):

$$T_e = \frac{3}{2}\frac{M}{L_s} n_p(-\Psi_{ds} I_{qr} + \Psi_{qs} I_{dr}) \tag{7}$$

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

The reactive and active powers of the stator side are defined as:

$$\begin{cases} Q_s = 1.5(-V_{ds} I_{qs} + V_{qs} I_{ds}) \\ P_s = 1.5(V_{qs} I_{qs} + V_{ds} I_{ds}) \end{cases} \tag{8}$$

3. TRADITIONAL DTC TECHNIQUE

The DTC strategy aims to regulate the torque and rotor flux using a switching table and two hysteresis comparators. The DTC technique is more efficient, simple, and robust than the FOC technique. The DTC strategy is more effective at improving the performance of electric machines than the FOC technique.

The DTC strategy has become one the most popular linear methods in recent years and used in the field of renewable energy, especially wind, because of its many advantages. Fig. 3 presents the traditional DTC technique of the DFIG using proportional-integral (PI) controllers. The inverter of the DFIG is controlled by the space vector modulation (SVM) strategy. This control scheme is simpler and easier to implement than the vector control and FOC strategies. Using the SVM technique to control the inverter increases system durability and helps improve the quality of the current. Compared to the pulse width modulation (PWM) technique, the SVM is better for obtaining a signal at the inverter output with a constant frequency. The SVM strategy is detailed in [37].

Among the disadvantages of this system are the estimation of both torque and rotor flux and, consequently, there is an urgent need for high-quality tension and current measuring devices.

The DTC technique based on traditional PI controllers represents a modification of the traditional DTC technique with a switching table. The PI controllers are used to regulate the quadrature and direct rotor voltages, as detailed in [22]. The DTC-PI technique is more robust than the FOC, DTC, and vector control strategies. In addition, the DTC-PI technique is better at reducing the torque and flux ripples than the FOC, vector control, and DTC strategies. Both the torque and rotor flux need to be estimated in this control scheme. Furthermore,

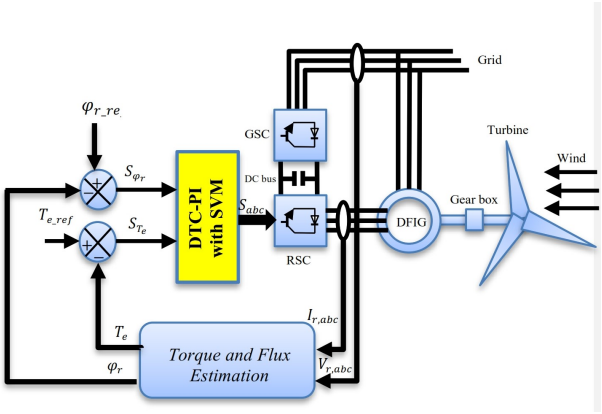

***Fig. 3**: Traditional DTC technique for the DFIG.*

a two-level SVM inverter is used to control the DFIG rotor. Due to its simplicity, the PWM technique can generate control signals in IGBTs, while reducing the cost of implementation and simplifying the system. However, the system is less robust compared to the SVM technique.

Eq. (9) represents how to calculate the direct and quadrature rotor flux of the DFIG

$$\begin{cases} \Psi_{qr} = \int_0^t (-R_r i_{qr} + V_{qr})dt \\ \Psi_{dr} = \int_0^t (-R_r i_{dr} + V_{dr})dt \end{cases} \tag{9}$$

The following equation can calculate the magnitude flux:

$$\Psi_r = \sqrt{\Psi_{qr}^2 + \Psi_{dr}^2} \tag{10}$$

Eq. (11) represents the phase of rotor flux of the DFIG. The phase can be calculated using both direct and quadrature rotor flux of the DFIG.

$$\theta_r = arctg\left(\frac{\Psi_{qr}}{\Psi_{dr}}\right) \tag{11}$$

The stator flux is related to stator voltage, as represented by Eq. (12). With this equation, the stator flux and stator voltage can be calculated.

$$\left|\overline{\Psi_s}\right| = \frac{\overline{\left|\overline{V_s}\right|}}{w_s} \tag{12}$$

To estimate the flux and torque, the rotor voltage, and current must be measured. The rotor current and stator flux are required due to their relationship with the torque. On the other hand, the torque is also related to the resistance value. Eq. (13) represents the torque estimation used in this work.

$$T_e = \frac{3}{2}\frac{M}{L_s} n_p(-\Psi_{ds} I_{qr} + \Psi_{qs} I_{dr}) \tag{13}$$

Eq. (14) represents the estimation of the stator flux.

$$\begin{cases} \Psi_{ds} = \int_0^t (-R_s i_{qs} + V_{qs})dt \\ \Psi_{ds} = \int_0^t (-R_s i_{ds} + V_{ds})dt \end{cases} \tag{14}$$

Eqs. (15) and (16) represent the phase and magnitude of the stator flux, respectively.

$$\theta_s = arctg\left(\frac{\Psi_{s\beta}}{\Psi_{s\alpha}}\right) \tag{15}$$

$$\Psi_s = \sqrt{\Psi_{s\alpha}^2 + \Psi_{s\beta}^2} \tag{16}$$

The DTC-PI technique involves a simple algorithm and is easier to use and more robust than the vector control, FOC, and DTC techniques. It is widely accepted that a PI controller reduces the degree of durability and increases the rate of ripples, especially when changing the system parameters. Consequently, the current quality is low, which is undesirable. However, the problems with torque fluctuation and changing the machine parameters remain. In this case, this control loses its durability and gives more torque and flux ripples. To solve these problems, it is suggested that the proposed nonlinear controllers be used. These proposed nonlinear controllers are explained in Section 4.

4. PROPOSED NONLINEAR CONTROLLERS

This section proposes and confirms the suitability of two different nonlinear controllers using the DTC strategy. The first is the FOSTA controller and the FOSOCSMC. These nonlinear controllers are simpler, easy to implement, and more robust than the PI, STA, and SOCSMC. The two proposed nonlinear controllers are based on FO control to achieve robustness while improving the performance and characteristics of the traditional DTC strategy.

