



ENHANCED CONTROL OF DFIG-BASED WIND TURBINE USING HYBRID FUZZY SUPER-TWISTING SLIDING MODE CONTROL FOR IMPROVED POWER QUALITY AND ROBUSTNESS

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ABSTRACT

In the pursuit of advancing renewable energy technologies, optimizing wind turbine performance through sophisticated control systems is pivotal for addressing energy variability and enhancing system efficiency. This paper presents a novel hybrid fuzzy super-twisting sliding mode control (HFSTSMC) strategy for Doubly Fed Induction Generators (DFIGs) used in modern wind turbine configurations. DFIGs are favored for their adaptability and efficiency in managing variable wind speeds, making them integral to sustainable energy solutions. The proposed HFSTSMC integrates the robustness of super-twisting sliding mode control (STSMC) with the adaptive capabilities of fuzzy logic control (FLC), aiming to mitigate the chattering effect inherent in traditional sliding mode controls while maintaining high tracking accuracy and robustness. The hybrid controller utilizes fuzzy logic to dynamically adjust control gains based on system states, enhancing the dynamic performance and stability of DFIG-based wind turbines. Extensive modeling and simulation using MATLAB/SIMULINK validate the effectiveness of HFSTSMC in improving power quality, reducing mechanical stresses, and optimizing energy capture. The results demonstrate significant improvements in system response to rapid wind condition changes and overall operational efficiency under transient and uncertain conditions. This research underscores the substantial benefits of implementing HFSTSMC, highlighting its potential to revolutionize wind turbine control systems and contribute significantly to the global transition towards reliable and efficient renewable energy sources.



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I. INTRODUCTION

As the global demand for renewable energy sources intensifies, wind energy has emerged as a vital component of sustainable energy portfolios [1]. The efficiency and reliability of wind turbines are paramount for harnessing this resource effectively. Doubly Fed Induction Generators (DFIGs) are widely employed in modern wind turbine systems due to their superior ability to handle variable wind speeds and contribute to the stability of electrical grids [2]. Traditional control strategies for DFIG-based wind turbines often face challenges such as chattering phenomena and sensitivity to system uncertainties, which can compromise performance and reliability. Sliding Mode Control (SMC) has been recognized for its robustness and effectiveness in dealing with non-linearities and uncertainties. However, conventional SMC techniques are prone to chattering, which can lead to excessive mechanical stress and energy losses [3]. [4]. To address these challenges, this paper proposes a novel Hybrid Fuzzy Super-Twisting Sliding Mode Control (HFSTSMC) approach.

This advanced control strategy combines the robustness of Super-Twisting Sliding Mode Control (STSMC) with the adaptability of Fuzzy Logic Control (FLC). The integration of fuzzy logic allows for dynamic adjustment of control parameters, thereby enhancing system performance and mitigating chattering effects[4-7]. The proposed HFSTSMC strategy aims to improve the dynamic performance, power quality, and operational stability of DFIG-based wind turbines. Extensive modeling and simulation studies are conducted using MATLAB/SIMULINK to evaluate the effectiveness of the proposed control approach. The results demonstrate significant improvements in system responsiveness to rapid changes in wind conditions, reduction in mechanical stresses, and overall optimization of energy capture. This research highlights the potential of HFSTSMC to revolutionize wind turbine control systems, offering a robust and efficient solution for maximizing wind energy utilization. The findings underscore the importance of advanced control strategies in the global transition towards renewable energy sources and the sustainable development of wind energy technology.

II. SYSTEM MODELING

II.1 AERODYNAMIC MODELING

The rotation of the blades due to wind speed generates mechanical power in the shaft. This mechanical power is then converted into electrical power by the Doubly Fed Induction Generator (DFIG)[8-10].

