

Super-Twisting Sliding Mode Control for a DSIG-Based Dual-Rotor Wind Turbine System

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ABSTRACT

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dual-star induction generator, dual-rotor wind turbine system, vector control, super-twisting sliding mode control, voltage-oriented control

This work presents an improved vector control (VC) approach based on a super-twisting continuous sliding mode controller (STCSMC) applied to a dual-star induction generator (DSIG) with a dual-rotor wind turbine (DRWT) system. The proposed approach aims to improve the dynamic performance, speed-tracking accuracy, robustness, and chattering attenuation. The dual-rotor configuration is considered to further enhance the energy-capture capability of the wind energy conversion system. The STCSMC is evaluated through MATLAB/Simulink simulations and compared with conventional proportional-integral (PI) and super-twisting sliding mode control (STSMC) strategies under identical operating conditions. The obtained results demonstrate a significant improvement in the transient and steady-state performance. In particular, the proposed controller reduces the rise time to 0.049 s and the settling time to approximately 1.5 s, while limiting the speed overshoot to about 1%. The RMS tracking error is reduced to approximately 0.4%, with a negligible steady-state error. Moreover, STCSMC maintains stable speed tracking under a 50% increase in the system inertia and significantly reduces chattering in comparison with the conventional controllers. The harmonic analysis also shows a Total Harmonic Distortion (THD) reduction from 74.29% with STSMC to 73.96% with the STCSMC. These outcomes confirm the effectiveness and robustness of the STCSMC strategy compared to PI and STSMC for high-performance in wind energy conversion.

1. INTRODUCTION

Driven by the growing demand for clean and sustainable electricity, wind energy has experienced remarkable global expansion outpacing other forms of renewable energy. Power capacities have swiftly evolved from a few kilowatts to several hundred megawatts within a short period [1]. Currently, conventional single-rotor wind turbines (WTs) with three blades and a horizontal axis dominate the global WT market. These turbines achieve an energy efficiency of approximately 40%, constrained by Betz's limit, which has a theoretical maximum of 59%; nevertheless, this limitation can be effectively addressed [2]. Recent research has focused on designing more advanced WTs with improved power characteristics [3]. One promising innovation is the dual-rotor wind turbine (DRWT), which, still under development, has the potential to surpass Betz's limit (0.59) in terms of energy efficiency. This work specifically explores the use of this advanced turbine technology [3, 4]. Given the continuous fluctuations in wind speed, variable-speed WT systems are well suited to maintaining efficient energy extraction over a wide operating range [3, 4]. Numerous designs employing diverse generator types exist in the wind energy sector. Among these, the doubly-fed induction generator (DFIG) is the most prevalently implemented [5], especially for high-capacity

applications, due to several benefits, including a 30% reduction in the costs associated with the machine-side inverter. In recent times, alternative generator technologies have significantly evolved and now rival the DFIG. These include permanent magnet synchronous generators (PMSG) and other specialized machines, such as multiphase systems and doubly-excited machines, among others [6]. Owing to their remarkable benefits over standard three-phase generators, such as dividing power delivery across phases, lowering per-phase current without increasing voltage, enhanced dependability, reduced rotor current harmonics, smaller torque ripple amplitudes, higher pulsation frequencies, and reduced direct current distortions, multiphase machines have attracted significant interest for integration into WT systems. Of these, the dual-star induction generator (DSIG) has emerged as the most frequently adopted in such implementations [7]. This study emphasizes a WTS powered by a DSIG. This generator features dual stator windings displaced electrically by a 30-degree angle and linked to the electrical network via a bidirectional converter. Such an arrangement facilitates optimal power harnessing from the wind while dynamically regulating voltage magnitude and frequency. The most commonly utilized control strategy in wind power applications is vector control (VC) augmented with proportional-integral (PI) controllers. However, despite

its extensive deployment in industrial contexts, this methodology exhibits significant robustness challenges owing to PI controller limitations [8]. Several advanced solutions have been suggested recently to overcome this issue. Among these, SMC, introduced by Utkin in 1977, has seen substantial adoption. SMC has showcased impressive reliability and adaptability in managing rotating machinery. Nevertheless, its applicability has been constrained by the adverse effects of the "chattering" phenomenon [9]. To address this drawback caused by the discontinuity in the control mechanism, researchers have proposed various approaches, such as smoothing the sign function approximation, employing fuzzy systems, leveraging neural networks, and utilizing second-order sliding mode strategies [10]. More recently, groundbreaking methods have emerged; these developments demonstrate promising progress, including adaptive terminal and exponential variable discrete-time SMC laws, fractional-order SMC, and adaptive higher-order sliding modes. Additionally, hybrid sliding mode techniques have gained traction in modern studies, including combinations like backstepping sliding mode, passivity-oriented sliding mode strategies, H_∞ sliding mode approaches, and predictive sliding mode frameworks [11]. Among the advanced sliding mode control techniques, the super-twisting continuous sliding mode controller (STCSMC) has emerged as an effective solution for significantly reducing the chattering effect. Initially introduced by Levant [12], this method has demonstrated excellent performance, particularly in the management of rotating electrical machines. Consequently, it has been adopted for the purposes of this study.

The primary contributions of this research are outlined as follows:

- Design of a resilient and high-performance control framework for a DSIG-driven WT system utilizing STCSMC.
- Comparative analysis of the performance of PI, STSMC, and the proposed STCSMC applied to the DSIG-based DRWT under variable wind speed conditions and robustness tests involving a 50% increase in the system inertia.

