



# Article Improved Rotor Flux and Torque Control Based on the Third-Order Sliding Mode Scheme Applied to the Asynchronous Generator for the Single-Rotor Wind Turbine

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**Abstract:** In this work, a third-order sliding mode controller-based direct flux and torque control (DFTC-TOSMC) for an asynchronous generator (AG) based single-rotor wind turbine (SRWT) is proposed. The traditional direct flux and torque control (DFTC) technology or direct torque control (DTC) with integral proportional (PI) regulator (DFTC-PI) has been widely used in asynchronous generators in recent years due to its higher efficiency compared with the traditional DFTC switching strategy. At the same time, one of its main disadvantages is the significant ripples of magnetic flux and torque that are produced by the classical PI regulator. In order to solve these drawbacks, this work was designed to improve the strategy by removing these regulators. The designed strategy was based on replacing the PI regulators with a TOSMC method that will have the same inputs as these regulators. The numerical simulation was carried out in MATLAB software, and the results obtained can evaluate the effectiveness of the designed strategy relative to the traditional strategy.

**Keywords:** asynchronous generator; single-rotor wind turbine; direct flux and torque control (DFTC); third-order sliding mode controller (TOSMC); integral proportional (PI) regulator; DFTC-PI control; DFTC-TOSMC strategy

# 1. Introduction

The strategies of direct flux and torque control (DFTC) scheme or DTC of the asynchronous generator (AG) with constant switching frequency have become a focal point due to their easy design of the AC harmonic filter and power converter, and also due to the reduction in the ripples of the rotor flux and torque [1]. This work introduces a new technique for this technology. It is shown that the DFTC strategy with constant switching frequency is mainly achieved by using the PWM [2], SVM [3,4], DSVM-DFTC [5], and P-DFTC [6], respectively. There are many techniques in the literature that have been proposed to minimize the ripples of magnetic flux and torque [7–11]. However, the sliding mode control (SMC) technique has better dynamics and robustness compared to any other regulators [12]. It also has a better ability to reduce the ripples of torque and magnetic flux. Several works on the SMC technique for the control of an alternating current (AC) machine are available in the literature, which analyzes and discusses its disadvantages and advantages [13–19]. In [13], the SMC provided better results compared to the traditional proportional-integral (PI) controller.

Chattering at very high frequencies is defined as a shortcoming of SMC technology, which causes ripples in the motor. The high-end SMC technology is suitable for reducing this chattering phenomenon [14]. Many strategies like suboptimal, twisting and super twisting [15], terminal SMC [16], non-singular terminal SMC [17], fast integral terminal



**Citation:** Benbouhenni, H.; Bizon, N. Improved Rotor Flux and Torque Control Based on the Third-Order Sliding Mode Scheme Applied to the Asynchronous Generator for the Single-Rotor Wind Turbine. *Mathematics* **2021**, *9*, 2297. https:// doi.org/10.3390/math9182297

