SVU-International Journal of Engineering Sciences and Applications (2025) 6(1): 54-60
Print ISSN 2785-9967| Online ISSN 2735-4571
DOI 10.21608/svusrc.2024.331190.1244

A Robust Fuzzy Super Twisting Sliding Mode Control (FSTSMC) for the Wind Turbine System

Sara Kadi [1], Habib Benbouhenni [2], and Emad Abdelkarim [3, 4,]

Abstract This paper presents an enhanced Super Twisting Sliding Mode Control (STSMC) technique for wind turbine systems by integrating a fuzzy logic controller (FLC) to dynamically regulate the STSMC gain. The FLC adjusts the gain based on the error signal from the STSMC, leading to improved adaptability and system performance. This approach enhances responsiveness to sudden changes and disturbances, resulting in better transient response and reduced steady-state error. Simulation results confirm that the Fuzzy Super Twisting Sliding Mode Control (FSTSMC) outperforms the standard STSMC, offering automatic gain adjustment and eliminating the need for manual tuning. The proposed method significantly improves system performance in dynamic conditions.

Keywords:. Sliding mode control; super twisting sliding mode control; chattering phenomenon; fuzzy logic system; wind energy conversion systems.

1 Introduction

Wind energy is a significant renewable resource, with global generation reaching 744 GW in 2020, as reported by the World Wind Energy Association (WWEA), with an increase of 94 GW during that year [1]. Researchers focus on maximizing wind power extraction while minimizing mechanical stress. Due to the nonlinear dynamics of wind turbines, traditional control methods like PI and PID are insufficient [1,2]. Sliding mode control (SMC) has emerged as a robust nonlinear control technique, effective against parameter uncertainties and external disturbances [3]. SMC addresses issues in wind turbine systems such as excessive DC link voltage during grid faults in traditional back-to-back converter setups [4,5].

Chattering remains a primary challenge of SMC [6]. Various approaches have been proposed to mitigate chattering, such as the Smoothed Sliding Mode Control scheme, which replaces the sign function with a saturation function [7]. Adaptive sliding gain functions have also been explored to reduce control effort in induction motor applications [8]. In another approach, a sliding surface combining proportional (P) and derivative (D) terms of a PD controller aims to reduce chattering in both system output and sliding surface dynamics [9].

Super Twisting Sliding Mode Control (STSMC) represents a second-order sliding mode technique designed to drive not only the sliding surface but also its derivative to zero, further reducing chattering [10].

The paper is structured as follows: it begins with the modeling of the wind turbine in Section 2. Section 3 provides an overview of SMC, followed by the STSMC in Section 4. In Section 5, the STSMC is applied to the wind turbine system. Section 6 details the construction of the

Received: 25 October 2024/ Accepted: 5 December 2024

Corresponding Author: Emad Abdelkarim, e.abdelkarim@aswu.edu.sa
1. University of Science and Technology Houari Boumediene Algiers, Algeria
2. Faculty of Engineering and Architecture, Department of Electrical & Electronics Engineering Nisantasi University, Istanbul, Turkey
3. Department of Electric Engineering, Aswan University, Aswan, Egypt
4. Department of Electric Engineering, Buraydah Private Colleges, Qassim, KSA

FSTSMC for the wind turbine system. Section 7 discusses the integration of the FLC with FSTSMC for Maximum Power Point Tracking (MPPT). The simulation results are presented in Section 8. Finally, the paper concludes with Section 9.

2 Modelling of Wind Turbine

Wind turbines harness the kinetic energy from moving air masses, converting it into mechanical energy that can drive an electric generator. The kinetic energy available from wind, based on air movement, is determined by [11]:

$$P_{wind} = 0.5.\rho.A.V_{wind}^{3} \qquad (1)$$

Where, P_{wind} represents the total power available in the wind (W), ρ is the air density, typically around 1.225 kg/m³, A is the swept area of the turbine blades (m²), given by $A=\pi.R^2$, where R is the radius of the rotor (m), V_{wind} is the wind speed (m/s).

However, not all of this kinetic energy can be captured due to physical and aerodynamic limitations. The mechanical power extracted by the turbine is described by [12]:

$$P_m = 0.5.C_p\ (\lambda,\ \beta).\rho.\pi.R^2.V_{wind}^{3} \qquad (2)$$

P_m is the actual mechanical power extracted by the turbine (W), $C_p(\lambda,\beta)$ is the power coefficient, a dimensionless factor that represents the efficiency of the turbine in converting wind power to mechanical power.