The remainder of this paper is organized as follows. Section II presents the mathematical model of the DSIG-based wind energy conversion system. Section III provides an in-depth explanation of the VC method applied to the DSIG. Section IV describes the control approach implemented for the Grid-Side Converter (GSC). Section V introduces an advanced control strategy for the DSIG WT system utilizing Sliding Mode Control with Super Twisting (STCSMC). Section VI discusses the simulation results and their analysis. Finally, Section VII concludes the study with key findings.

2. THE SYSTEM MODELING

2.1 Dual-rotor wind turbine model

The overall configuration of the proposed wind energy conversion system is illustrated in Figure 1. It consists of a DRWT driving a doubly-fed squirrel-cage induction generator (DSIG), whose output is connected to the electrical grid through power electronic converters. These converters ensure proper energy transfer and enhance the operational flexibility of the system. The mathematical description of each subsystem is presented in the subsequent sections. The aerodynamic power generated by the auxiliary and main rotors can be written as:

$$P_1 = 0.5\rho\pi R_1^2 V_1^3 \quad (1)$$

$$P_2 = 0.5\rho\pi R_2^2 V_2^3 \quad (2)$$

where, ρ represents the air density, R_1 and R_2 are the radii of the auxiliary and main rotors, respectively, and V_1 and V_2 correspond to the wind speeds passing through these rotors.

The expressions for the power captured by the auxiliary and main rotors are presented below.

$$P_{c1} = C_p(\lambda_1)P_1 \quad (3)$$

$$P_{c2} = C_p(\lambda_2)P_2 \quad (4)$$

The power coefficient C_p is commonly estimated as a function of the tip-speed ratio λ and the blade pitch angle β using the following empirical relationship [10]:

$$C_p = (0.44 - 0.167\beta) \cdot \sin\left[\frac{\pi(\lambda - 3)}{15 - 0.3 \cdot \beta}\right] - 0.0018 \cdot (\lambda - 3) \beta \quad (5)$$

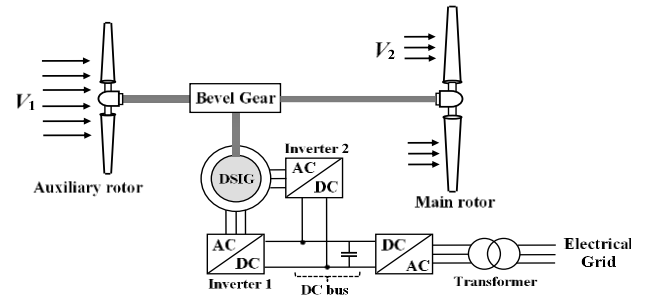


Figure 1. System presentation

The tip-speed ratios of the main and auxiliary rotors, denoted by λ_1 and λ_2 , respectively, are defined as follows:

$$\lambda_1 = \frac{\Omega_{t1} R_1}{V_1} \quad \lambda_2 = \frac{\Omega_{t2} R_2}{V_2} \quad (6)$$

where, Ω_{t1} and Ω_{t2} represent the mechanical speeds of the auxiliary and main rotors, respectively. For optimal results, the following simulations are performed with $\beta_1 = \beta_2 = 2^\circ$ and $\lambda_1 = \lambda_2 = 8$ rad.

The expressions for the aerodynamic torques of the auxiliary and main turbines are given as follows:

$$T_1 = \frac{C_p \rho \pi R_1^2 V_1^3}{2\Omega_{t1}} \quad (7)$$

$$T_2 = \frac{C_p \rho \pi R_2^2 V_2^3}{2\Omega_{t2}} \quad (8)$$

2.2 Dynamic modeling of the dual-star induction generator

The DSIG mathematical model, expressed in the (d, q) Park reference frame, comprises the stator and rotor voltage equations, magnetic flux linkage relationships, and the electromagnetic torque equation, which are presented in Eqs. (9)-(11), respectively [13].

$$\begin{cases} U_{ds1} = R_{s1}i_{ds1} + \frac{d}{dt}\phi_{ds1} - \omega_s\phi_{qs1} \\ U_{qs1} = R_{s1}i_{qs1} + \frac{d}{dt}\phi_{qs1} + \omega_s\phi_{ds1} \\ U_{ds2} = R_{s2}i_{ds2} + \frac{d}{dt}\phi_{ds2} - \omega_s\phi_{qs2} \\ U_{qs2} = R_{s2}i_{qs2} + \frac{d}{dt}\phi_{qs2} + \omega_s\phi_{ds2} \\ U_{dr} = R_r i_{dr} + \frac{d}{dt}\phi_{dr} - \omega_{sl}\phi_{qr} = 0 \\ U_{qr} = R_r i_{qr} + \frac{d}{dt}\phi_{qr} + \omega_{sl}\phi_{dr} = 0 \end{cases} \quad (9)$$

$$\begin{cases} \phi_{ds1} = L_{s1}i_{ds1} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \phi_{qs1} = L_{s1}i_{qs1} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \\ \phi_{ds2} = L_{s2}i_{ds2} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \phi_{qs2} = L_{s2}i_{qs2} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \\ \phi_{dr} = L_r i_{dr} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \phi_{qr} = L_r i_{qr} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \end{cases} \quad (10)$$

$$T_{em} = p \frac{L_m}{L_m + L_r} ((i_{qs1} + i_{qs2})\phi_{dr} - (i_{ds1} + i_{ds2})\phi_{qr}) \quad (11)$$