Academic Editors: Francesc Pozo and Amir Mosavi

Received: 8 August 2021 Accepted: 13 September 2021 Published: 17 September 2021

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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). SMC [18], and fast terminal SMC technique [19] are available in the references abovementioned, but also in other works. These techniques are used to improve the performance of electric machines. There are several proposed techniques for controlling and reducing torque ripples, and these methods are divided into two main classes, namely, direct control and indirect control such as DFTC in the first class, and direct power control (DPC) and field-oriented control (FOC) in the second class. For the two methods in the second class, DPC and FOC, the active and reactive power are controlled. As is well-known, the torque is related to the active power and its reference value. In [20], the authors proposed using the virtual flux DPC control (VF-DPC) to minimize the electromagnetic torque of the AGbased wind power. This proposed strategy further minimizes torque ripple compared to the classic DPC method. On the other hand, the VF-DPC is easy to implement. In [21], a new DPC technique was proposed based on the terminal synergetic control theory to reduce ripples of rotor flux, current, and electromagnetic torque. This designed strategy was more robust compared to the traditional DPC strategy and other strategies such as the traditional DFTC and FOC control. A new FOC method was proposed in [22] to minimize the ripples of active power, current, rotor flux, and electromagnetic torque of the induction generator. This designed FOC strategy based on a hysteresis rotor current controller and experimental results showed the performance of the designed strategy. Another intelligent robust technique was designed in [23] to control and reduce the rotor flux and torque of the induction generator. The proposed method was a combination of two different methods. The first method was the SMC technique, where durability is its biggest advantage compared to its counterparts. Regarding the second method, it was based on fuzzy logic, where simplicity is the biggest advantage that distinguishes it compared to other methods. The obtained method was more robust, and the simulation results showed its effectiveness in reducing the value of harmonic distortion (THD) of the current compared to the traditional strategy. The second-order continuous SMC technique (SOCSMC) was proposed to improve the performances of the DFTC control of the induction generator [24]. The designed strategy minimizes the ripples of rotor flux, stator current, and electromagnetic torque compared to the traditional DFTC strategy with proportionalintegral (PI) controllers. Although the designed strategy is simpler, more robust, and easier to implement, the THD value remains quite high. Additionally, it does not completely remove the torque ripples of the electric machine. DPC control with PI controllers (DPC-PI) reduces the ripples of electromagnetic torque, rotor flux, and stator current compared to traditional DPC and FOC strategies [25]. The experimental results showed a better performance obtained for the DPC-PI strategy, which is also easier to implement compared to traditional direct and indirect FOC strategies. In [26], the author combined two methods, different in principle, in order to obtain a more robust method. Thus, the SMC method was incorporated into the DTC method. One of the advantages of the resulting method is that it obtains much lower current ripples than in the classical method [26]. Moreover, the method obtained is very simple and can be easily accomplished.

Another robust strategy was proposed in [27] to minimize the ripple of electromagnetic torque of the induction generator-based dual-rotor wind power. This proposed method combines two different nonlinear methods: the SMC method, where chattering phenomenon is its biggest disadvantage compared to other nonlinear methods, and the synergetic control method, where simplicity is the biggest advantage that distinguishes it compared to other nonlinear methods. The resulting nonlinear strategy reduces the ripple of electromagnetic torque, stator current, and rotor flux compared to traditional direct FOC control and other strategies such as the DFTC, FOC, and SMC methods. However, the proposed nonlinear strategy is more robust and easier to implement and further reduces the chattering phenomenon compared to traditional SMC control. Using a research direction similar to the one in [27], the merger between the synergetic control and super twisting algorithm was proposed to reduce the ripple of electromagnetic torque of the AG-based dual-rotor wind turbine [28]. This proposed nonlinear strategy is more robust compared to traditional controllers such as the PI controller and SMC. Super Twisting algorithm (STA)- based SOSM controllers have been proposed to control the AG-based wind power [29]. In order to show the effectiveness and superiority of the designed controller, the thermal exchange optimization (TEO) method was used. The integral sliding-mode DFTC method (ISM-DFTC) with space-vector modulation (SVM) for AG-based wind turbine conversion systems under unbalanced grid voltage was designed in [30]. This proposed DFTC method minimizes the torque ripples compared to the traditional DFTC strategy.

In this paper, a new high-order SMC technique was proposed and designed to improve the characteristics of the DFTC control and reduce the rotor flux, current, and torque ripples of the AG-based wind power. Compared to the classical SMC technique, the chattering phenomenon was reduced or eliminated. This proposed control technique was based on a super twisting algorithm (STA) applied for the third-order sliding mode controller (TOSMC) technique, called below as the DFTC-TOSMC method. In order to improve the performance of the conventional DFTC technique, the standard hysteresis comparators will be replaced by two TOSMC methods and the switching table by the SVM technique. The rotor flux and electromagnetic torque estimation block maintain the same shape as that established for classical DFTC, as described in [31,32]. In this DFTC control strategy, the rotor flux and torque are regulated by two proposed TOSMC regulators, while the SVM technique replaces the traditional switching table. The principle as well as the advantages and disadvantages of the DFTC-TOSMC method have been comparatively analyzed with other advanced control strategies proposed in the literature [10,20-29]. The main contributions of the proposed designed control scheme are to minimize the total harmonic distortion (THD) of current for an AG-based SRWP system, increases the robustness and stability of the controlled system, provides methodical and less-complicated techniques based on a novel SOSMC method to adjust the rotor voltage of DFIG, and reduced ripples of both rotor flux and electromagnetic torque.