The power coefficient C_p is subject to the Betz limit, which states that no turbine can capture more than 59.3% of the wind's kinetic energy ($Cp \leqslant 0.593$) [12].

The mechanical torque T_m produced by the turbine is related to the mechanical power and rotor speed by [13]:

$$T_g = \frac{P_m}{\Omega_g} = \frac{0.5.C_p\ (\lambda,\beta).\rho.\pi.R^2.V_{wind}^{3}}{\Omega_g} \qquad (3)$$

Where Ω_g is the angular velocity of the turbine rotor (rad/s).

The power coefficient C_p a key performance indicator for the turbine, depends on both λ and β, C_p is defined by [12]:

$$\begin{cases} C_p(\lambda,\beta) = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda i}} + 0.0068\lambda \\ \frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \end{cases} \qquad (4)$$

Notably, the curve shows that the optimal performance, represented by the maximum value $C_{p\max}$ =0.515, occurs at a tip speed ratio λ=9.15 and β=2º.

This information underscores the importance of optimizing the operational parameters of wind turbines to approach the theoretical limits of energy conversion efficiency.

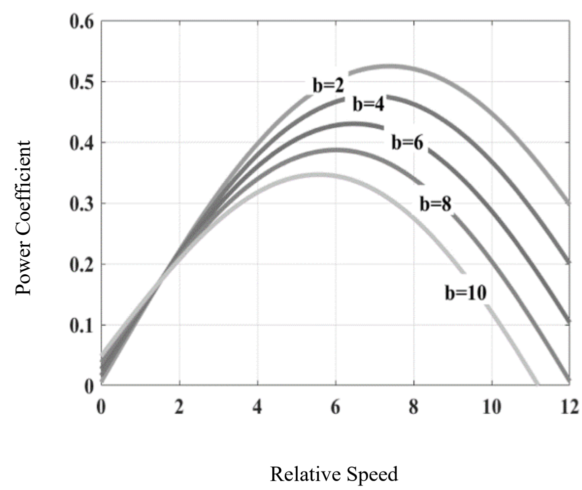


Fig. 1 Power Coefficient C_p for WT model [13].

The mechanical angular speed Ω_g of the turbine (rad/s) is determined by (5):

$$J\frac{d\Omega_g}{dt} + f\ \cdot \Omega_g = T_{em} - T_g \qquad (5)$$

The mathematical model of the turbine is illustrated in Fig. 2.

To optimize energy capture and conversion efficiency, the turbine's rotational speed must be continuously adjusted in response to variations in wind speed. This dynamic adjustment is essential for maintaining a consistent speed ratio [14].

In this section, the turbine operates under a MPPT algorithm, integrated with a speed control loop utilizing conventional sliding mode control. This control approach is designed to improve the accuracy of the MPPT process, ensuring that the turbine consistently operates at its optimal performance levels [10,11].

3 Sliding Mode Control

Sliding Mode Control (SMC) is a robust, nonlinear control strategy designed to maintain system trajectories on a predefined sliding surface despite the presence of uncertainties and external disturbances [11]. The SMC technique operates by defining a sliding surface, $S(x)$=0, where x represents the system states.

The system's control objective is to drive the states onto this surface and keep them there, ensuring stability and robustness. The control law in SMC consists of two main components, the equivalent component maintains the system's trajectory on the sliding surface by compensating for system dynamics and external disturbances, and the discontinuous component that drives the trajectory toward the sliding surface with high gain, ensuring convergence. However, this discontinuous nature introduces the well-known chattering phenomenon, characterized by high-frequency oscillations in the control signal due to switching between control actions. Chattering can negatively affect system performance, leading to excessive wear in mechanical components or even instability in certain applications. Therefore, several strategies have been developed to reduce or eliminate chattering while maintaining the robustness of SMC [15].

4 Super Twisting Sliding Mode Control

To address the limitations of classical SMC, higher-order sliding modes (HOSM) have been proposed by researchers such as Emelyanov [16] and Levantovsky [17]. These methods extend the robustness of conventional sliding modes while reducing or eliminating the chattering effects associated with first-order SMC. Higher-order sliding modes control the derivatives of the sliding surface, which allows smoother control signals and better system performance in practical applications [12,15].