The slip speed ω_{sl} is given by:

$$\omega_{sl} = \omega_s - \omega_r \quad (12)$$

3. FIELD-ORIENTED CONTROL OF THE DSIG

The fundamental purpose of the VC method is to emulate the decoupled torque and flux control characteristics of a DC machine in the DSIG. This is achieved by decoupling the flux and torque control. A decoupled control structure is obtained by orienting the rotor flux along the direct axis. Under this condition, the direct-axis flux component is regulated to its reference value, whereas the quadrature-axis component is maintained at zero.

$$\phi_{dr} = \phi_r^* \text{ and } \phi_{qr} = 0 \quad (13)$$

Substituting Eqs. (13) into (9), we can express:

$$i_{dr} = 0 \quad (14)$$

$$i_{qr} = -\frac{\omega_{sl}^* \phi_r^*}{R_r} \quad (15)$$

where, $\omega_{sl}^* = \omega_s^* - \omega_r$, with ω_{sl}^* denoting the reference slip speed. By incorporating Eqs. (13) into (10), the rotor current components can be written as follows:

$$i_{qr} = -\frac{L_m}{(L_m + L_r)}(i_{qs1} + i_{qs2}) \quad (16)$$

$$i_{qr} = -\frac{L_m}{(L_m + L_r)}(i_{qs1} + i_{qs2}) \quad (17)$$

By substituting Eqs. (17) into (15), the following expression is obtained:

$$\omega_{sl}^* = \frac{R_r L_m}{(L_m + L_r)} \frac{(i_{qs1} + i_{qs2})}{\phi_r^*} \quad (18)$$

By incorporating Eqs. (13) into (11), the electromagnetic torque expression is reformulated as:

$$T_{em}^* = p \frac{L_m}{L_m + L_r} ((i_{qs1} + i_{qs2})\phi_r^*) \quad (19)$$

The application of rotor field orientation enables the derivation of the system's electrical and mechanical dynamic model, expressed by the following equations:

$$\begin{cases} \frac{di_{ds1}}{dt} = \frac{1}{L_1} (U_{ds1}^* - R_{s1}i_{ds1} + \omega_s^* (L_1 i_{qs1} + T_r \phi_r^* \omega_{sl}^*)) \\ \frac{di_{qs1}}{dt} = \frac{1}{L_1} (U_{qs1}^* - R_{s1}i_{qs1} + \omega_s^* (L_1 i_{ds1} + \phi_r^*)) \\ \frac{di_{ds2}}{dt} = \frac{1}{L_2} (U_{ds2}^* - R_{s2}i_{ds2} + \omega_s^* (L_2 i_{qs2} + T_r \phi_r^* \omega_{sl}^*)) \\ \frac{di_{qs2}}{dt} = \frac{1}{L_2} (U_{qs2}^* - R_{s2}i_{qs2} - \omega_s^* (L_2 i_{ds2} + \phi_r^*)) \\ \frac{d\phi_r}{dt} = -\frac{R_r}{(L_r + L_m)} \phi_r + \frac{R_r L_m}{(L_r + L_m)} (i_{ds1} + i_{ds2}) \\ \frac{d\Omega_g}{dt} = \frac{1}{J} \left(T_g - f_r \Omega_g - p \frac{L_m}{(L_r + L_m)} (i_{ds1} + i_{ds2}) \phi_r^* \right) \end{cases} \quad (20)$$

where, $T_r = L_r/R_r$.

4. GRID-SIDE CONVERTER CONTROL STRATEGY

The main function of the GSC is to transfer the electrical power generated by the DSIG to the utility grid with maximum efficiency. In recent studies [14], the voltage-oriented control (VOC) method has been widely adopted to achieve independent regulation of active and reactive power supplied to the electrical network. This approach ensures a unit power factor while maintaining a stable DC link voltage, regardless of power fluctuations in magnitude or direction [15]. In the Park reference frame, the grid voltages can be expressed as:

$$\begin{cases} U_{dg} = R_f i_{dg} + L_f \frac{di_{dg}}{dt} - \omega_s L_f i_{qg} + U_{di} \\ U_{qg} = R_f i_{qg} + L_f \frac{di_{qg}}{dt} + \omega_s L_f i_{dg} + U_{qi} \end{cases} \quad (21)$$

The grid-side power flow is described by the following active and reactive power equations:

$$\begin{cases} P_g = U_{dg} i_{dg} + U_{qg} i_{qg} \\ Q_g = U_{qg} i_{dg} - U_{dg} i_{qg} \end{cases} \quad (22)$$

By adopting the VOC strategy and orienting the synchronous reference frame with the grid voltage vector ($U_{dg} = 0$ and $U_{dg} = V_d$), the resulting equations are expressed as:

$$\begin{cases} P_g = U_d i_{dg} \\ Q_g = -U_d i_{qg} \end{cases} \quad (23)$$

Based on this result, it becomes simple to apply the power references (P_g^* and Q_g^*) given to the grid by applying the following currents:

$$\begin{cases} i_{dg}^* = \frac{P_g^*}{V_d} \\ i_{qg}^* = -\frac{Q_g^*}{V_d} \end{cases} \quad (24)$$

