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Sliding-mode assisted direct torque control for reliable wind turbine operation

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ABSTRACT

This paper investigates and compares the performance of two advanced control strategies, direct torque control (DTC) and sliding mode control (SMC), applied to a permanent magnet synchronous generator (PMSG) used in wind energy conversion systems. The control schemes aim to ensure efficient energy conversion and stable operation under variable wind conditions. The comparison is carried out through detailed simulations considering electromagnetic torque response, stator flux behavior, speed regulation, and robustness to disturbances and parameter variations. The results show that DTC provides a fast dynamic response with a relatively simple control structure, but suffers from torque and flux ripples and sensitivity to parameter variations. In contrast, SMC demonstrates higher robustness against uncertainties and disturbances, with smoother torque characteristics and improved speed regulation. Overall, the study indicates that SMC is a promising approach for enhancing the stability and performance of PMSG-based wind energy systems. Future work may explore hybrid strategies combining the fast response of DTC with the robustness of SMC, as well as intelligent control techniques to further optimize energy extraction.

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1. INTRODUCTION

The growing global demand for clean and sustainable energy has intensified research efforts toward improving the performance of wind energy conversion systems (WECS) (Figure 1). Among the various technologies used in wind power generation, wind turbines equipped with permanent magnet synchronous generators (PMSGs) have gained considerable attention due to their high efficiency, compact structure, reduced maintenance requirements, and excellent dynamic performance. However, the effective control of PMSG-based wind turbine systems remains a significant challenge because of the nonlinear characteristics of the machine, parameter uncertainties, and the highly variable nature of wind conditions.

Conventional linear control techniques such as proportional–integral (PI) and proportional–integral–derivative (PID) controllers are widely used in electrical drive systems. Nevertheless, these controllers often show limited performance when dealing with nonlinearities, parameter variations, and external disturbances commonly encountered in wind energy applications [1]. Consequently, advanced nonlinear control strategies have been increasingly investigated to improve the robustness and dynamic response of such systems.

Among these strategies, direct torque control (DTC) and sliding mode control (SMC) [2], [3] have emerged as promising approaches for the control of permanent magnet synchronous machines (PMSM). DTC is particularly attractive because of its simple control structure and fast dynamic response, as it directly regulates the electromagnetic torque and stator flux without requiring current control loops or coordinate transformations. Despite these advantages, classical DTC suffers from certain drawbacks, such as torque and flux ripples as well as sensitivity to parameter variations. On the other hand, SMC is well known for its strong robustness against model uncertainties and external disturbances. Its nonlinear control structure allows the system to maintain stable operation even under severe operating conditions. As a result, SMC has been widely investigated and applied in electric drive systems to enhance performance and reliability [4].

Several studies in the literature have explored the application of these control strategies to PMSM. For instance, some works have investigated DTC algorithms for multi-phase PMSM supplied by multiple inverters, highlighting their potential for high-power industrial applications such as traction and naval propulsion [5], [6]. Other studies have focused on improving SMC techniques, including the development of super-twisting sliding mode controllers and compensation strategies to reduce speed overshoot and improve dynamic performance. Additionally, hybrid approaches combining DTC with sliding mode techniques have been proposed to reduce torque ripple, stabilize switching frequency, and enhance overall system robustness.