The FOC is a mathematical technique involving the generalization of integration and normal differentiation to arbitrary non-integer orders [38]. The use of this strategy gives very satisfactory results, as evidenced by previous work carried out in this field. It is not limited to mathematics alone but can also be applied to physics and electricity.

In this work, the FOC technique is used to improve the performance and effectiveness of both STA and SCOSMC controllers due to features such as its simplicity and durability.

The STA controller can be expressed by Eq. (17) [39].

$$u(t) = u_1(t) + u_2(t) \tag{17}$$

$u(t)$ is the output of the proposed STA controller. Where

$$u_1(t) = \lambda_1 \sqrt{|S|}.sign(S) \tag{18}$$

$$u_2(t) = \lambda_2 \int sign(S)\, dt \tag{19}$$

The proposed FOSTA controller differs from the traditional STA in that simplicity is one of its biggest advantages. Eq. (20) expresses the controller proposed in this work, where α is the proposed FO control ($\alpha \neq 0$).

$$w(t) = \left(\lambda_1 \sqrt{|S|}.sign(S) + \lambda_2 \int sign(S).dt \right)^{\alpha} \quad (20)$$

where $w(t)$ is the output of the FOSTA controller, and α is an adjustable parameter by which the performance and durability of the entire system can be greatly improved. If it is 1, the proposed FOSTA controller becomes a traditional STA controller. The proposed FOSTA controller is a simple algorithm, more robust, and easy to adjust. It also gives better results than the traditional STA controller [39]. Fig. 4 shows the proposed FOSTA controller.

The second suggested nonlinear controller is the FOSOCSM, based on SOCSMC and fractional-order control theory. The proposed FOSOCSMC controller is more robust than the traditional SOCSMC, PI, and STA controllers. The SOCSMC principle can be illustrated by the following equation [32]:

$$y(t) = -K_1|S|^{a_1}\ sign(s) - K_2 \cdot sign|S|^{1/2} + \int \alpha \cdot sign(s)\, dt \quad (21)$$

where S is the surface. K_1 and K_2 represent the constant gains.

The FOSOCSMC is a combination of fractional order control and the SOCSMC controller. The FOC technique is introduced into the SOCSMC controller to increase durability and maintain the simplicity of the SOCSMC. In similarity to the FOSTA controller, the proposed FOSOCSMC can be expressed by Eq. (22), where the λ is the proposed fractional order control used in this work ($\lambda \neq 0$).

$$Y(t) = (-K_1|S|^{a_1}\ sign(S) - K_2 \cdot sign|S|^{1/2} + \int \alpha \cdot sign(S)\, dt)^{\lambda} \quad (22)$$

where K_1 and K_2 represent the constant gains.

$Y(t)$ is the output of the proposed FOSOCSM controller.

Eq. (22) represents the proposed FOSOCSMC controller. K_1 and K_2 control the stability of the FOSOCSMC. On the other hand, λ represents the FO control and $\lambda \neq 0$. It can take positive or negative values, depending on the system used. If λ is equal to 1, the proposed controller becomes the classical controller. Fig. 5 shows the proposed FOSOCSMC controller used in this work which gives better results than the traditional SOCSMC controller.

The proposed FOSTA and FOSOCSM controllers are used to improve the performance and effectiveness of the traditional DTC technique, while also reducing the THD value of the stator current and torque ripples. The proposed nonlinear DTC techniques in this paper are detailed in Section 5.

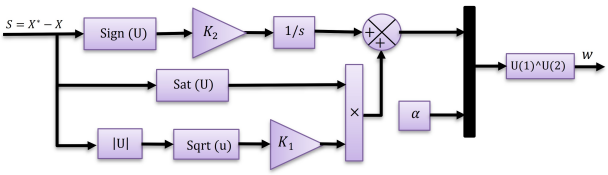

***Fig. 4**: Proposed FOSTA controller.*

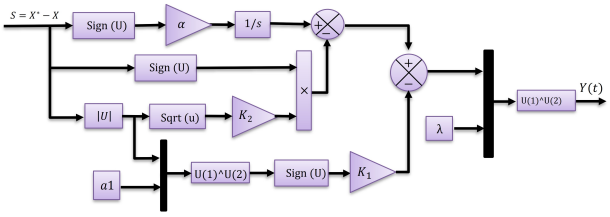

***Fig. 5**: Proposed FOSOCSMC controller.*

5. PROPOSED NONLINEAR DTC TECHNIQUES

This section proposes two different approaches to the nonlinear DTC control of the DFIG-based wind turbine. The first control is the DTC-FOSTA technique, and the second the DTC-FOSOCSM. Durability, simplicity, and ease of implementation are the main elements characterizing each proposed control. Moreover, the two proposed control schemes give very satisfactory results compared to the classical DTC strategy.

5.1 Design of the Proposed DTC-FOSTA Strategy

The proposed DTC-FOSTA represents a modification of the traditional DTC strategy. The proposed FOSTA controller replaces the hysteresis comparator to provide a more robust DTC strategy, while the two-level SVM technique replaces the switching table. Fig. 6 presents the proposed DTC-FOSTA technique. Compared to the traditional DTC technique, this control scheme is simple, easy to implement, robust, and has a fast response dynamic. In contrast to the classical DTC strategy, the proposed DTC-FOSTA technique reduces torque and flux ripples. Fig. 7 shows the internal structure of the proposed DTC-FOSTA technique. The proposed DTC-FOSTA uses the same torque and flux estimation equations as the classical DTC technique explained in Section 3 of this paper.