Alternatively, the DC bus voltage can be represented as follows:

$$\frac{dU_{dc}}{dt} = \frac{1}{C}(i_{dc} - i_m) \quad (25)$$

Assuming no losses in the GSC and filter components (R_f , L_f), the reference active power delivered to the grid is defined by:

$$P_g^* = U_{dc} (i_m - i_{dc}^*) \quad (26)$$

To maintain a constant DC bus voltage, a PI controller can be used, which results in the following equation:

$$i_{dc}^* = \text{PI}(U_{dc}^* - U_{dc}) \quad (27)$$

The transfer function governing the closed-loop regulation of the DC-link voltage is expressed as:

$$\frac{U_{dc}}{U_{dc}^*} = \frac{K_p s + K_i}{Cs^2 + K_p s + K_i} \quad (28)$$

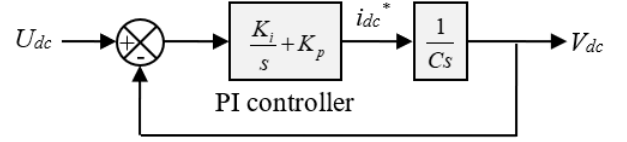


Figure 2. Closed-loop control scheme of the DC-link voltage

The closed-loop control structure adopted for DC-link voltage regulation is presented in Figure 2. The gains of the PI controller are determined based on the system's capacity C and dynamics, as shown below:

$$K_p = \frac{6\xi C}{t_r}, \quad K_i = \frac{9C}{t_r^2} \quad (29)$$

In this work, the controller parameters are selected as $t_r = 0.1s$ and $\xi = 0.7$. The active power delivered to the grid is regulated through the i_{dg} and i_{qg} current components using two PI controllers, as illustrated in Figure 3.

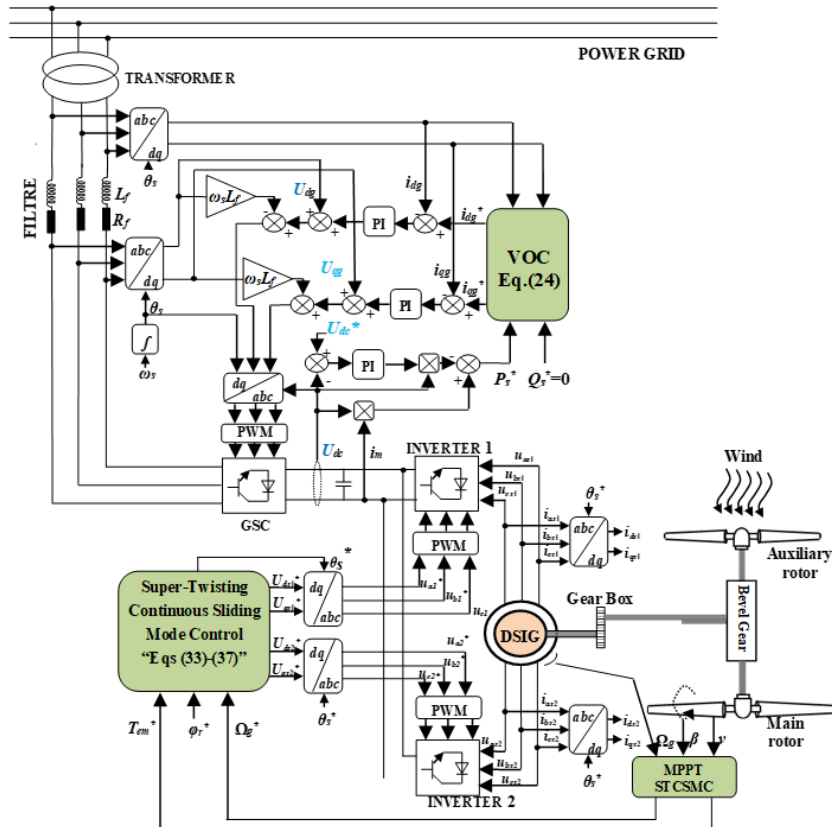


Figure 3. Control architecture of the dual-star induction generator (DSIG)-based dual-rotor wind turbine (DRWT)

5. SUPER-TWISTING CONTINUOUS SLIDING MODE CONTROLLER OF THE DSIG-BASED DRWT

5.1 Principle of Super-twisting continuous sliding mode controller

As highlighted in Section 1, extensive research has focused on overcoming the chattering problem associated with traditional SMC. In electrical drive applications, chattering produces high-frequency switching, increases power losses, and generates electromagnetic interference [16, 17]. To address this issue, high-order sliding mode control (HOSMC) has emerged as an advanced technique. Unlike traditional SMC, which acts on the first derivative of the system's deviation from the desired state, HOSMC operates on higher-order derivatives and has shown promising theoretical and practical results in reducing chattering [18, 19]. However, its implementation requires extensive information about the sliding surface. Specifically, synthesizing an n -order controller requires knowledge of n derivatives of the sliding surface [18, 19]. To overcome this limitation, the super-twisting algorithm (STA), combined with quasi-continuous functions, is employed in this study. This approach reduces the dependency on higher-order derivative information while effectively mitigating chattering. The corresponding control law applied in this work is described by Eq. (30) [12].

$$u(t) = -l_1 |S|^{a_1} \text{sgn}(S) \dots - l_n |S^{(n-1)}|^{a_n} \text{sgn}(S^{(n-1)}) - z \quad (30)$$

With z defined by Eq. (31) and $(a_1, a_2, \dots, a_n)$ as constants satisfying the condition in Eq. (32). Furthermore, $(l_1, l_2, \dots, l_n)$ represent the parameters of the Hurwitz polynomial: $s^n + l_n s^{n-1} + \dots + l_2 s + l_1$.