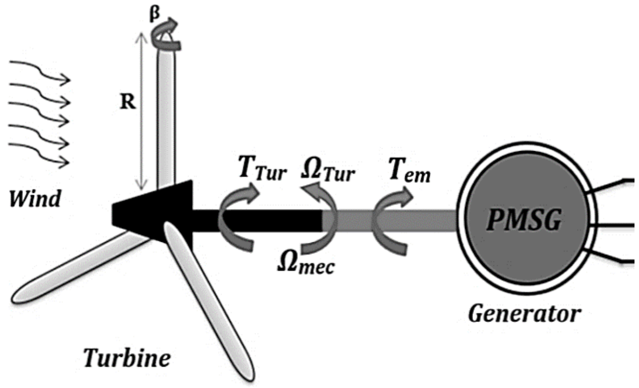

Figure1. PMSG connected to the wind turbine

Despite the considerable research conducted in this area, a comprehensive comparative evaluation of DTC and SMC when applied to PMSG-based wind turbine systems remains an important topic for investigation. Therefore, this work aims to analyze and compare the performance of DTC and SMC applied to a PMSG used in wind energy conversion systems [7]-[9]. The comparison focuses on key performance criteria including torque response, stator flux behavior, speed regulation, and robustness under disturbances and parameter variations. The results provide valuable insights into the advantages and limitations of each control strategy and their suitability for modern wind turbine applications.

2. METHOD

The methodology adopted in this study is structured around four main components. First, the modeling of the PMSM is developed based on fundamental electromagnetic principles, allowing an accurate representation of the electrical and mechanical dynamics of the system. Then, the synchronous machine theory [10]-[12] and its mathematical modeling are presented using the dq reference frame, which simplifies the analysis and control design by transforming the three-phase variables into a two-axis rotating coordinate system. Subsequently, an SMC strategy is designed to ensure robust performance against parameter uncertainties and external disturbances, with a particular focus on achieving precise tracking of reference signals. Finally, simulation results are analyzed to evaluate the effectiveness of the proposed control approach in terms of dynamic response, stability, and tracking accuracy. The overall study is concluded by highlighting the advantages and potential improvements of the implemented method.

3. MODELING OF PERMANENT MAGNETIC SYNCHRONOUS MACHINE

The modeling of a PMSM involves developing a mathematical representation, often using the d-q reference frame and Park's transform [13]-[15], to describe its electrical and mechanical behavior. This model typically includes differential equations for voltages, currents, and flux linkages, as well as a torque equation, to facilitate analysis, design, and control of the motor for applications like electric vehicles [16].

The electric and magnetic equations permanent magnet synchronous motor in dq frame (Figure 2) are expressed as (1)-(4).

$$\Phi_d = L_d i_d + \varphi_f \quad (1)$$

$$\Phi_q = L_q i_q \quad (2)$$

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \quad (3)$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \Phi_d \quad (4)$$

The equivalent circuit of the permanent magnet synchronous motor is shown in Figure 3. The electromagnetic torque of the PMSM is given by (5).

$$T_e = p\{(L_d - L_q) i_d\, i_q + \Phi_f i_q\} \quad (5)$$

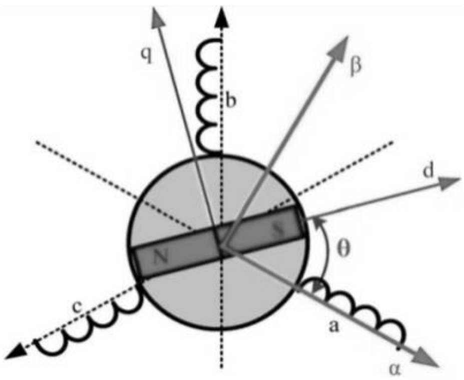

Figure 2. Representation of the synchronous motor permanent magnet [16]