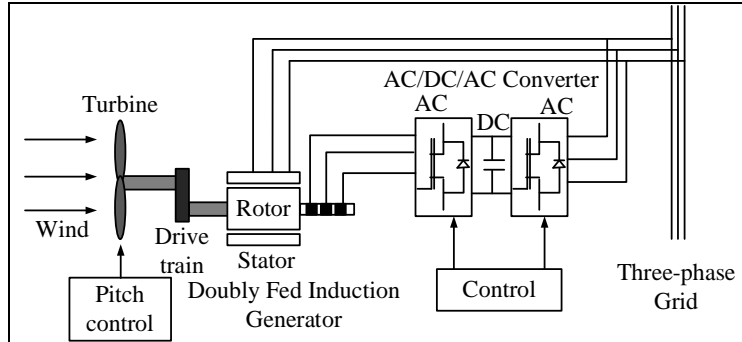


Figure 1: Wind power system.
Source: Authors, (2026).

The power output of the turbine can be described by Eq.(1):

$$P_T = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V_w^3 \quad (1)$$

The power coefficient $C_p(\lambda, \beta)$ is determined using the equations provided in [1]:

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3 \beta - C_4 \right) e^{\frac{C_5}{\lambda_i}} + C_6 \lambda \quad (2)$$

With $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$, $C_1 = 0.52$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$ and $\lambda = \frac{R\omega_{mech}}{v_w}$

By maintaining the tip speed ratio λ at its optimal value (λ_{opt}) the coefficient is at its maximum then as shown in figure (2), the optimal power can calculate using the following equation :

$$P_s^* = \frac{1}{2} C_{pmax}(\lambda_{opt}) \rho \pi R^2 V_w^3 \quad (3)$$

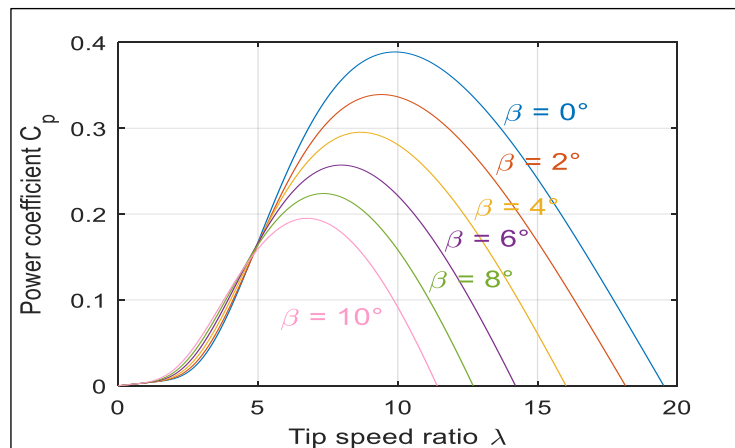


Figure 2: tip speed ratio (λ) vs. Power coefficient (C_p) curve.
Source: Authors, (2026).

II.2 DFIG SYSTEM MODELING

The Doubly Fed Induction Generator (DFIG) is a variable-speed wind turbine generator that efficiently converts wind energy into electrical power. DFIG employs both rotor and grid-side converters, allowing for better control of generator speed and enhanced power quality in the generated output [6-7].

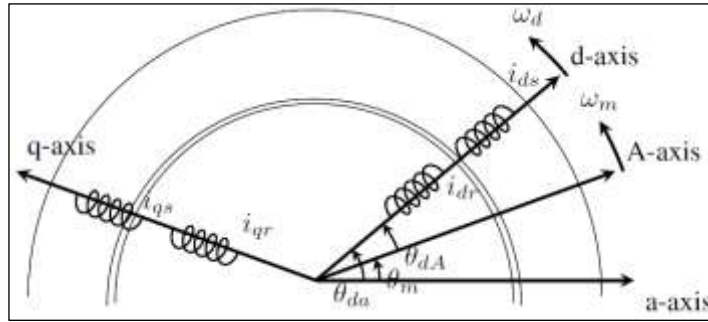


Figure 3: Illustration of stator and rotor with equivalent dq winding. Source: [6].