$$\begin{cases} z(t) = k \cdot |S|^{1/2} \text{sgn}(S) + z_1(t) \\ \dot{z}_1(t) = \alpha \cdot \text{sgn}(S) \end{cases} \quad (31)$$

$$\begin{cases} a_{i-1} = \frac{a_i a_{i-1}}{2a_{i+1} - a_i}, \quad i = 2, \dots, n \\ a_n + 1 = 1 \quad \text{and} \quad a_n = a \end{cases} \quad (32)$$

5.2 Application to the dual-star induction generator-based dual-rotor wind turbine

Figure 3 depicts the application of the STCSMC to the DSIG-based DRWT system. In this configuration, the proposed control architecture replaces the conventional PI-based design with STCSM controllers for both mechanical speed and current regulation of the DSIG. These controllers generate the reference values for the q-axis current and voltages, as defined in Eqs. (33)-(37).

$$i_q^* = -l_1 |S_\omega|^{a_1} \text{sgn}(S_\omega) - k_1 \cdot \text{sgn}|S_\omega|^{1/2} + \int \alpha_1 \cdot \text{sgn}(S_\omega) \quad (33)$$

With: $i_q^* = i_{qs1}^* + i_{qs2}^*$.

$$U_{ds1}^* = -l_2 |S_{ids1}|^{a_1} \text{sgn}(S_{ids1}) - k_2 \cdot \text{sgn}|S_{ids1}|^{1/2} + \int \alpha_2 \cdot \text{sgn}(S_{ids1}) \quad (34)$$

$$U_{qs1}^* = -l_2 |S_{iqs1}|^{a_1} \text{sgn}(S_{iqs1}) - k_2 \cdot \text{sgn}|S_{iqs1}|^{1/2} + \int \alpha_2 \cdot \text{sgn}(S_{iqs1}) \quad (35)$$

$$U_{ds2}^* = -l_2 |S_{ids2}|^{a_1} \text{sgn}(S_{ids2}) - k_2 \cdot \text{sgn}|S_{ids2}|^{1/2} + \int \alpha_2 \cdot \text{sgn}(S_{ids2}) \quad (36)$$

$$U_{qs2}^* = -l_2 |S_{iqs2}|^{a_1} \text{sgn}(S_{iqs2}) - k_2 \cdot \text{sgn}|S_{iqs2}|^{1/2} + \int \alpha_2 \cdot \text{sgn}(S_{iqs2}) \quad (37)$$

where, S_ω , S_{ids1} , S_{iqs1} , S_{ids2} , S_{iqs2} are the sliding mode surfaces corresponding to the mechanical speed and stator currents, respectively. The constants k_1 and k_2 must be properly selected to satisfy the stability criteria.

To ensure a consistent comparison of the investigated control strategies, the GSC control structure is maintained unchanged for all simulation cases. The PI regulators used in the GSC are dedicated to DC-link voltage and grid-side power regulation and are therefore not included in the controller comparison. The machine-side DSIG control is instead evaluated using three different strategies: conventional PI, STSMC, and the proposed STCSMC. Hence, the control cases differ only in the machine-side regulation law, while the GSC, system parameters, operating conditions, and reference signals remain identical. This configuration provides a consistent basis for assessing the contribution of the proposed STCSMC in terms of tracking accuracy, dynamic response, robustness, and chattering reduction.

5.3 Stability analysis and gain selection

Consider the following dynamic system described in state-space form:

$$\frac{dx}{dt} = a(x, t) + b(x, t)u, \quad y = c(x, t) \quad (38)$$

where, x , u and y represent the system's state, input, and output, respectively.

The objective of the proposed controller is to determine a control input that drives the tracking error to zero within finite time. The sliding variable is defined as $S = y - y^*$, where y^* denotes the reference signal. The STA does not require the explicit computation or numerical differentiation of the sliding variable. Instead, it uses the sliding variable directly, while its integral term generates the required corrective action. For the proposed current-control loops, the relative-degree-one assumption is satisfied because the control voltages directly affect the current dynamics, while the lumped perturbations remain bounded over the considered operating range. Under these conditions, the STA ensures finite-time convergence of the sliding variable without explicit numerical differentiation. Consequently, the controller can be implemented directly from the measured current errors, thereby avoiding numerical differentiation and reducing sensitivity to measurement noise. According to the finite-time convergence theory established by Levant [12], the STA guarantees finite-time convergence of the sliding variable and its first derivative under the stated assumptions. Therefore, the necessary condition for stability and convergence can be expressed as follows:

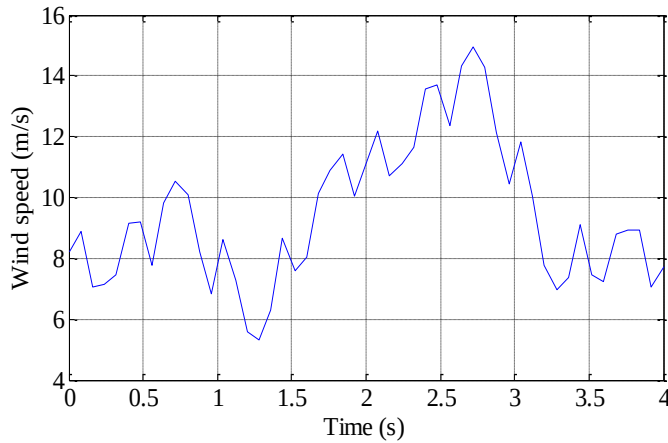
$$k_1 > \frac{A_M}{B_m}, \quad k_2 \geq \frac{4A_M}{B_m^2} \cdot \frac{B_M(K_1 + A_M)}{B_m(K_1 - A_M)} \quad (39)$$

where, A_M denotes the upper bound of $|A|$, while B_M and B_m represent the upper and lower bounds of B , respectively, in the second-order dynamics of the output y .