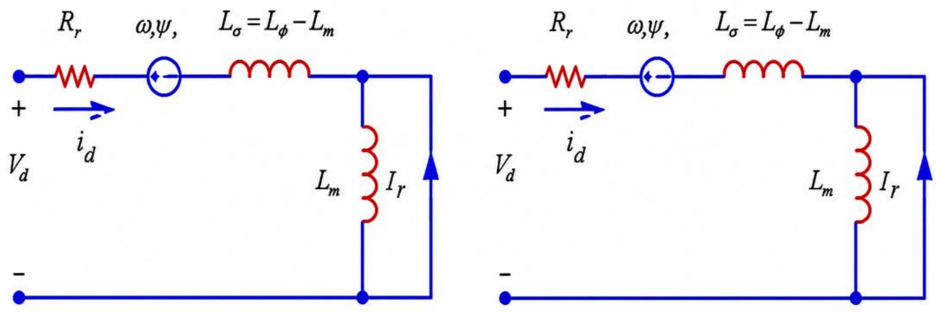

Figure 3. Modeling of the PMSM in the d-q frame

3.1. Characterization of manufactured terracotta briquettes control of stator flux

The stator flux vector can be estimated using the measured current and voltage vectors. The estimation is performed as described in [17], [18]. The differential and integral forms of the stator flux estimation are given in (6) and (7), respectively.

$$\frac{d\varphi_s(t)}{dt} = V_s - R_s I_s \quad (6)$$

$$\varphi_s(t) = \int_0^t (Vs - R_s I_s)dt \quad (7)$$

Neglecting the stator resistance, we find (8).

$$\varphi_s(t) = \varphi_{s0} + \int_0^t V sdt \quad (8)$$

Where φ_{s0} is the initial stator flux linkage at the instant of switching, during the switching interval, each voltage vector is constant and the stator flux linkage of a PMSM can be expressed in the Stationary reference frame as (9) and (10) [19].

$$\varphi_s(K+1) = \Phi_s(K) + V_s T \quad (9)$$

$$\Delta\varphi_s = \varphi_s - \varphi_{s0} = V_s T \quad (10)$$

The (10) implies that the end of the stator flux vector will move in the direction of the applied voltage vector.

3.2. Electromagnetic torque control

Electromagnetic torque control is a key aspect in achieving precise regulation of the dynamic behavior of electrical machines, particularly in applications such as wind turbines, where rapid variations in operating conditions occur. The objective of torque control is to ensure that the machine develops the required torque in response to load and speed demands, while minimizing oscillations and maximizing efficiency. One of the most widely applied strategies for this purpose is DTC, which enables fast and accurate adjustment of both torque and flux without requiring complex coordinate transformations or current regulators. In the DTC approach, the electromagnetic torque and the stator flux linkage are continuously estimated from measured voltages and currents. These estimated values are then compared against their respective reference values [20]. The differences, defined as torque error and flux error, are used as inputs to two hysteresis comparators. The torque hysteresis controller ensures that the developed torque remains within the prescribed band around its reference, while the flux hysteresis controller regulates the amplitude of the stator flux linkage [21], [22]. The outputs of the hysteresis comparators are then used to determine the appropriate switching state of the voltage source inverter through a table of optimum switching (TOS). This switching table maps the torque and flux error signals to the most suitable voltage vector that will correct the deviations. By dynamically selecting the inverter switching states, the DTC method ensures direct control of electromagnetic torque and stator flux without the need for intermediate current controllers or modulation stages.

The main advantages of electromagnetic torque control using DTC include: i) Fast torque response**,** owing to the direct control structure; ii) Robustness against parameter variations**,** especially stator resistance; iii) Simplified control implementation, avoiding the complexity of traditional field-oriented control. However, DTC is also associated with certain drawbacks such as torque and flux ripples due to the use of hysteresis controllers and variable switching frequency. These limitations motivate the exploration of more advanced nonlinear control strategies, such as SMC, which can enhance performance by reducing oscillations and improving system robustness [23], [24]. The hysteresis-based decision rules for stator flux and electromagnetic torque control are summarized in (11).

$$\begin{aligned}
&if \quad |\varphi sref| - |\varphi s| \leqq \Delta\varphi \quad then\ d\varphi s = 0\\
&If \quad |\varphi sref| - |\varphi s| \geqq \Delta\varphi \quad then\ d\varphi s = 1\\
&If \quad |Tref| - |Test| < |\Delta Te| \quad then\ dTe = -1\\
&If \quad |Tref| - |Test| = |\Delta Te| \quad then\ dTe = 0\\
&If \quad |Tref| - |Test| > |\Delta Te| \quad then\ dTe = 1
\end{aligned} \quad (11)$$