One of the most effective HOSM algorithms is the Super-Twisting Sliding Mode Control (STSMC), a second-order sliding mode control algorithm. The Super-Twisting algorithm is particularly suited for systems with a relative degree of one. Unlike conventional SMC, which operates on the first derivative of the sliding surface, STSMC controls the system by acting on the first and second derivatives, thus ensuring both stability and chattering reduction [11].

The control law for the Super-Twisting algorithm is divided into two components, the continuous control term U_1, responsible for stabilizing the system without generating chattering, and the discontinuous derivative control term U_2, which guarantees finite-time convergence to the sliding surface while also mitigating chattering effects by smoothing the control signal. The STSMC law can be expressed as [11]:

$$\begin{cases} U = U_1 + U_2 \\ U = \left(-\alpha.|S|^{0.5}.sign(S)\right) + \left(-\beta.\int sign(S).dt\right). \end{cases} \quad (6)$$

Where, S is the sliding surface for the controlled system state, representing error signal in different states of the system, α and β are positive control gains that define the behavior of the control law, Sign(S) is the sign function that switch the control action based on the sliding surfaces' sign.

The Super-Twisting algorithm has demonstrated excellent performance in a variety of applications, especially where reducing chattering and improving control precision are critical. By effectively combining robust sliding mode properties with reduced switching, STSMC provides a significant improvement over classical SMC in systems with uncertainties and external disturbances.

5 Super Twisting Sliding Mode Control for The Wind Turbine

The control surface is defined with:

$$S_{\Omega} = \Omega_g^* - \Omega_g \quad (7)$$

Substituting (5) into the previous equation results in [11]:

$$T_{em}^* = \left(-\alpha.|S_{\Omega}|^{0.5}.\mathrm{sign}(S_{\Omega})\right) + \left(-\beta.\int \mathrm{sign}(S_{\Omega}).\mathrm{dt}\right) \quad (8)$$

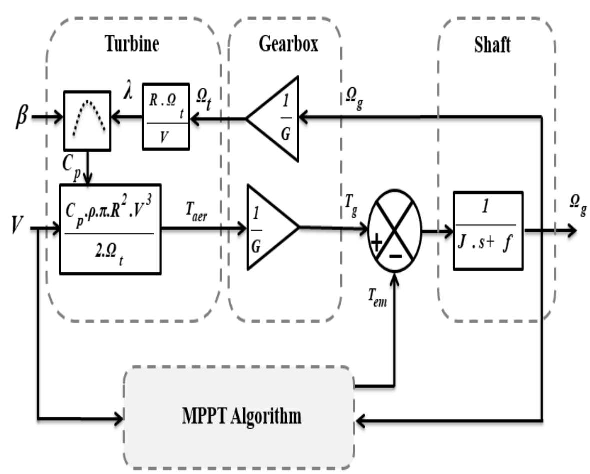


Fig. 2 The wind turbine schematic diagram with MPPT using STSMC controller [12].

6 Construct of Fuzzy Super Twisting Sliding Mode Control for The Wind Turbine System

Fuzzy logic is frequently utilized in nonlinear systems with inherent uncertainties, as it allows for flexible control without the need for precise system modeling or parameter identification. This characteristic makes it particularly beneficial for applications like MPPT in wind energy systems [10].

FLC effectively address uncertainty and nonlinear behavior in control systems. Developed by Lotfi Zadeh over 30 years ago, FLCs provide an adaptive solution based on fuzzy rules and membership functions derived from expert knowledge or data. This approach is especially useful in scenarios where accurate modeling is challenging [10]. Structure and Process of Fuzzy Logic Controllers:

The design of an FLC involves three primary processes [10]:

Fuzzification: This process transforms crisp numerical inputs (such as error signals and their time derivatives) into fuzzy sets using membership functions. These fuzzy sets represent the degree to which the inputs belong to different categories, such as "small," "medium," or "large."

Application of the Fuzzy Rule Base: The fuzzified inputs are processed using a set of fuzzy rules, which represent logical relationships between the inputs and the desired control outputs. These rules are typically structured as "if-then" statements, allowing for flexible decision-making based on the current state of the system.

Defuzzification: The fuzzy outputs are then converted back into a crisp control signal, which can be applied to the system to achieve the desired response.