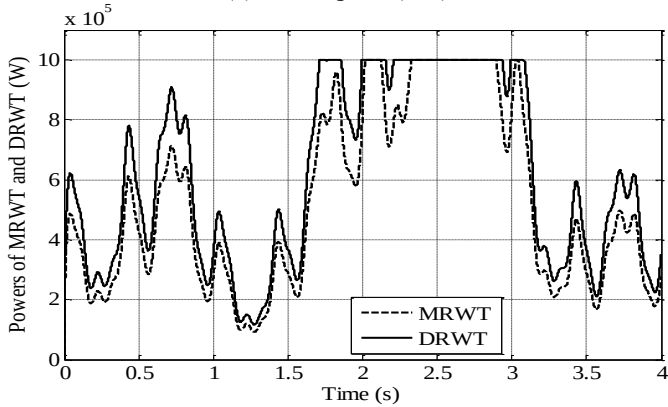
6. RESULTS AND DISCUSSIONS OF THE SIMULATION

To evaluate the effectiveness of the proposed control strategies and investigate the dynamic response of the DSIG under both nominal and disturbed operating conditions, including parameter uncertainties, two simulation scenarios were implemented in the MATLAB/Simulink environment.

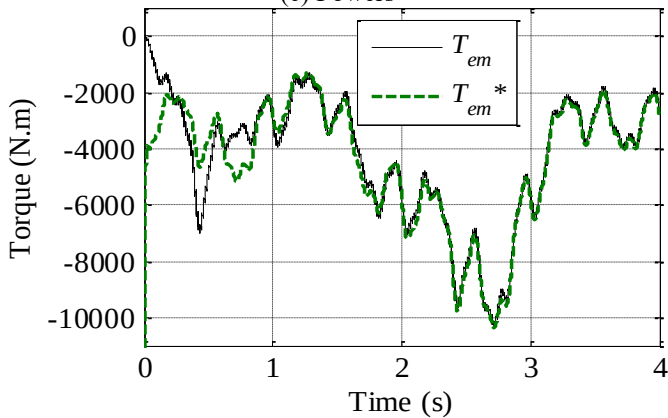
These scenarios were designed to assess the controller response under representative variations in system operating conditions and to examine its ability to maintain the desired system behavior when disturbances or parameter deviations are introduced. The simulations focused on the steady-state performance, transient behavior, tracking capability, and overall control response of the proposed method under different operating conditions. The parameters adopted in the numerical model are summarized in the Appendix, which provides the electrical, mechanical, and control-related parameters used to configure the simulation model. For consistency across the different test conditions, the reactive power reference was fixed at $Q^* = 0$, while the DC-link voltage was regulated at $V_{dc} = 1130$ V. The corresponding wind speed profile is illustrated in Figure 4.



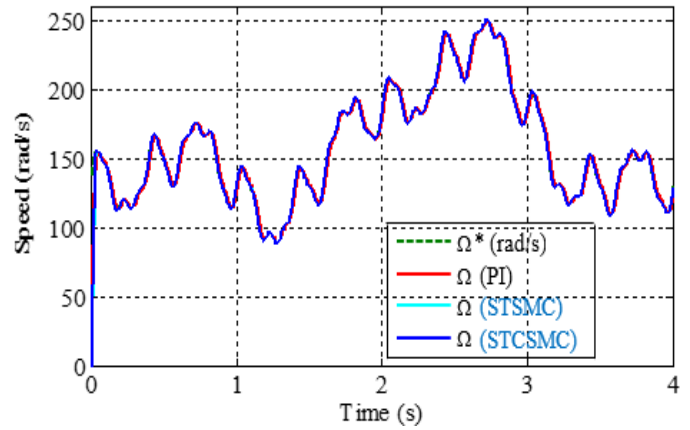
(a) Wind speed (m/s)



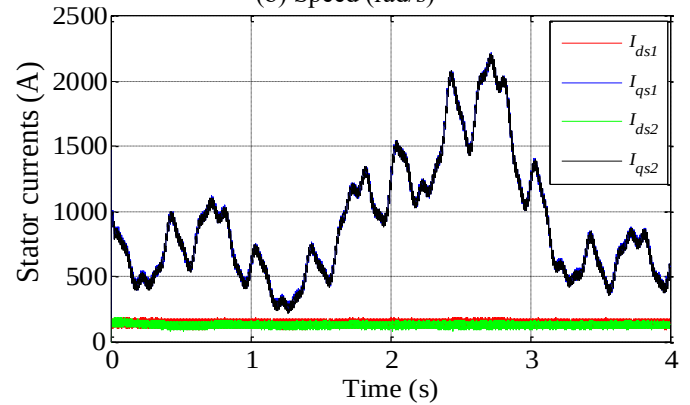
(c) Powers



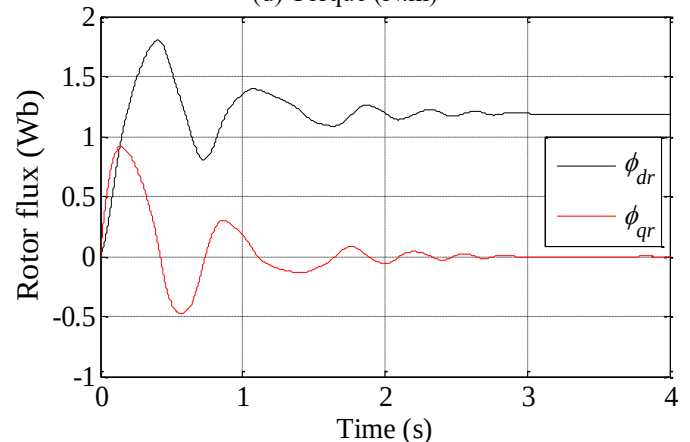
(e) Stator currents (A)