4. SYNCHRONOUS MACHINE THEORY AND MODELING

A synchronous machine is an electromechanical device that operates at a speed directly proportional to the frequency of the supply voltage, known as the synchronous speed [25], [26]. Depending on the rotor construction, synchronous machines are classified into two main categories: machines with a salient-pole (reluctance) rotor and those with a permanent magnet rotor. In this study, the focus is placed on the PMSM due to its high efficiency, compact size, and superior dynamic performance in renewable energy applications such as wind turbines.

The PMSM consists of a rotor embedded with permanent magnets, which establish a constant magnetic field. The rotor poles are distributed axially and symmetrically around the rotor surface, ensuring uniform flux distribution in the air gap. In synchronous operation, the interaction between the stator is rotating magnetic field, generated by the three-phase AC supply, and the rotor's stationary magnetic field produced by the permanent magnets results in the generation of electromagnetic torque. This torque is the fundamental mechanism by which electrical energy is converted into mechanical energy.

The angular speed of the PMSM is locked to the supply frequency of the stator voltages, meaning that the rotor operates synchronously with the rotating magnetic field. To achieve the desired speed or torque, the phase voltages must be adjusted according to the rotor angular position. Therefore, accurate measurement or estimation of the rotor position is required, typically performed using encoders, Hall-effect sensors, or observer-based estimators. Unlike induction machines, which allow slip between the rotor and the stator fields, PMSMs operate strictly at synchronous speed. Dynamic variations in speed are obtained by controlling the supply frequency of the three-phase stator voltages. This feature makes PMSMs highly suitable for variable-speed wind energy systems, where power electronic converters can regulate frequency and voltage according to wind conditions. For control and analysis, the dynamic model of the Permanent PMSG is often expressed in the d-q rotating reference frame. In this frame, the q-axis leads the d-axis by 90° with respect to the direction of rotation, simplifying the representation of voltages, currents, and flux linkages. The mathematical formulation provides a foundation for analyzing and controlling PMSMs under variable operating conditions. By transforming the machine model into the d-q reference frame, the system becomes easier to control while preserving accuracy in representing its dynamic behavior. This framework is essential for implementing advanced control techniques such as DTC and SMC in wind energy applications [24]. The mathematical model of the PMSM in the d-q reference frame is given by (12)–(15).

$$V_d = R_s I_d + \frac{d\varphi_d}{dt} - w_r \varphi_q \tag{12}$$

$$V_q = R_s I_q + \frac{d\varphi_q}{dt} - w_r \varphi_d \tag{13}$$

$$\varphi_d = L_d I_d + \varphi_q \tag{14}$$

$$\varphi_q = L_q I_q \tag{15}$$

The electromagnetic torque T_e is given by (16) [24], [25].

$$T_e = \frac{3}{2} P(\left(L_d - L_q\right) I_d I_q + I_q \varphi \tag{16}$$

5. DESCRIPTION OF SLIDING MODE CONTROL

The implementation of this control method requires mainly three steps.

5.1. Sliding surfaces

They propose a form of general equation to determine the sliding surface [26]. The mathematical formulation of the sliding surface, error function, and Lyapunov stability condition is presented in (17)–(19).

$$s(x,t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(t) \tag{17}$$

Here, $e(t)$ is the error in the output state and λ is a positive coefficient.

$$e(t) = x_{ref}(t) - x(t) \tag{18}$$

The convergence condition is defined by the equation of Lyapunov:

$$s\dot{s} \prec 0 \tag{19}$$

5.2. Controller design

Consequently, the structure of a controller consists of two parts: a first concerning the exact linearization and a second stabilizing [27].

$$u(t) = u_{eq}(t) + u_n \tag{20}$$

$u_{eq}(t)$ corresponds to the equivalent control suggested [28], it is calculated on basis of the system behavior along the sliding mode described by (21) and (22).

$$\dot{s}(x,t) = 0 \quad (21)$$

$$u_n = -Ksgn(s) \quad (22)$$

5.3. Simulation and results

Based on the aforementioned description of the system and its operating modes, the simulation model of the studied system is developed in MATLAB. The simulation model is presented as follows. Figure 4 illustrates the developed simulation model of the studied system.