The parameters used to observe the performance of the designed strategy are the total harmonic distortion (THD) for current, torque ripple, steady-state error, response time, and rotor flux undulations. The DFTC-PI structure shown in Figure 1 is the system considered in this paper as a reference to compare the improved performances of the proposed DFTC-TOSMC method.



Figure 1. Structure of the DFTC strategy with PI controllers.

In summary, the novelty and main findings of this paper are as follows:

 A new TOSMC method based on the DFTC method was designed to minimize ripples of both rotor flux and electromagnetic torque;

- Third-order sliding mode controllers reduces the tracking error for rotor flux and electromagnetic torque toward the references of AG-based SRWT systems; and
- The DFTC-TOSMC method with SVM strategy reduces harmonic distortion of the stator current and torque ripple of AG-based SRWT systems.

Thus, the rest of the paper is structured as follows. Section 2 presents models of single-rotor wind systems. The model of the AG is presented in Section 3 using Park transformations. The proposed TOSMC technique is presented in Section 4. DFTC-TOSMC control of the AG-based SRWP is presented in Section 5. Sections 6 and 7 present and discuss the results of the research carried out.

## 2. Single-Rotor Wind Power

Equation (1) expresses the power obtained from a wind turbine [33]:

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

where  $\lambda$  is the tip speed ration; *R* is the radius of the turbine (m);  $\rho$  is the air density (kg/m<sup>3</sup>); *V* is the wind speed (m/s);  $\beta$  is the blade pitch angle (deg); and *C*<sub>*P*</sub> is the power coefficient.

Equation (2) expresses the  $C_P$  of the wind turbine. The  $C_P$  is a nonlinear function [34]:

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

The  $\lambda$  is given by:

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

where  $\Omega_t$  is the rotational speed of the SRWP.

## 3. The AG Model

The asynchronous generator is one of the most popular and widely used in the field of wind energy due to its low maintenance, reduced cost, robustness, efficiency, ease of control, minimum energy losses, and ability to work at a speed that varies by  $\pm 33\%$ around the synchronous speed [35]. On the other hand, this is evident in the number of papers published on AG, where several controls have been developed in order to improve the characteristics of this generator [36–40]. In order to obtain the mathematical form of the generator, the Park transform was used. The following equations represent the mathematical form of the generator [41,42]:

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

$$\begin{cases}
\Psi_{dr} = MI_{ds} + L_r I_{dr} \\
\Psi_{qr} = L_r I_{qr} + MI_{qs} \\
\Psi_{qs} = MI_{qr} + L_s I_{qs} \\
\Psi_{ds} = MI_{dr} + L_s I_{ds}
\end{cases}$$
(5)

The electric machine consists of two main parts: the electrical part, and the mechanical part. The electrical part is represented in the equations of tension and flux, while the mechanical part of the electric machine is represented in the following equation:

$$T_e - T_r = J \frac{d\Omega}{dt} + f\Omega \tag{6}$$

Torque can be given by the following equation:

$$T_e = 1.5 \ p \frac{M}{L_s} \left( -\Psi_{sd} I_{rq} + \Psi_{sq} I_{rd} \right) \tag{7}$$

#### 4. Third-Order Sliding Mode Controller

There are many controllers proposed to regulate and reduce the torque of AC machines in the literature. Among all the techniques designed for the high-order SMC technique, the STA strategy is an exception, which only requires information on the nonlinear surface [43]. The proposed high-order SMC controller, named the third-order sliding mode controller (TOSMC), is an effective strategy for uncertain systems and overcomes the main drawbacks of the classical SMC technique described in the literature. TOSMC is a robust strategy and is an alternative to non-linear and linear strategies. In the STA strategy, the command input applies to the second-order derivative of the nonlinear surface, and reverses the SMC, which acts on the first derivative of the sliding surface. The proposed TOSMC technique is based on the STA algorithm. The control input of the proposed TOSMC technique uses the sum of three inputs, as defined below:

$$u(t) = u_1 + u_2 + u_3 \tag{8}$$

$$u_1(t) = \lambda_1 \sqrt{|S|} sign(S)$$
(9)

$$u_2(t) = \lambda_2 \int sign(S)dt \tag{10}$$

$$u_1(t) = \lambda_1 \sqrt{|S| sign(S)}$$
(11)

The control input of the proposed TOSMC method is obtained as Equation (12).

$$u(t) = \lambda_1 \sqrt{|S|} sign(S) + \lambda_2 \int sign(S) dt + \lambda_3 sign(S)$$
(12)

where *S* is the sliding surface.