The torque and rotor flux FOSTA controllers influence the two rotor voltage components, as in Eqs. (23) and

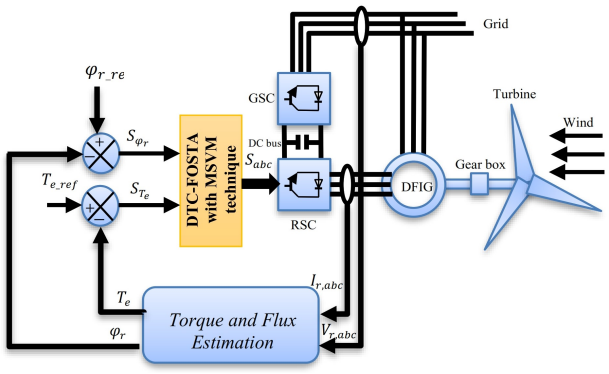

***Fig. 6**: The DTC-FOSTA technique of DFIG.*

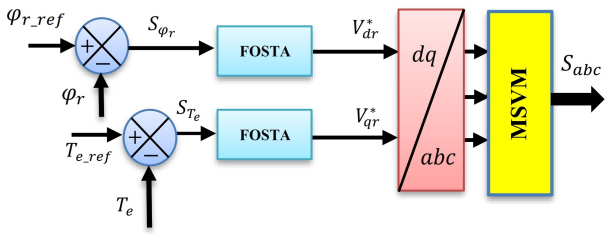

***Fig. 7**: Internal structure of the DTC-FOSTA technique.*

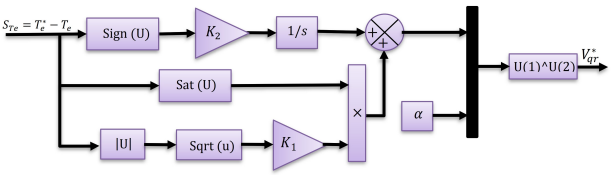

***Fig. 8**: Proposed FOSTA torque controller.*

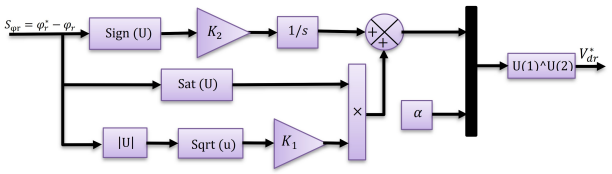

***Fig. 9**: Proposed FOSTA rotor flux controller.*

(24).

$$V_{dr}^{*}=\left(\lambda_{1}\sqrt{\left|S_{\varphi r}\right|}.sign\left(S_{\varphi r}\right)+\lambda_{2}\int sign\left(S_{\varphi r}\right).dt\right)^{\alpha} \tag{23}$$

$$V_{qr}^{*}=\left(\lambda_{1}\sqrt{\left|S_{Te}\right|}.sign\left(S_{Te}\right)+\lambda_{2}\int sign\left(S_{Te}\right).dt\right)^{\alpha} \tag{24}$$

where $S_{\varphi r}$ is the rotor flux surface ($S_{\varphi r}=\varphi_{r}^{*}-\varphi_{r}$), S_{Te} is the torque surface ($S_{Te}=T_{e}^{*}-T_{e}$).

Figs. 8 and 9 show the proposed FOSTA torque and FOSTA rotor flux controllers. As can be observed, the new proposed nonlinear controller is very simple and can be easily accomplished.

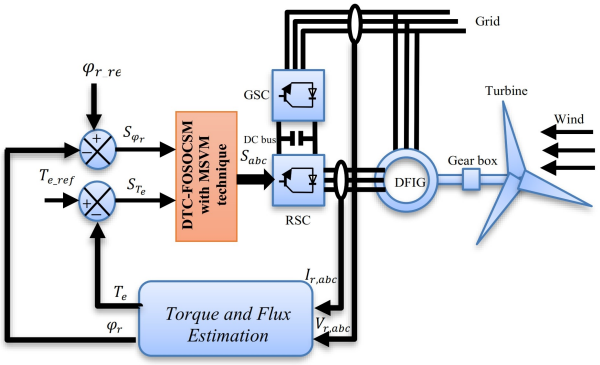

***Fig. 10**: The DTC-FOSOCSM strategy of the DFIG.*

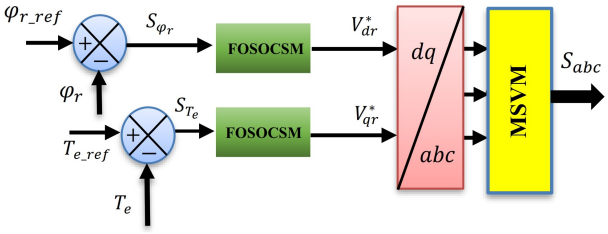

***Fig. 11**: Internal structure of the DTC-FOSOCSMC strategy.*

5.2 Design of the Proposed DTC-FOSOCSMC Technique

Using the same implementation method as the DTC-FOSTA, the traditional hysteresis comparator is replaced by the proposed FOSOCSMC controller designed in Section 3. The objective of the proposed DTC-FOSOCSMC technique is to control the torque and flux as well as reduce ripples and the THD value of stator current. Robustness is one of the biggest advantages of the proposed DTC-FOSOCSMC strategy. It involves a simple algorithm and can be easily implemented. A block diagram of the proposed DTC-FOSOCSMC strategy is shown in Fig. 10, while Fig. 11 presents a block diagram of the DTC-FOSOCSMC strategy.

The torque and rotor flux FOSOCSMC controllers influence the two rotor voltage components, as in Eqs. (25) and (26).

$$V_{dr}^{*}=(-K_{1}\left|S_{\varphi r}\right|^{a_{1}}sign\left(S_{\varphi r}\right)-K_{2}\cdot sign\left|S_{\varphi r}\right|^{1/2}+\int\alpha\cdot sign\left(S_{\Psi_{r}}\right)dt)^{\lambda} \tag{25}$$

$$V_{qr}^{*}=(-K_{1}\left|S_{Te}\right|^{a_{1}}sign\left(S_{Te}\right)-K_{2}\cdot sign\left|S_{Te}\right|^{1/2}+\int\alpha\cdot sign\left(S_{Te}\right)dt)^{\lambda} \tag{26}$$

The proposed rotor flux and torque FOSOCSMC controllers are shown in Figs. 12 and 13, respectively.