7 FLC Integration with The FSTSMC for MPPT

In the proposed MPPT strategy, the FLC plays a crucial role in enhancing the STSMC by dynamically adjusting the control gain α. The FLC uses the error between the reference electromagnetic torque T^{*}_{em} and the measured electromagnetic torque T_{em} to estimate the optimal value of α in real-time. This enables the controller to adapt to changing conditions quickly, improving system performance in the face of disturbances or sudden changes.

To simplify the control design, the Mamdani-type fuzzy inference system is employed. This method allows for efficient rule-based decision-making without adding unnecessary complexity to the control algorithm. The fuzzy rule base, consisting of 49 rules (Table I), defines the relationship between the error signal, its derivative, and the output control signal. The fuzzy variables used in the control system are defined as: P (Positive), N (Negative), V (Very), B (Big), M (Medium), S (Small), Z (Zero).

Example: N.V.B is Negative Very Big.

The general fuzzy rule structure can be described as follows:

Rule i: If e is $in_1(j)$ and $e^{\cdot}$ is $in_2(j)$, then $u(j)$ is $out(j)$

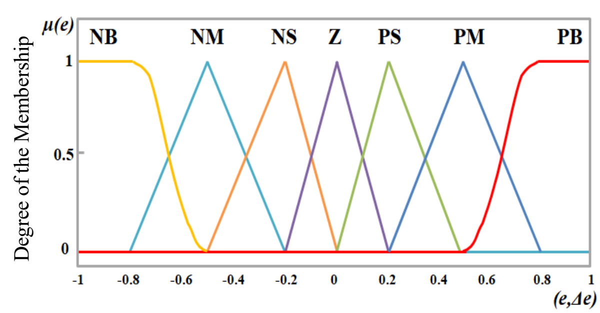
TABLE I. Fuzzy rules.

Δe \ e	N.B	N.M	N.S	Z	P.S	P.M	P.B
N.B	P.V.B	P.V.B	P.V.B	P.B	P.M	P.S	Z
N.M	P.V.B	P.V.B	P.B	P.M	P.S	Z	N.S
N.S	P.V.B	P.B	P.M	P.S	Z	N.S	N.M
Z	P.B	P.M	P.S	Z	N.S	N.M	N.B
P.S	P.M	P.S	Z	N.S	N.M	N.B	N.V.B
P.M	P.S	Z	N.S	N.M	N.B	N.V.B	N.V.B
P.B	Z	N.S	N.M	N.B	N.V.B	N.V.B	N.V.B

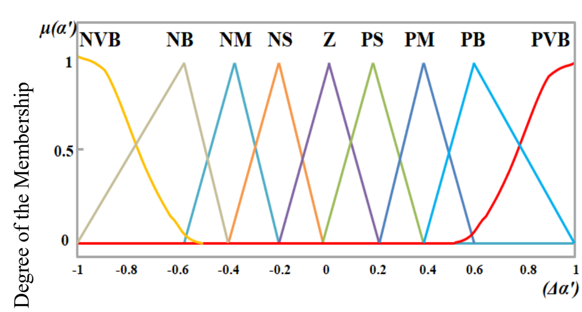
Where, e is the error signal between the reference and actual output, $e^{\cdot}$ is the derivative of the error, $in_1(j)$ and $in_2(j)$ are the fuzzified inputs, $u(j)$ is the output control signal produced by the fuzzy inference process.

This approach allows the controller to respond effectively to system variations without requiring precise modeling of the plant, making it a versatile and robust solution for wind energy applications.

In contrast to traditional designs, symmetric triangles are selected as membership functions to enhance precision [18-20]. The inputs and outputs of these membership functions are defined within the normalized range of [-1,1], as demonstrated in Fig. 3.



The inputs MFs



The output membership function

Fig. 3 The MFs of the inputs-output of the proposed FLS.

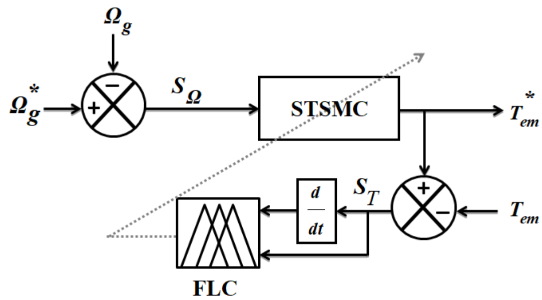


Fig. 4 The proposed FSTSMC schematic diagram.