The tuning constants  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  were used to improve the performance of the TOSMC method. Therefore, this was the design process using TOSMC for the DFTC strategy. Figure 2 shows the structure of the TOSM controller for the DFTC strategy in wind power systems.



Figure 2. The command law structure of the proposed TOSM controller.

The stability condition is given by:

$$S \times S < 0 \tag{13}$$

This proposed controller was used in this paper to reduce the THD of the current and ripples of the electromagnetic torque and rotor flux in the case of an AG-based SRWP system using the DFTC technique. Note that the inverter was controlled by the SVM strategy.

## 5. DFTC-TOSMC Control of the AG-Based SRWP

The traditional DFTC technique has been developed and investigated as a replacement for the classical FOC method in high-performance AC machine drives. DFTC is well-known for its robust strategy, simple algorithm, and fast-flux/torque response, which requires no

modulation techniques, current control, or coordinate transformation [44]. This method has been applied to several electric machines such as induction motor [45], a brushless DC electric motor [46], interior permanent magnet synchronous motor [47], five-phase induction motor [48], brushless doubly-fed machine [49,50], permanent magnet synchronous motor (PMSM) [51], six-phase induction motor [52], and five-phase PMSM [53,54]. In [55], the DFTC control scheme reduced the electromagnetic torque, stator current, and rotor flux compared to the FOC method. The DFTC strategy was designed based on a model predictive controller [56]. This proposed DFTC is simpler and, in addition, reduces the torque ripple compared to the classical DFTC strategy. A DFTC method with a modified finite set model predictive technique was designed in [57]. Simplicity and durability are the two main advantages of this proposed method. A flexible switching table (FST) was designed for the DFTC method applied to PMSMs to enhance the dynamic performances and steady-state of the drive system [58]. The simulation results showed that the proposed method improved the efficiency of the electric machine.

Despite the many advantages that characterize the DFTC method, there are several problems that characterize it, for example, high ripples in rotor flux and torque, several current harmonics, and low-speed problems. Torque ripples represent the major problem of the traditional DFTC strategy, which can be very hurtful for the AG because of the use of hysteresis comparators and switching table or PI controllers [59]. Some solutions have been designed to avoid this disadvantage [60–65]. The essential idea was to replace the switching table and hysteresis comparators with intelligent techniques and at the same time conserve the essential performance of the traditional method.

In this section, a new DFTC control scheme was designed based on TOSMC techniques. In order to improve the performance of the classical DFTC strategy, the standard hysteresis comparators were replaced by two TOSMC controllers and the switching table by the traditional SVM strategy. The electromagnetic torque and rotor flux estimation block keep the same shape as that established for traditional DFTC with PI controllers, as described in [66,67]. In this proposed DFTC control strategy, the electromagnetic torque and rotor flux are regulated by two proposed TOSMC controllers, while the SVM technique replaces the switching table. However, this control by DFTC-TOSMC or DFTC-SVM-TOSMC has the advantages of vector control and conventional DFTC to overcome the problem of fluctuations in rotor flux and electromagnetic torque generated by the DFIG. TOSMC regulators and SVM techniques were used to obtain a fixed switching frequency and less pulsation of the rotor flux and torque.

This proposed strategy can be minimized more than the electromagnetic torque and rotor flux compared to traditional DFTC and strategies such as FOC, DPC control, and other control techniques. The DFTC-TOSMC principle is proposed to control the rotor flux and the torque of the AG-based SRWT systems. The electromagnetic torque is regulated utilizing the quadrature axis voltage  $V_{qr}^*$ , while the flux is regulated utilizing the direct axis voltage  $V_{dr}^*$ .

In this paper, we proposed the use of a new nonlinear controller (based on the TOSMC technique) to replace the conventional PI controllers.

The designed DFTC-TSOMC strategy is shown in Figure 3 and was designed to reduce the undulations of the torque and rotor flux of an AG, as presented below.