6. RESULTS

In this section, three DTC techniques are proposed, simulated, and compared to identify which of them is

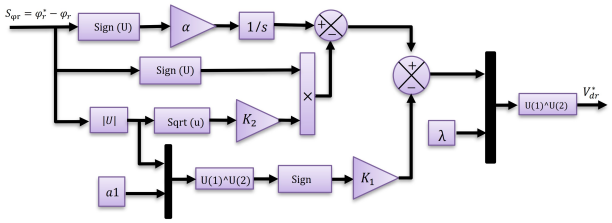

***Fig. 12**: Proposed FOSOCSM flux controller.*

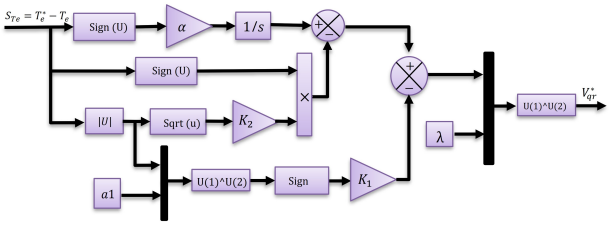

***Fig. 13**: Proposed FOSOCSM torque controller.*

better for improving the performance of the DFIG-based wind turbine system. The proposed DTC techniques are DTC-PI, DTC-FOSTA, and DTC-FOSOCSMC. The DFIG used in this paper is the same as that used in [22, 32]. These DTC techniques were compared for traceability, response time, torque ripples, flux, current ripples, THD value of current, and durability. Therefore, three tests were carried out to determine the best DTC technique.

6.1 Reference Tracking Test

The results obtained from the reference tracking test are presented in Figs. 14 to 22. As can be observed, the torque and flux follow the references very well (see Figs. 14 and 15). However, the preference of the two proposed nonlinear DTC techniques is determined in terms of response time for comparison to the DTC-PI technique.

The electric current of the three DTC techniques is shown in Fig. 15. As can be observed, the value and shape of the current are related to the torque reference due to the existence of a direct relationship between them. Figs. 16-18 show that the DTC-FOSTA gives a lower value for the THD than the DTC-PI and DTC-FOSOCSMC techniques.

The zooms of the flux, torque, and current are shown in Figs. 20, 21, and 22, respectively. As can be observed, in contrast to the DTC-PI and DTC-FOSOCSMC, the DTC-FOSTA technique reduces the torque, current, and rotor flux.

Table 3 summarizes the results of this test, indicating the best method for providing satisfactory results in terms of torque ripples, simplicity, THD value, and response time. It can be concluded that the DTC-FOSTA strategy is better than the other controls tested due to the effectiveness of its performance.

In order to confirm that this method produced the best performance, the machine parameters were changed and

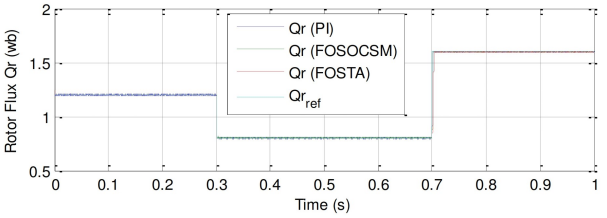

***Fig. 14**: Rotor flux.*

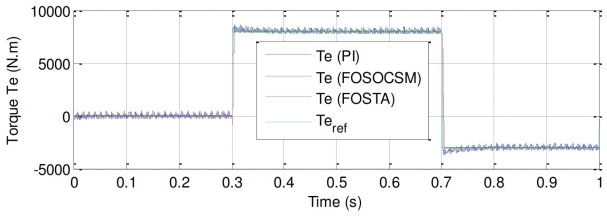

***Fig. 15**: Torque.*

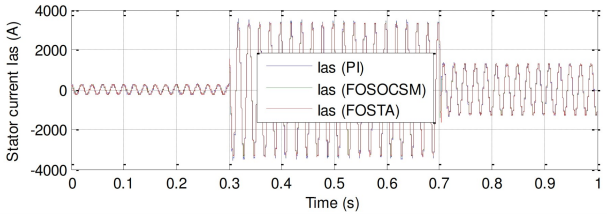

***Fig. 16**: Current.*

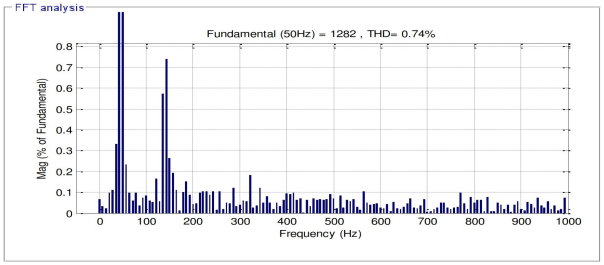

***Fig. 17**: THD (DTC-PI).*

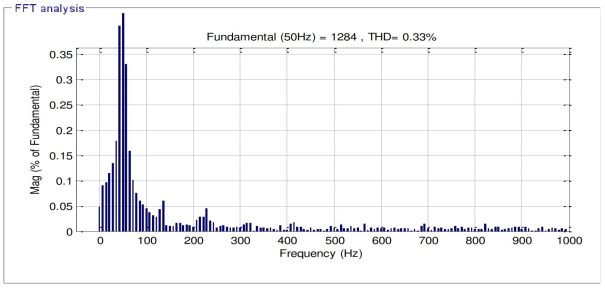

***Fig. 18**: THD (DTC-FOSOCSMC).*

the effects observed in the next test

***Table 3**: Comparison between the results obtained from the proposed nonlinear DTC techniques and the DTC-PI control.*

Criteria	Control Methods		
	DTC-PI	DTC-FOSOCSMC	DTC-FOSTA
Flux and torque tracking	Acceptable	Good	Excellent
THD (%)	0.74	0.33	0.17
Dynamic response (s)	Medium	Fast	Fast
Settling time (ms)	High	Medium	Medium
Reduce torque and flux ripples	Acceptable	Very good	Excellent
Overshoot (%)	21%	1.2%	1%
Simplicity of converter and filter design	Simple	Simple	Simple
Current ripple (A)	Around 30	Around 10	Around 4
Torque ripple (Nm)	Around 400	Around 100	Around 50
Rise time (s)	High	Medium	Medium
Simplicity of calculations	Simple	Rather complicated	Rather complicated
Flux ripple (wb)	Around 0.02	Around 0.003	Around 0.001
Improvement of transient performance	Good	Excellent	Excellent
Quality of stator current	Acceptable	Very good	Excellent