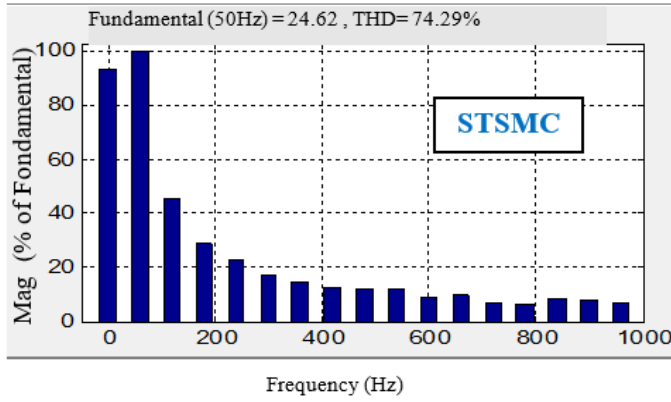
(b) Speed (rad/s)



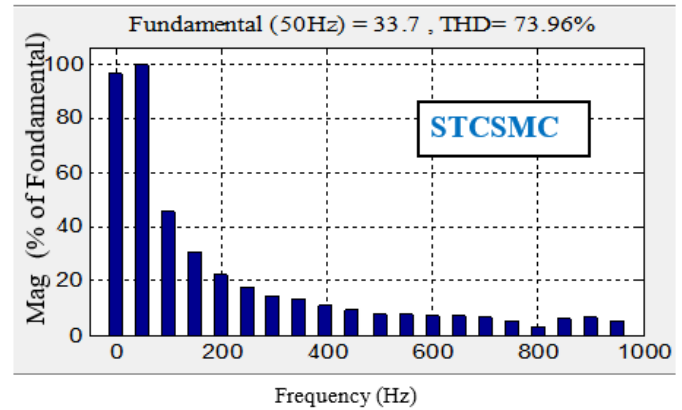
(d) Torque (N.m)



(f) Rotor flux (Wb)



(g) Harmonic spectrum and THD (STSMC)



(h) Harmonic spectrum and THD (STCSMC)

Figure 4. Reference tracking test

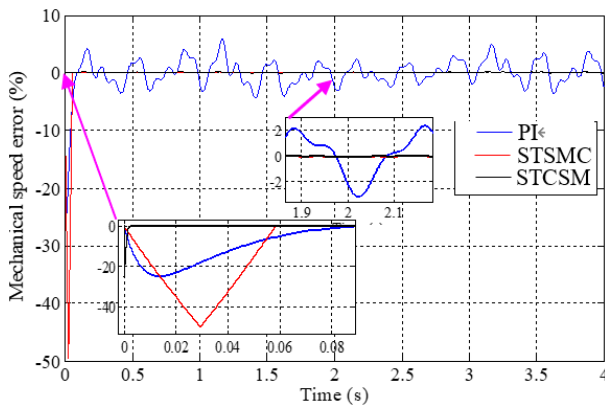


Figure 5. Comparison of the tracking error obtained using the PI, STSMC, and STCSMC controllers

Note: PI = proportional-integral, STSMC = super-twisting sliding mode control, STCSMC = super-twisting continuous sliding mode controller.

Table 1. Quantitative comparison of the investigated controllers

Controller	Rise Time (s)	Settling Time (s)	Overshoot (%)	RMS Error (%)	Steady-State Error (%)
PI	0.151	2.61	25	3.51	2.5
STSMC	0.081	2.0	50	1.125	0.75
STCSMC (Proposed)	0.049	1.5	1	0.4	0

Note: PI = proportional-integral, STSMC = super-twisting sliding mode control, STCSMC = super-twisting continuous sliding mode controller.

In the speed response curve, it is clear that the two sliding mode controllers, STSMC and STCSMC outperform the conventional PI controller, particularly in terms of dynamic response and steady-state accuracy. Among the two sliding mode strategies, both designed to mitigate the chattering phenomenon, the STCSMC exhibits superior performance, as demonstrated by the lower Total Harmonic Distortion (THD) in the electromagnetic torque waveform. The effectiveness of the field-oriented control (FOC) strategy is confirmed by the flux component responses: the direct-axis (d-axis) stator flux component remains close to zero, while the quadrature-axis (q-axis) component reaches its rated value, ensuring proper decoupling and alignment. Similarly, the stator current responses reflect theoretical expectations: the d-axis current remains zero, and the q-axis current follows the electromagnetic torque profile, validating the

control approach. A robustness test involving a 50% increase in the system's moment of inertia was carried out. The results show that this parameter variation had negligible impact on both sliding mode controllers, confirming their robustness. In contrast, the PI controller exhibited noticeable degradation in performance, particularly in the mechanical speed response. Based on the overall outcomes, it can be concluded that a wind energy conversion system utilizing a DSIG and controlled with a STCSMC approach offers a highly effective and robust solution for reliable and efficient power generation.