The estimation of the rotor flux can be done in different ways using the voltage model, and the rotor flux can be estimated by integrating from the rotor voltage equation.

$$Q_r = \int_0^t (V_r - R_r i_r) dt \tag{14}$$

In the reference  $(\alpha - \beta)$ , the components of the rotor flux are determined as follows:

$$\begin{cases} Q_{r\alpha} = \int_0^t (V_r - R_r i_{r\alpha}) dt \\ Q_{r\beta} = \int_0^t (V_r - R_r i_{r\beta}) dt \end{cases}$$
(15)

where 
$$V_r = V_{r\alpha} + jV_{r\beta}$$
;  $i_r = i_{r\alpha} + ji_{r\beta}$ ;  $Q_r = Q_{r\alpha} + jQ_{r\beta}$ .

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Figure 3. Bloc diagram of the AG with the DFTC-TOSMC method.

From these two equations, the modulus of the rotor flux and the angle  $\theta r$  result is as follows:

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$$Q_r| = \sqrt{\left(Q_{r\beta}^2 + Q_{r\alpha}^2\right)} \tag{16}$$

$$\theta r = artg \frac{Q_{r\beta}}{Q_{r\alpha}} \tag{17}$$

The errors of the flux and electromagnetic torque are shown in Equations (18) and (19).

$$S_{Tem} = T_{em}^* - T_{em} \tag{18}$$

$$S_{Qr} = Q_r^* - Q_r \tag{19}$$

where the surfaces are the flux magnitude error  $S_{Qr} = Q_r^* - Q_r$  and the electromagnetic torque error  $S_{Tem} = T_{em}^* - T_{em}$ .

The errors shown in Equations (18) and (19) were used as input to the TOSMC techniques. Electromagnetic torque and rotor flux TOSMC regulators were used to respectively influence the  $V_{dr}^*$  and  $V_{qr}^*$  as in Equations (20) and (21):

$$V_{dr}^* = \lambda_1 \sqrt{|S_{Qr}|} sign(S_{Qr}) + \lambda_2 \int sign(S_{Qr}) dt + \lambda_3 sign(S_{Qr})$$
(20)

$$V_{qr}^* = \lambda_1 \sqrt{|S_{Tem}|} \cdot sign(S_{Tem}) + \lambda_2 \int sign(S_{Tem}) dt + \lambda_3 sign(S_{Tem})$$
(21)

The TOSMC controller structure for the torque and flux of the DFTC strategy are presented in Figures 4 and 5, respectively.

This proposed controller was applied for a DFTC strategy based on the TOSMC technique to obtain a minimum torque ripple and to minimize the chattering phenomenon.



Figure 4. Proposed TOSMC torque controller.



Figure 5. Proposed TOSMC flux controller.

### 6. Analysis of the Simulation Results

This work aimed to reduce the flux and torque ripples of an asynchronous generator. The latter operated at nominal speed. The values of the electric machine elements are shown in Table A1 (see Appendix A). A generator with a power of 1.5 megawatts was used, operating under a voltage of 380 V, and the frequency of the network was 50 Hz. The two DFTC techniques, DFTC-PI and DFTC-TOSMC, were studied, simulated, and compared in terms of torque ripple, reference tracking, THD value of the current, and rotor flux ripple.

The results obtained by using the MATLAB/Simulink<sup>®</sup> software are shown in Figures 6–10. The Simulink diagrams presented above and built-in MATLAB functions were run on a personal computer with an Intel<sup>®</sup> Core<sup>TM</sup> i9-9900K processor. Looking at Figures 8 and 9, it is worth noting that the rotor flux and electromagnetic torque for the designed DFTC techniques followed their reference values almost perfectly.



Figure 6. THD value of the stator current (DFTC-PI).



Figure 7. THD value of the stator current (DFTC-TOSMC).



Figure 8. Electromagnetic torque.



Figure 9. Rotor flux.



Figure 10. Stator current.

Figure 10 shows the stator current of the designed DFTC strategies and it can be seen that the current was correlated with the torque and flux reference values.

Figures 6 and 7 show the THD value of the stator current of the designed DFTC techniques. It is worth noting that the THD value was lower for DFTC-TOSMC (0.19%) when compared to DFTC-PI (0.54%).

The zoom in the torque, flux, and current is shown in Figures 11–13, respectively. The DFTC-TOSMC technique minimized the undulations in torque, flux, and current compared to the DFTC-PI technique.



Figure 11. Zoom in the torque.



Figure 12. Zoom in the rotor flux.



Figure 13. Zoom in the stator current.