***Table 4**: Comparison of the effect ratio between the designed and traditional techniques.*

Strategy	THD (%)	Ratio (%)
DTC-FOSTA	0.23	54.90
DTC-FOSOCSMC	0.12	76.47

***Table 5**: Results of the first test.*

Criteria	in DTC	Strategy 1	Strategy 2
THD (%)	0.51	0.23	0.12
Rise time (s)	High	Medium	Medium
Flux ripples (wh)	0.01	0.0064	0.0021
Torque ripples (Nm)	980	200	60
Quality of current	Low	Medium	High
Overshoot (%)	$\approx 30\%$	$\approx 2\%$	$\approx 1.5\%$
Settling time (ms)	High	Medium	Medium
Tracking references	Acceptable	Good	Very good
Dynamic response (s)	Medium	Fast	Fast
Steady-state error	High	Medium	Low
Current ripples (A)	40	28	17

Note: Strategy 1 is the DTC-FOSOCSMC and strategy 2 the DTC-FOSTA technique

***Table 6**: Results of the second test.*

Criteria	in DTC	Strategy 1	Strategy 2
THD (%)	0.51	0.23	0.12
Rise time (s)	High	Medium	Medium
Flux ripples (wh)	0.014	0.0041	0.0038
Torque ripples (Nm)	770	52	31
Quality of current	Low	Medium	High
Overshoot (%)	$\approx 19\%$	$\approx 1.5\%$	$\approx 1\%$
Settling time (ms)	High	Medium	Medium
Tracking references	Acceptable	Good	Very good
Dynamic response (s)	Medium	Fast	Fast
Steady-state error	High	Medium	Low
Current ripples (A)	27	17	8