Figure 5 compares the speed tracking errors achieved by the PI, STSMC, and STCSMC controllers under the same operating conditions. As seen in Figure 4, the conventional PI controller exhibits persistent oscillations around the zero-error reference, indicating limited disturbance rejection and reduced tracking accuracy. In contrast, both sliding mode controllers rapidly drive the tracking error to zero immediately after the transient period. The STSMC controller provides fast convergence with negligible steady-state error, whereas the proposed STCSMC controller achieves an even smoother response with significantly reduced oscillations and virtually zero residual error.

The quantitative performance of the three controllers, PI, STSMC, and the proposed STCSMC controllers are summarized in Table 1. The PI controller exhibits the slowest transient response, with a rise time of approximately 0.151 s and a settling time of about 2.61 s, while maintaining noticeable steady-state oscillations. The STSMC controller improves the convergence speed. However, it exhibits a relatively large transient overshoot of approximately 50%. In contrast, the proposed STCSMC controller achieves the fastest response, with a rise time of approximately 0.049 s and a settling time of about 1.5 s. Moreover, its overshoot is strongly reduced, while the RMS tracking error is limited to approximately 0.4% and the steady-state error is practically negligible. These results demonstrate the improved transient and steady-state tracking performance of the proposed STCSMC controller.

These findings demonstrate the superior robustness and tracking ability of the suggested STCSMC controller compared with both the conventional PI and STSMC methods. To provide a quantitative assessment of the proposed controller, Table 2 summarizes the main qualitative performance indicators obtained from the simulation results. The comparison confirms the superiority of the proposed STCSMC in terms of tracking accuracy, robustness,

harmonic performance, and dynamic response.

In contrast, both sliding mode controllers rapidly drive the tracking error to zero immediately after the transient period. The STSMC controller provides fast convergence with negligible steady-state error, whereas the proposed STCSMC controller achieves an even smoother response with significantly reduced oscillations and virtually zero residual error.

Table 2 summarizes the main comparative performance

Table 2. Overall comparative assessment of the investigated controllers

Performance Index	PI	STSMC	STCSMC (Proposed)	Improvement of STCSMC
Rotor speed tracking	Good	Very good	Excellent	Highest tracking accuracy
Chattering phenomenon	High	Reduced	Practically eliminated	Significant chattering reduction
Maximum speed tracking error	Highest	Lower	Lowest	Minimum percentage error (Figure 5)
Dynamic response	Moderate	Fast	Fastest	Improved transient performance
Robustness to 50% inertia increase	Sensitive	Robust	Most robust	Stable operation under parameter variations
THD (%)	–	74.29	73.96	0.33 percentage-point reduction ($\approx 0.44\%$)

Note: PI = proportional-integral, STSMC = super-twisting sliding mode control, STCSMC = super-twisting continuous sliding mode controller, THD = Total Harmonic Distortion.

7. CONCLUSION

This paper presented an advanced vector-control strategy for a DRWT based on a DSIG, using a STCSMC. The proposed strategy was developed to improve rotor-speed tracking, dynamic performance, chattering attenuation, and robustness against system parameter variations. The performance of the proposed controller was evaluated through MATLAB/Simulink simulations and compared with conventional PI and STSMC strategies under identical operating conditions.

The quantitative results confirm the effectiveness of the proposed STCSMC. The rise time was reduced to 0.049 s, compared with 0.151 s for the PI controller, corresponding to a reduction of approximately 67.5%. The settling time was also reduced from 2.61 s to 1.5 s, which meant an improvement of around 42.5%. Furthermore, the speed overshoot was reduced from 25% for PI and 50% for STSMC to approximately 1% with the proposed STCSMC, corresponding to reductions of 96% and 98%, respectively. The RMS tracking error was reduced from 3.51% for PI and 1.125% for STSMC to only 0.4% with STCSMC, representing reductions of approximately 88.6% and 64.4%, respectively. According to the findings, the steady-state tracking error was practically eliminated with the proposed controller.

The harmonic analysis also demonstrated a modest reduction in the THD, from 74.29% with STSMC to 73.96% with STCSMC, which is equivalent to a fall of 0.33 percentage points or approximately 0.44% in relative terms. Moreover, the proposed controller effectively reduces chattering and provides smoother electromagnetic torque and stator-flux responses. Even with an increased inertia by 50%, the STCSMC-based wind energy system maintains stable and accurate speed tracking, whereas the PI controller shows a more pronounced degradation in dynamic performance.

Overall, the obtained outcome demonstrates that the proposed STCSMC provides a faster, more accurate, and more robust control solution for the DSIG-based DRWT. The combination of reduced transient error, lower overshoot, negligible steady-state error, reduced chattering, and improved robustness makes the proposed strategy a promising candidate for high-performance wind-energy conversion systems. Future

indicators obtained from the simulation results, including rotor-speed tracking accuracy, chattering behavior, maximum tracking error, dynamic response, robustness to a 50% increase in the system inertia, and THD. The comparison highlights the relative advantages of the proposed STCSMC controller over the conventional PI and STSMC controllers in terms of transient performance, tracking accuracy, robustness, and control quality.

work will focus on experimental validation of the proposed controller and its implementation on a real-time control platform under a wider range of operating conditions.

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NOMENCLATURE

Nominal power	1.5 MW
R_1	13.2 m
R_2	25.5 m
J	$4.87 \times 10^6 \text{ Kg}\cdot\text{m}^2$
R	3.174 mΩ
L_d	3.07 mH
L_q	3.07 mH
ϕ_m	7.0172 wb
n_p	80
f_r	200, N·m·s/rad