## 7. Discussion

Based on the above results, it can be said that the DFTC-TOSMC strategy has proven its effectiveness in minimizing undulations and the chattering phenomenon, in addition to keeping the other advantages of the DFTC-PI technique. This proposed strategy minimized the THD value of stator current compared to other strategies (see Table 1).

Reference	Strategy	THD (%)
Ref. [20]	DPC	4.88
	VF-DPC	4.19
Ref. [21]	DPC-TSC	0.25
Ref. [10]	PI controller	0.77
	STA-SOSMC controller	0.28
Ref. [22]	FOC	3.70
Ref. [23]	Fuzzy SMC control	3.05
Ref. [24]	DFTC-SOCSMC	0.98
Ref. [25]	DPC-IP	0.43
Ref. [26]	DFTC	1.45
Ref. [27]	Direct FOC with synergetic sliding mode controller	0.50
Ref. [32]	Two-level DFTC method	9.87
	Three-level DFTC method	1.52
Ref. [36]	DFTC method	7.54
	DFTC method with genetic algorithm	4.80
Ref. [66]	Traditional DFTC strategy	6.70
	Fuzzy DFTC technique	2.04
Ref. [68]	FOC with Type 2 fuzzy logic controller (FOC-T2FLC)	1.14
	FOC with neuro-fuzzy controller (FOC-NFC)	0.78
Ref. [69]	ISMC	9.71
	MRSMC	3.14
Ref. [70]	DPC control with intelligent metaheuristics	4.05
Proposed strategy	DFTC-TOSM	0.19

**Table 1.** Comparison of the THD values obtained from the proposed method with values from several published methods.

The FOC-T2FLC strategy [68] is used as a reference strategy in the same class as the FOC-NFC strategy. The multi-resonant sliding mode controller (MRSMC) and the integral sliding mode controller (ISMC) have been proposed for the DFIG-based wind system in unbalanced and harmonic grid conditions [69].

Table 2 presents a brief comparative study using the simulation results of Figures 6–13. It is clear that the designed DFTC technique based on TOSMC controllers was more robust than the traditional one using the PI controller, except for the dynamic response, which was faster in TOSMC than PI. The analytical reason that proves that the overshoot is very small in the designed DFTC technique using TOSMC is the absence of zero in the transfer function of this one. On the other hand, the designed DFTC technique based on TOSMC controllers improved the rise time, THD, torque and flux tracking, transient performance, quality of stator current, sensitivity to a parameter change, and settling time compared to the DFTC with PI controllers.

Critoria	Control		
Cmena	DFTC-PI	DFTC-TOSMC	
Dynamic response (s)	Medium	Fast	
Settling time (ms)	High	Medium	
Overshoot (%)	Remarkable $\approx 22\%$	Neglected near $\approx 1.5\%$	
Torque and flux tracking	Good	Excellent	
Sensitivity to parameter change	High	Medium	
Rise Time (s)	High	Medium	
THD (%)	0.54	0.19	
Simplicity of converter and filter design	Simple	Simple	
Torque: ripple (N.m)	Around 500	Around 60	
Simplicity of calculations	Simple	Simple	
Rotor flux: ripple (wb)	Around 0.006	Around 0.004	
Improvement of transient performance	Good	Excellent	
Reduce torque and flux ripples	Acceptable	Excellent	
Quality of stator current	Acceptable	Excellent	

Table 2. Comparison of the results obtained from the proposed method with the classical method.

## 8. Conclusions

The paper addressed a third-order sliding mode control-based STA technique for a DFTC technique used in wind power. An SVM technique was used for controlling the inverter of AG-based SRWP systems. The mathematical design of the proposed TOSMC technique was discussed in detail for the DFTC technique. The controller was applied both on the torque and flux to regulate the direct and quadrature rotor voltage and also to minimize the undulations in stator current, electromagnetic torque, and rotor flux of the AG. The proposed strategy minimized the THD value of stator current compared to traditional DFTC, FOC, DPC, FSMC, and DFTC-SOCSMC methods (see Table 1). The proposed DFTC technique has improved the robustness of the traditional DFTC method, increasing its performances in transient and dynamic conditions in terms of efficiency, rapidity, overshoot, rise time, and stability. It was observed that this designed DFTC technique is robust with less steady-state error and less settling time compared to a traditional PI controller (for more information, see Table 2). On the other hand, this proposed strategy is a simple structure, no dynamic coordinate transforms are needed, no PI current controllers, and the switching frequency of the transistors is constant. At higher speeds, the proposed technique is not sensitive to any generator parameters. Good tracking capabilities of the desired variable, very fast steady-state reaching speed, robust dynamic nature of the controller, and also the elimination of chattering problem in SMC were realized. Zoom has been shown to compare and highlight its performance. This controller can be an alternative to STA. This proposed controller can be applied to direct power control and a field-oriented control scheme. A comparison was undertaken concerning the PI controller in terms of ripple, tracking, and output current THD for use of this proposed controller for the DFTC technique. Indeed, this proposed DFTC technique deserves attention because it solves the problem of high ripples torque and flux for wind turbines.