Note: Strategy 1 is the DTC-FOSOCSMC and strategy 2 the DTC-FOSTA technique

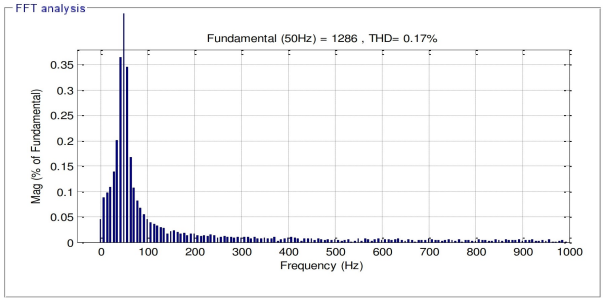

***Fig. 19**: THD (DTC-FOSTA).*

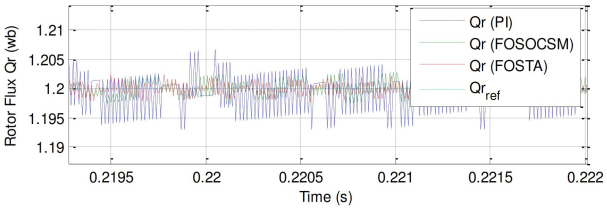

***Fig. 20**: Zoom of the flux.*

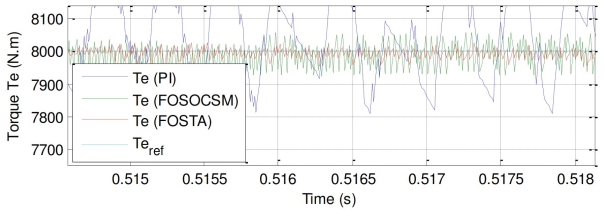

***Fig. 21**: Zoom of the torque.*

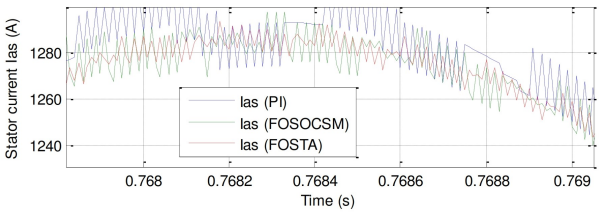

***Fig. 22**: Zoom of the current.*

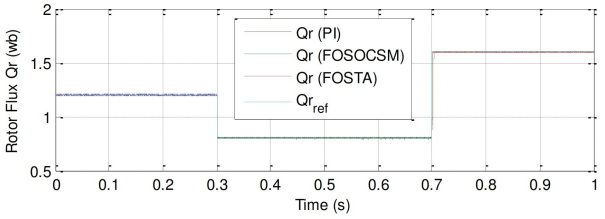

***Fig. 23**: Rotor flux.*

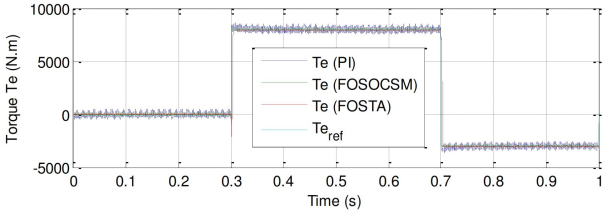

***Fig. 24**: Torque.*

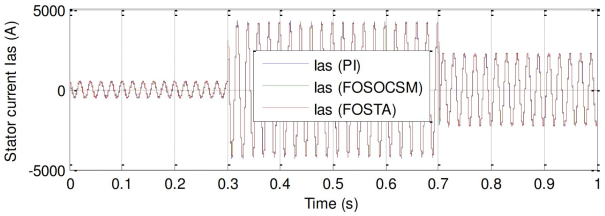

***Fig. 25**: Current.*

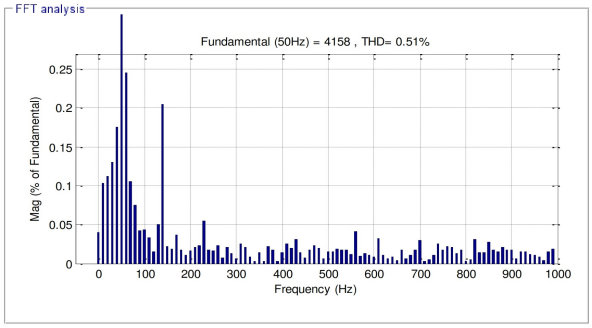

***Fig. 26**: THD (DTC-PI).*

6.2 Robustness Test

The principal objective of the robustness test is to examine the influence of variations in DFIG parameters on the current, rotor flux, THD value, torque, and behavior of three proposed DTC strategies. The obtained results presented in Figs. 23 to 31 indicate that the torque and rotor flux follow the references well for all the proposed controls (see Figs. 23 and 24). As for the stator current, its value remains related to the system and reference value of the torque (see Fig. 25).

Changing the DFIG parameters led to a change in the THD value for all three DTC techniques. However, the DTC-FOSTA technique still gives less value than other controls. Table 4 presents the percentage reduction of THD for the classical control, indicating that the DTC-FOSTA technique provides much larger percentages than the DTC-FOSOCSMC strategy. As for the percentage reduction compared to the DTC-FOSOCSMC strategy, it is about 47.82%. These percentages are very acceptable and indicate the robustness of this technique (DTC-FOSTA) compared to the remainder of the proposed DTC techniques.

The results of the DTC-FOSOCSMC and DTC-PI control strategies are presented in Table 5. As can be observed, the DTC-FOSTA technique is better than the other control schemes in all respects. The DTC-FOSTA technique reduced the torque ripple value by about 93.87% compared to the classical DTC strategy. The DTC-FOSOCSMC reduced the torque ripple by an estimated 79.59% compared to the classical DTC technique. It can therefore be concluded that the DTC-

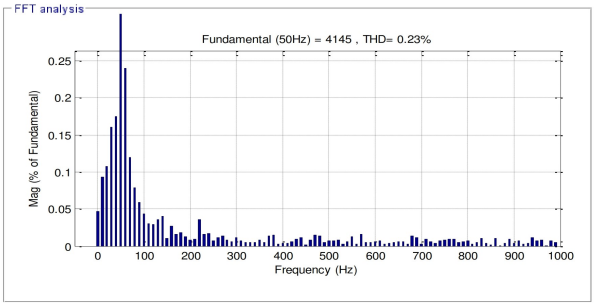

***Fig. 27**: THD (DTC-FOSOCSMC).*

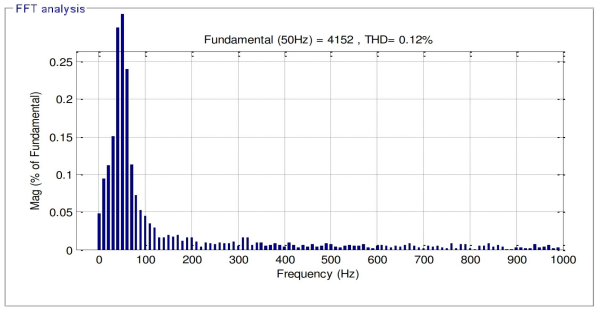

***Fig. 28**: THD (DTC-FOSTA).*

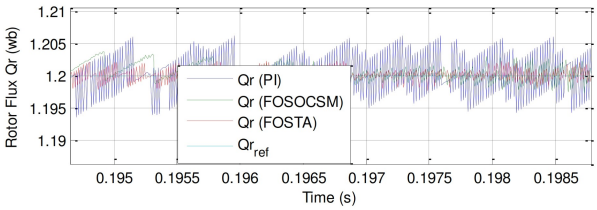

***Fig. 29**: Zoom of the flux.*

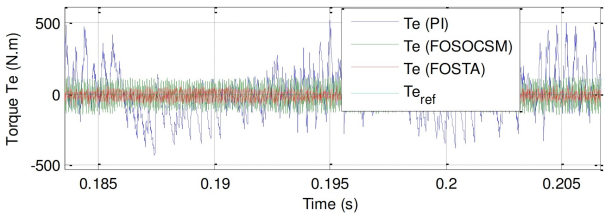

***Fig. 30**: Zoom of the torque.*

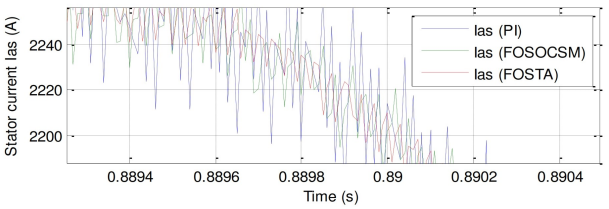

***Fig. 31**: Zoom of the current.*

FOSTA technique is better than the DTC-FOSOCSMC in reducing torque ripples. The same applies to the stator current ripples, where the percentage reduction

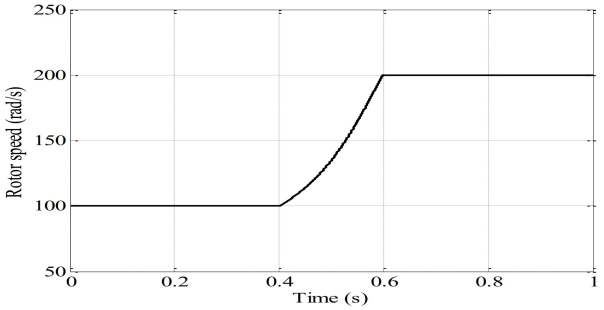

***Fig. 32**: Rotor speed profile.*

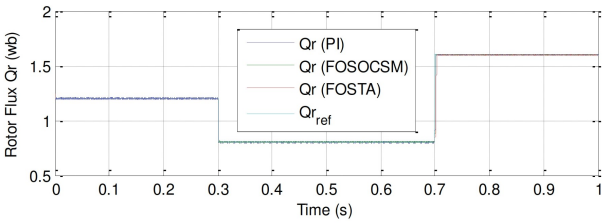

***Fig. 33**: Rotor flux.*

percentage was about 30% for the DTC-FOSOCSMC and 57.50% for the DTC-FOSTA techniques compared to the classical DTC strategy. Furthermore, the rotor flux reduction ratios compared to the traditional DTC technique were approximately 36% and 79% for the DTC-FOSOCSMC and DTC-FOSTA techniques, respectively.