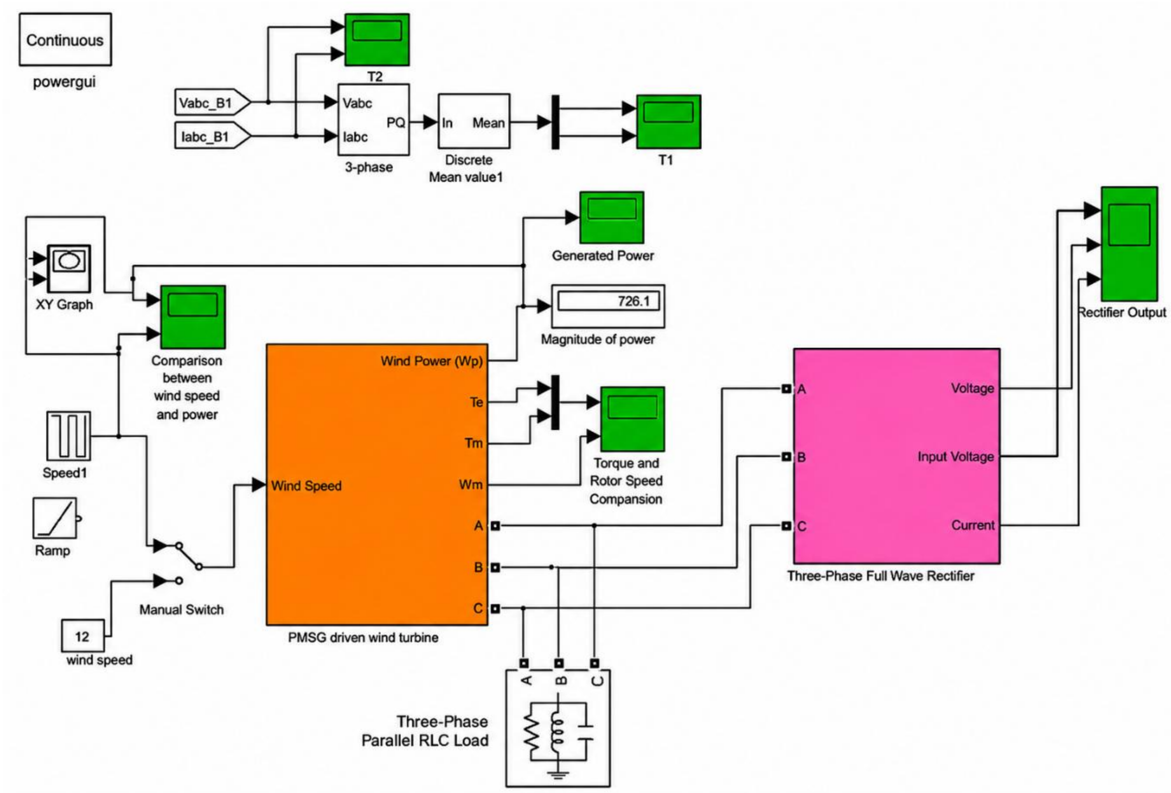

Figure 4. General simulation block of PMSG/wind-turbine

6. ANALYSIS OF RESULTS

The comparative analysis of simulation (Figure 4) results reveals clear distinctions between the two control strategies. For torque control, DTC achieves rapid dynamic response with minimal computational complexity; however, noticeable torque ripples are observed, which may lead to mechanical stress and reduce system lifetime. In contrast, SMC maintains a smoother torque response with negligible oscillations, demonstrating superior robustness under sudden wind speed variations and parameter uncertainties (Figures 5 and 6). In terms of flux control, DTC provides accurate flux tracking but is sensitive to stator resistance variations and temperature effects. SMC, on the other hand, exhibits a stable flux