The current research work is limited given that the wind speed was fixed. Furthermore, the designed DFTC control scheme investigated a high voltage dip condition. Robustness enhancement of the AG-SRWP system under the previous concerns will be carried out in future papers. This will be implemented through interactions among AGs with various strategies such as neural algorithm, fractional-order PI, and a type 2 fuzzy logic controller.

- Therefore, in summary, the main findings of this research are as follows:
- Reduces the electromagnetic torque and rotor flux;
- Simple control was proposed;

- Minimization of the total harmonic distortion of stator current by 64.81%; and
  - A new nonlinear controller was presented and confirmed with numerical simulation.

The paper can be extended with fuzzy-TOSMC controllers (FTOSMC) to obtain zero settling time, minimum torque ripple, and zero steady-state error. DPC-based TOSMC controllers can also be taken up as an extension of this paper.

**Author Contributions:** Conceptualization, H.B.; Methodology, H.B.; Software, H.B.; Validation, N.B.; Investigation, H.B.; Resources, H.B. and N.B.; Data curation, N.B.; Writing—original draft preparation, H.B.; Supervision, N.B.; Project administration, N.B.; Formal analysis: N.B.; Funding acquisition: N.B.; Visualization: N.B.; Writing—review and editing: N.B. and H.B. All authors have read and agreed to the published version of the manuscript.

Funding: There is no funding available for this.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

#### List of Symbols

$\phi_r, \phi_r^*$	Actual and reference rotor flux	
$V_s$ , $I_s$	Vectors of the stator voltage and current	
$Vr_{a,b,c}$ , $Ir_{a,b,c}$	Rotor voltage and current in <i>abc</i> frame	
$V_{\alpha,\beta}, I_{\alpha,\beta}$	Voltage and current in $\alpha\beta$ frame	
$T_e, T_e^*$	Actual and reference torques	
$\omega_n, \omega_r$	Nominal and rotor speeds	
$R_s, R_r$	Stator and rotor resistances	
$\phi_{\alpha s}, \phi_{\beta s}$	Stator flux components in $\alpha\beta$ frame	
$\theta r$	Rotor flux angle	
Ki, Kp	Integral and proportional gains	
Lr, Ls, Lm	Rotor, stator and mutual inductances	
р	Generator pole pairs	
Wb	Weber (unit)	
Hz	Hertz (unit)	
Mw	Migawatt (Unit)	
mH	Millihenry (unit)	
N.m	Newton-meter (Unit)	

#### List of Acronyms

DTC	Direct torque control
PI	Proportional integral
DPC	Direct power control
SMC	Sliding mode control
DFTC	Direct flux and torque control
THD	Total harmonic distortion
SOCSMC	Second-order continuous sliding mode control
FOC	Field oriented control
FSMC	Fuzzy sliding mode control
SVM	Space vector modulation
IP	Integral-proportional
AG	Asynchronous generator
TOSMC	Third-order sliding mode controller
STA	Super twisting algorithm
THD	Total harmonic distortion
ISM	Integral sliding mode.
MRSMC	Multi-resonant-based sliding mode controller
ISMC	Integral sliding mode controller.

# Appendix A

Table A1. The AG parameters [22,27,71].

P_SRWT	1.5 MW
Pn	1.5 MW
Rs	0.012 Ω
Ls	0.0137 H
Lm	0.0135 H
Rr	0.021 Ω
Lr	0.0136 H
fr	0.0024 Nm·s/rad
$V_n$	380 V
р	2
Ω	150 rad/s
F	50 Hz

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