6.3 Sensibility Test

In the sensibility test, the rotor speed is varied at different time intervals. Fig. 32 shows the rotor speed of the DFIG. The principal objective of this test is to examine the influence of a mechanical speed variation in the DFIG on the rotor flux and torque behaviors of the three proposed DTC techniques. The obtained results are presented in Figs. 33 to 41. Figs. 33 to 35 show that the torque and flux follow the references well, with the DTC-FOSTA being the preferred technique in terms of dynamic response compared to the remaining techniques. It can also be observed that the flux and torque change are not related to the three proposed techniques, confirming their robustness. Most of the results obtained from this test are presented in Table 6. The electric current of the three modes is shown in Fig. 35. As can be observed, the electric current is sinusoidal with a frequency of 50 Hz, whereby the current changes are unrelated to the rotor speed profile of the three modes. The electric current takes the same form as the torque, with its value related to that of the torque. Therefore, an increase in the value of the torque leads to an increase in the value of the resulting current and vice versa.

The ripples of torque, flux, and current are presented in Figs. 36, 37, 38, and Table 6. As can be observed, the DTC-FOSTA technique significantly reduced these ripples compared to the classical DTC technique, as

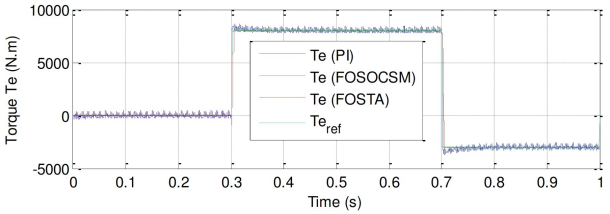

***Fig. 34**: Torque.*

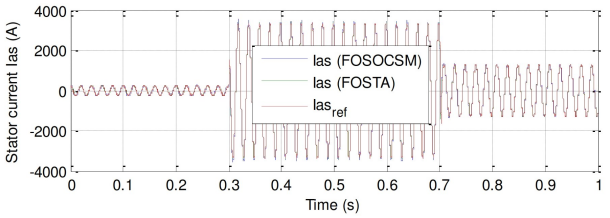

***Fig. 35**: Current.*

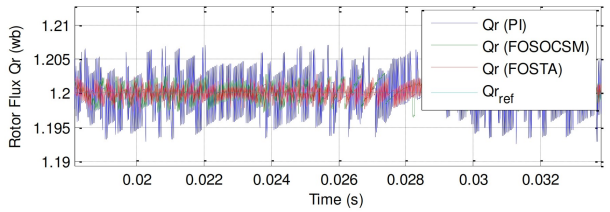

***Fig. 36**: Zoom of the flux.*

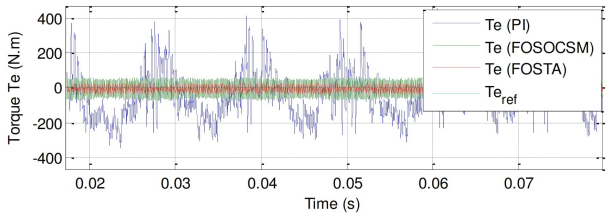

***Fig. 37**: Zoom of the torque.*

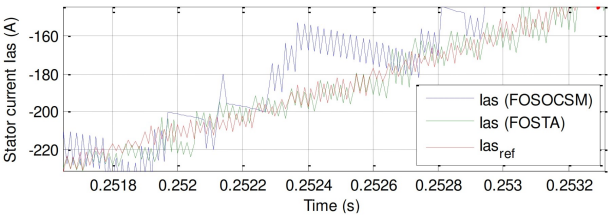

***Fig. 38**: Zoom of the current.*

indicated by the obtained ripple values. Whereas the speed variation produces a negligible effect on the rotor flux, current, THD value, torque, and curves for both DTC techniques. Furthermore, the DTC-FOSTA technique reduced the ripples of torque, current, and flux by about 93.24%, 37.03%, and 70.71%, respectively, compared to the classical DTC technique. Compared with the DTC-FOSOCSMC technique, the DTC-FOSTA technique reduced the current, torque, and flux ripples by about