The architecture of the proposed FSTSMC for the speed controller is depicted in Fig. 4.

8 Simulation Results

This part outlines the simulation outcomes for the wind turbine, demonstrating the efficiency of the proposed FSTSMC. The simulations were performed using Matlab/Simulink, with the specific parameters of the wind turbine employed in these tests listed in Table II.

TABLE II. Parameters of the wind turbine (WT) [11,12].

Parameters	Value
P_n (kw)	10
R (m)	3
G	5.4
J (Kg.m²)	0.042
f (N.m/s)	0.017

These techniques are compared based on reference tracking for variable random wind speeds and the overall performance of the wind turbine using SMC and FSTSMC methods.

8.1 First Test: Tracking References Test

An irregular wind profile was employed for this test, as illustrated in Fig. 5.

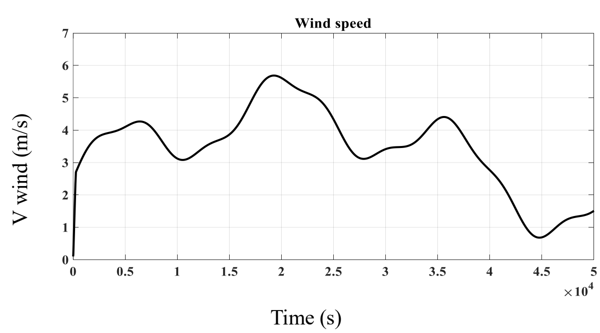


Fig. 5 The wind profile.

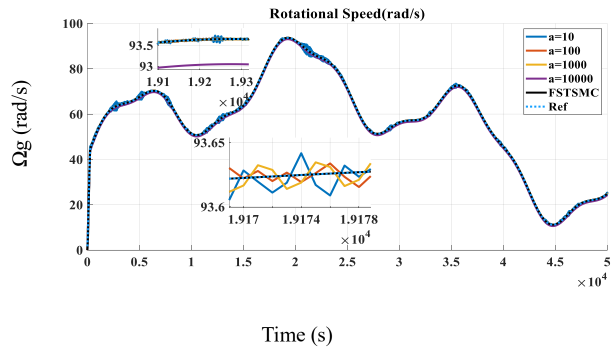


Fig. 6 The Rotational Speed.

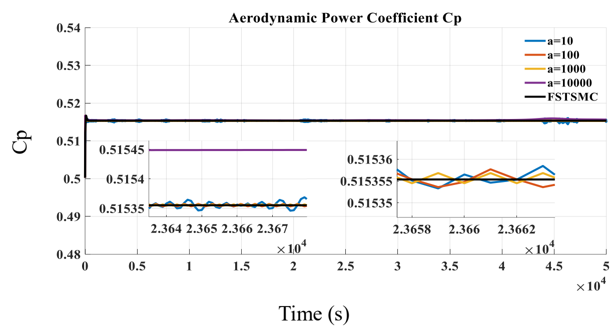


Fig. 7 The Power Coefficient.

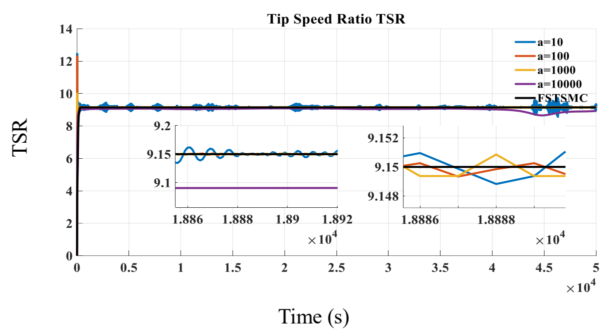


Fig. 8 The Tip Speed Ratio.

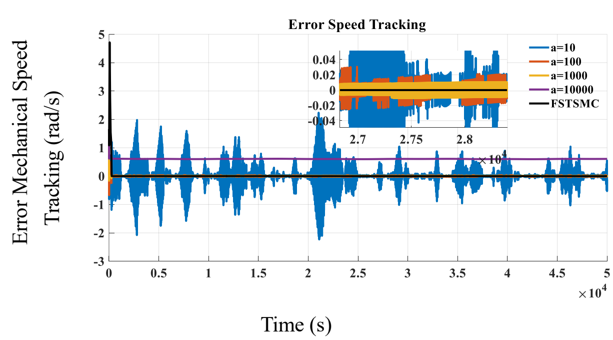


Fig. 9 The Error Mechanical Speed Tracking.