trajectory that remains consistent even under parameter deviations, ensuring reliable machine performance. Speed regulation results further confirm that SMC offers faster settling times and smaller overshoot compared to DTC, particularly under abrupt changes in wind speed (Figures 7 and 8). Overall, the integration of SMC into PMSM-based wind energy systems enhances the efficiency of power extraction, reduces *stress* on the mechanical components, and ensures stable operation under fluctuating environmental conditions. These findings suggest that SMC can be considered a more reliable alternative to conventional DTC for advanced wind energy conversion systems.

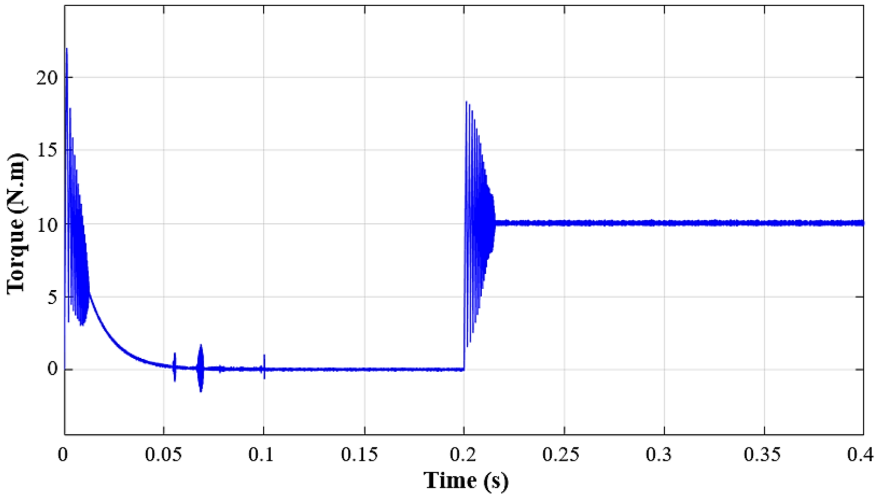

Figure 5. Evolution of the torque (SMC)

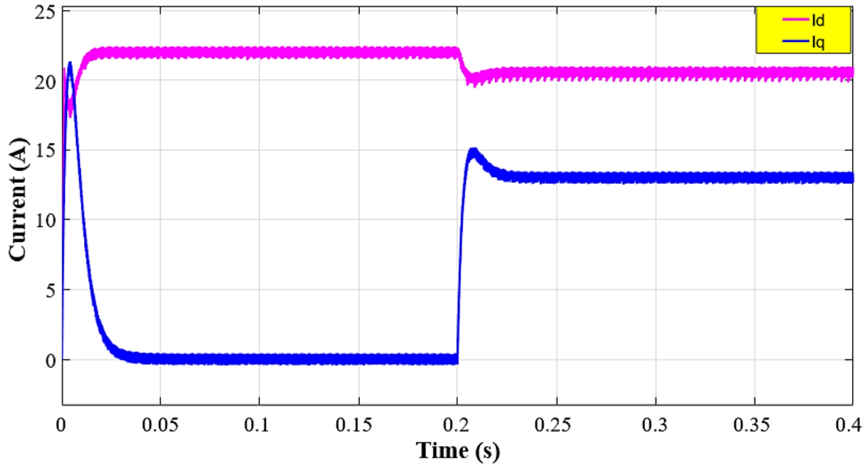

Figure 6. Evolution of the currents (DTC)