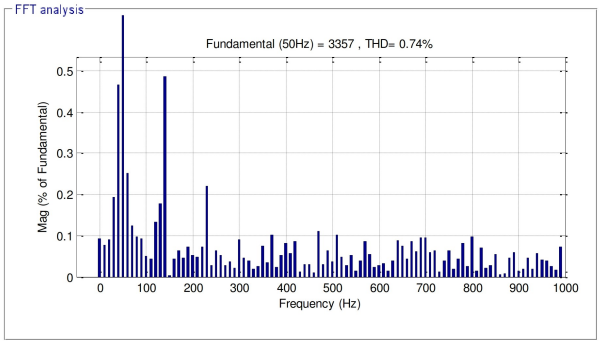

***Fig. 39**: THD (DTC-PI).*

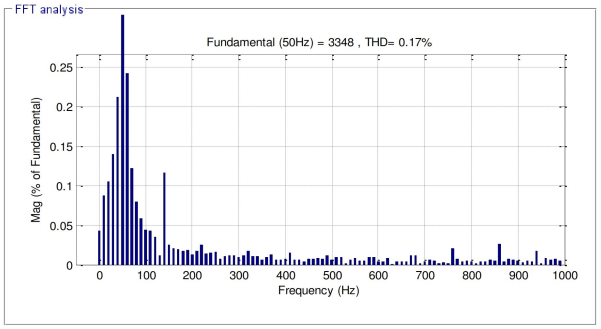

***Fig. 40**: THD (DTC-FOSOCSMC).*

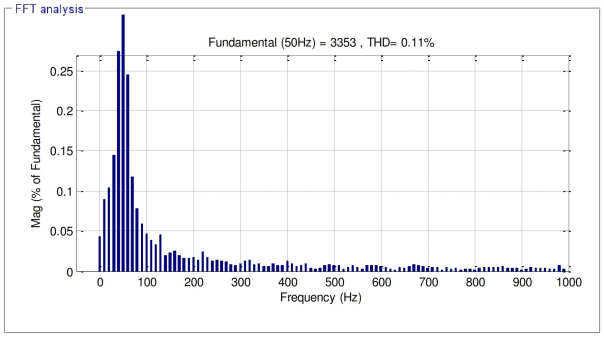

***Fig. 41**: THD (DTC-FOSTA).*

52.94%, 40.38%, and 7.31%, respectively. Accordingly, it can be said that the DTC-FOSTA technique is the best solution for controlling electrical power generation.

Figs. 39, 40, and 41 show the THD value of the current for the designed DTC techniques. It should be noted that the THD value is lower for DTC-FOSTA (0.11%) compared to DTC (0.74%) and DTC-FOSOCSMC (0.17%). These results indicate that the DTC-FOSTA technique reduces the THD value by 85.13% and 35.29% compared with the DTC and DTC-FOSOCSMC, respectively.

Finally, the THD value of the current is compared between the proposed nonlinear DTC techniques and several published works, the results of which are presented in Table 7. As can be observed, the proposed nonlinear DTC strategies gave much lower THD values than some published strategies, such as FOC, fuzzy DTC,

***Table 7**: Summary of comparative results.*

Reference	Techniques	THD (%)
[27]	DTC control	6.70
	Fuzzy DTC control	2.04
[32]	DTC-SOCSMC	0.95
[40]	12 sectors DPC control	0.40
[41]	DPC with IP controllers	0.43
[42]	DARPC control with STA controller	1.66
[2]	DPC with terminal synergetic controller	0.25
[43]	SOSMC method	3.13
[44]	FOC with neuro-fuzzy controller (FOC-NFC)	0.78
	FOC with Type 2 fuzzy logic controller (FOC-T2FLC)	1.14
[45]	Integral SMC technique	9.71
	Multi-resonant-based sliding mode controller	3.14
[46]	Fuzzy SMC method	1.15
[47]	Direct FOC control	2.94
	Direct FOC with third-order sliding mode	1.42
[3]	Direct FOC control	1.45
	Direct FOC with synergetic-sliding mode	0.50
Proposed strategies	DTC-FOSOCSM	0.17
	DTC-FOSTA	0.11

and DPC. It can therefore be concluded that the proposed DTC-FOSTA strategy gives a sinusoidal current which gives an effective performance in terms of current, flux, and torque ripples. It also has a better THD value than the remainder of the published works, thereby increasing device longevity and reducing maintenance costs.

7. CONCLUSION

In this study, three DTC techniques are proposed for controlling the DFIG-based wind turbine, with the strengths of each compared to the remaining published works. Furthermore, the new nonlinear techniques have been embodied using MATLAB/Simulink software. The values of the designed nonlinear DTC techniques were compared in terms of torque and flux ripples, trace references, and the extent of influence in the case of changes in machine parameters.

The numerical simulation results evidence the efficiency of the adopted technique (DTC-FOSTA), especially in attenuating the ripples at the flux and torque levels due to the elimination of PI controllers and improvement in screw robustness. Furthermore, the DTC-FOSTA technique addresses the parametric variation issue and alleviates the chattering phenomenon.

The DTC-FOSTA technique provides an improvement over the DTC and DTC-FOSOCSMC techniques. This improvement is remarkable, especially in terms of the torque ripple, current quality, rotor flux ripple, value of THD, and the dynamic responses of torque and rotor flux. THD minimization can be estimated at 85% and 35% compared to the DTC and DTC-FOSOCSMC techniques, making it possible to limit the ripples at different electrical quantities. The minimization ratios were about 95%, 86%, and 87% for rotor flux, current, and torque, respectively, compared to the DTC technique. On the other hand, DTC-FOSTA reduced the values of ripples in current (60%), torque (50%), and flux (66%) compared to the DTC-FOSOCSMC strategy.

Although these percentages are high and indicate the robustness of the designed DTC-FOSTA technique for improving the performance of the DFIG-based wind turbine, the ripples, torque, and flux problems cannot be eliminated entirely. Therefore, for a more satisfactory improvement, futurework should take advantage of a technique based on artificial intelligence to further improve the performance of the DTC-DFIG system.

The current injected into the grid has a low THD value of 0.11%. The proposed nonlinear DTC-FOSTA strategy presents less rotor flux, torque, and current ripples than the DFIG-based wind turbine system.

In summary, the main findings of this research are as follows:

- A new FO high-order SMC technique, confirmed with numerical simulation.
- A new DTC strategy based on FO high-order SMC techniques for comparison with the traditional DTC technique.
- A reduction in the harmonic distortion value of the current.
- Minimization of the torque, current, and rotor flux ripples.
- A different robust nonlinear DTC technique, designed and confirmed using MATLAB software.

A future study will be conducted to improve the quality of torque and flux, with the DFIG controlled using other proposed nonlinear strategies such as the terminal-STA method, fuzzy third-order SMC technique, and fast terminal synergetic control.

NOMENCLATURE

DFIG	Doubly-fed induction generator
DTC	Direct torque control
PI	Proportional-Integral
SVM	Space vector modulation
PWM	Pulse width modulation
STA	Super twisting algorithm
SOCSMC	Second-order continuous sliding mode controller
SMC	Sliding mode controller
THD	Total harmonic distortion
FOSTA	Fractional-order super twisting algorithm
FOC	Field-oriented control
FOC	Fractional-order control
FOSOCSMC	Fractional-order second-order continuous sliding mode controller
T2FLC	Type 2 fuzzy logic controller

DPC	Direct power control
FLC	Fuzzy logic controller
NFC	Neuro-fuzzy controller
IP	Integral proportional

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