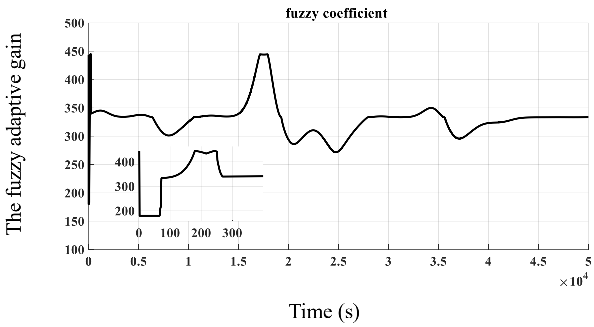


Fig. 10 The fuzzy adaptive gain for reference tracking test.

The dynamic variations in mechanical speed, shown in Fig. 6 , were extracted from the MPPT control system in response to fluctuating wind speeds. The MPPT technique effectively maintains the C_p at its peak value of 0.515, as observed in Fig. 7, while keeping the rotor speed optimized (Fig. 8).

Figure 9 present the tracking errors in mechanical speed and demonstrate the attenuation of chattering phenomena with the STSMC method. When FSTSMC is applied, this error approach zero, thanks to the optimal automatic selection of variable control gains (Fig. 10). This strategy significantly reduces chattering, bringing notable benefits to the system in terms of stability and overall performance.

The test evaluated STSMC performance across different values of α, revealing the critical importance of its selection. The results indicate that increasing α from 10 to 1000 enhances performance, but further increasing it to 10000 deteriorates the results. Fuzzy logic control enables highly adaptive adjustment of α in response to changing wind speeds, optimizing the system through the electromagnetic torque signals T_{em} and T_{em}*.

8.2 Second Test: Analytic Comparison

Four performance indices were used to statistically evaluate the system under various wind profiles, with lower values indicating optimal control [11,19]. The indices analyzed are IAE, ISE, ITSE, and ITAE. The FSTSMC algorithm outperforms STSMC on all key metrics. As shown in Table III, FSTSMC achieves the lowest values for Ω_g, C_p, and λ, proving that the FSTSMC strategy significantly improves the WT system's performance.

This reflects the superior efficiency of the FSTSMC approach, delivering substantial performance gains, particularly in reducing mechanical speed tracking errors, with improvements reaching over 99% in some key metrics.

TABLE III. Analytical comparison of wind turbine performance using SMC and FSTSMC methods.

	Method	**Performance index**			
		IAE	**ISE**	**ITSE**	**ITAE**
Ω_g	STSMC	7.833	18.62	46.56	19.58
	FSTSMC	0.066	0.1714	1.56e-3	0.016
	Improvement	**99.16%**	**99.08%**	**99.997%**	**99.92%**
C_p	STSMC	0.0026	4.46e-6	1.57e-5	0.008
	FSTSMC	2.5e-4	1.24e-7	2.5e-8	5.5e-4
	Improvement	**90.38%**	**97.22%**	**99.84%**	**93.13%**
λ	STSMC	1.66	1.46	4.91	5.14
	FSTSMC	0.052	0.20	7.1e-4	0.004
	Improvement	**96.87%**	**86.30%**	**99.99%**	**99.92%**

9 Conclusion

The proposed FSTSMC approach for wind turbine control demonstrates significant advancements in performance compared to traditional methods. The integration of fuzzy logic allows for dynamic adjustment of control gains, enhancing the system's adaptability to varying wind conditions. Simulation results indicate that FSTSMC effectively minimizes chattering, optimizes tracking speed, and maintains the power coefficient at its peak value during Maximum Power Point Tracking (MPPT). Performance metrics reveal substantial improvements in key indices, affirming the efficacy of FSTSMC in enhancing overall system responsiveness and efficiency. Future work could explore further optimizations and real-world applications to validate these findings.

References

[1] B . Desalegn, D. Gebeyehu, B.Tamrat , "Wind energy conversion technologies and engineering approaches to enhancing wind power generation: A review," Heliyon, vol. 8, pp. 1-21, 2022.

[2] M. Abolvafaei and S. Ganjefar, "Maximum power extraction from wind energy system using homotopy singular perturbation and fast terminal sliding mode method," Renewable Energy, vol. 148, pp. 611-626, 2020.