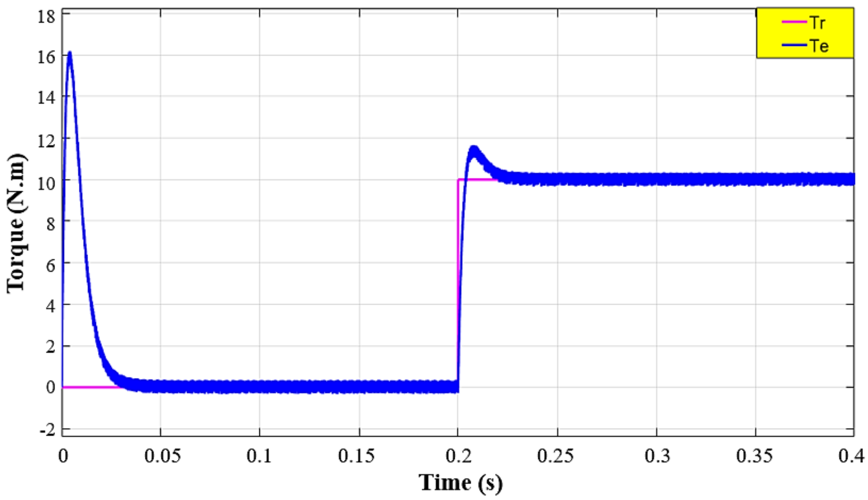

Figure 7. Evolution of the torque (DTC)

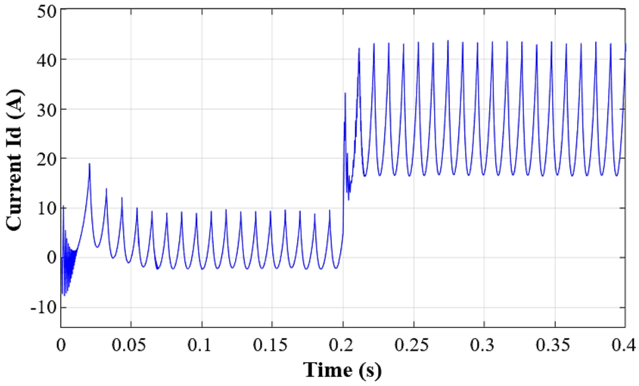

Figure 8. Evolution of the currents (SMC)

7. CONCLUSION

This study presented a comparative investigation of two advanced control strategies, DTC and SMC, applied to a PMSG integrated in a wind turbine (aerogenerator) for wind energy conversion. The analysis was carried out through detailed simulation results, focusing on key performance aspects such as electromagnetic torque response, stator flux behavior, speed regulation, and robustness under disturbances and parameter uncertainties. The simulation results demonstrated that the DTC strategy ensures a fast dynamic response and benefits from a relatively simple control structure, which makes it attractive for practical implementation. Nevertheless, this method exhibits significant torque and flux ripples and shows sensitivity to parameter variations, which may affect the overall performance of the wind energy conversion system.

In contrast, the SMC approach provides better robustness against model uncertainties and external disturbances. It also ensures smoother torque behavior and more stable speed regulation, which are essential for reliable operation and efficient energy conversion in wind turbine systems operating under variable wind conditions. Therefore, the obtained results indicate that SMC represents a promising control strategy for enhancing the stability, reliability, and overall performance of PMSG-based wind turbines. Future research may focus on hybrid control strategies that combine the rapid response of DTC with the robustness of SMC. Furthermore, the integration of intelligent control techniques, such as fuzzy logic or neural-network-based controllers, could further improve adaptability and optimize power extraction from wind energy systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Nehal Ouassila	✓	✓	✓	✓	✓	✓		✓	✓				✓	
Dib Djalel		✓				✓		✓		✓	✓	✓		
Billel Meghni	✓		✓	✓			✓		✓	✓	✓		✓	✓
Dib Nour Elhouda		✓				✓			✓	✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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