[3] Y. Dvir and A. Levant, "Accelerated Twisting Algorithm," IEEE Transactions on Automatic Control, vol. 60, pp. 2803-2807, 2015.

[4] J. Mérida, L. T. Aguilar and J. Dávila, "Analysis and synthesis of sliding mode control for large scale variable speed wind turbine for power optimization," Renewable Energy, vol. 71, pp. 715-728, 2014.

[5] S. Bellarbi, D. S. Koussa and A. Djoudi, "Sliding Mode Control for PMSG-based Wind Power System," Journal of Physics: Conference Series, vol. 1081, p. 012012, 9 2018.

[6] V. Utkin, A. Poznyak, Y. Orlov and A. Polyakov, "Conventional and high order sliding mode control," Journal of the Franklin Institute, vol. 357, pp. 10244-10261, 2020.

[7] Z. Xu, Q. Liu, and J. Yao," Funnel function-based adaptive prescribed performance output feedback control of hydraulic systems with disturbance observers," ISA transactions, vol 136, pp.701-714, 2023.

[8] F. A. Patakor, M. Sulaiman and Z. Ibrahim, "Adaptive sliding mode for indirect field oriented controlled of induction motor," Proceedings - 2011 IEEE Student Conference on Research and Development, SCOReD 2011, pp. 289-293, 2011.

[9] A. Alkamachi and E. Erçelebi, "A proportional derivative sliding mode control for an overactuated quadcopter," Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, vol. 233, pp. 1354-1363, 2019.

[10] Sara Kadi, Habib Benbouhenni, and Nicu Bizon. Using dual type 2 fuzzy logic technique to increase performance of the wind turbine system. In 2024 16th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), pages 1–6, 2024.

[11] Sara Kadi, Khoukha Imarazene, El Madjid Berkouk, Mohamed Horch, and Emad Abdelkarim. High order sliding mode of connected dfig-variable speed wind turbine. In 2022 19th International Multi-Conference on Systems, Signals Devices (SSD), pages 1275–1280, 2022.

[12] Sara Kadi, Habib Benbouhenni, Emad Abdelkarim, Khoukha Imarazene, and El Madjid Berkouk. Implementation of third-order sliding mode for power control and maximum power point tracking in dfig-based wind energy systems. Energy Reports, 0:3561–3579, 2023.

[13] S. Kouadria, E. M. Berkouk, Y. Messlem and M. Denaï, "Improved control strategy of DFIG-based wind turbines using direct torque and direct power control techniques," Journal of Renewable and Sustainable Energy, vol. 10, p. 043306, 2018.

[14] M. Mazen Alhato, S. Bouallègue and H. Rezk, "Modeling and Performance Improvement of Direct Power Control of Doubly-Fed Induction Generator Based Wind Turbine through Second-Order Sliding Mode Control Approach," Mathematics, vol. 8, 2020.

[15] ara Kadi, Khoukha Imarazene, El Madjid Berkouk, Habib Benbouhenni, and Emad Abdelkarim. A direct vector control based on modified smc theory to ontrol the double-powered induction generator-based variable-speed contra-rotating wind turbine systems. Energy Reports, 8:15057–15066, 2022.

[16] K. Mei, J. Liu and S. Ding, "Output Feedback SOSM Control of Constrained Systems With Unmatched Uncertainties," in IEEE Transactions on Automation Science and Engineering, doi: 10.1109/TASE.2024.3470779 , 2024.

[17] S. V. Emelyanov, S. K. Korovin and L. V. Levantovskiy, "A drift algorithm in control of uncertain processes.," Prob. Control Info. Theory., vol. 15, pp. 425-438, 1986.

[18] Y. Zhang, J. Zhu, Z. Zhao, W. Xu and D. G. Dorrell, "An Improved Direct Torque Control for Three-Level Inverter-Fed Induction Motor Sensorless Drive," IEEE Transactions on Power Electronics, vol. 27, pp. 1502-1513, 2012.

[19] A. Poorfakhraei, M. Narimani, and A. Emadi, "A review of modulation and control techniques for multilevel inverters in traction applications," Ieee Access, vol. 9, pp.24187-24204, 2021.

[20] Y.V. Sambhavi, and V. Ramachandran," A technical review of modern traction inverter systems used in electric vehicle application," Energy Reports, vol. 10, pp.3882-3907, 2023.