After applying the Park transformation and subsequent mathematical derivation as referenced in [8], it was determined:

- The stator, rotor voltages

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d}{dt} \phi_{ds} - \omega_d \phi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d}{dt} \phi_{qs} + \omega_d \phi_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d}{dt} \phi_{dr} - \omega_{dA} \phi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d}{dt} \phi_{qr} + \omega_{dA} \phi_{dr} \end{cases} \quad (4)$$

- The fluxes can be found in Eq.(5)

$$\begin{cases} \phi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \phi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \phi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \phi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \quad (5)$$

- The stator powers are presented in Eq.(6)

$$\begin{cases} P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \\ Q_s = v_{qs} i_{ds} - v_{ds} i_{qs} \end{cases} \quad (6)$$

- The electromagnetic torque equation

$$T_{em} = \frac{P}{2} L_m (\phi_{qr} i_{dr} - \phi_{dr} i_{qr}) \quad (7)$$

From Eq.(4), by replacing the fluxes with rotor currents and after Laplace transformation, we obtain:

$$\begin{cases} i_{dr} = \frac{1}{R_r + s\sigma L_r} v'_{dr} \\ i_{qr} = \frac{1}{R_r + s\sigma L_r} v'_{qr} \end{cases} \quad (8)$$

Table 1: Parameters of wind turbine & DFIG.

Parameter	Definition	Value	Unit
J_{Turb}	Wind Turbine Moment of Inertia	2.4×10^6	Kg.m^2
ρ	Air Density	1.2	Kg.m^3
D	Rotor Diameter for the Wind Turbine (2R)	70.5	M
R_r	Resistance of the Rotor	1.5	$m\Omega$
R_s	Resistance of the Stator	2.0	$m\Omega$
L_r	Leakage of the Rotor	24	mH
L_s	Leakage of the Stator	24	mH
L_m	Mutual Leakage	23	mH
f_{syn}	Rated Frequency	60	Hz
P	Poles	6	.
J	DFIG Moment of inertia	75	Kg.m^2

Source: Authors, (2026).

III. CONTROLLER

III.1 SUPER TWISTING SLIDING MODE CONTROL

Super-Twisting Sliding Mode Control (STSMC) is a robust control technique that enhances the traditional SMC by reducing the chattering effect without compromising the system's robustness. The STSMC is a second-order sliding mode control method that does not require the derivative of the sliding variable, making it suitable for practical applications [9-13].

The STSMC law can be described by the following equations:

$$u = u_{eq} + u_n \tag{9}$$

Designing the sliding mode surface as [9] was the initial stage in creating the Super-Twisting Sliding Mode Controller (STSMC):

$$S = \left(\lambda + \frac{d}{dt} \right)^{r-1} e \tag{10}$$

The tracking error is represented by e , the system order is indicated by r , and the variable λ needs to meet the Hurwitz condition. According to Eq. (8), since $r=1$, our surface become:

$$S = e = I_{dqrDesired} - I_{dr} \tag{11}$$

The Lyapunov function is defined as:

$$V = \frac{1}{2} S^2 \tag{12}$$

The Lyapunov function derivative in Eq. (12) must meet $\dot{V} < 0$ as $S\dot{S} < 0$ in order to guarantee the stability criterion. The sliding mode function's derivative is:

$$\dot{S} = \dot{e} = \dot{I}_{dqrDesired} - \dot{I}_{dr} \tag{13}$$

$$\dot{S} = \dot{e} = \dot{I}_{dqrDesired} + \frac{(R_r I_{dqr} - V_{dqr})}{\sigma L_r} \tag{14}$$

Therefore, the Lyapunov function may be derived as follows:

$$S\dot{S} = S \left(\dot{I}_{dqrDesired} + \frac{(R_r I_{dqr} - V_{dqr})}{\sigma L_r} \right) \tag{15}$$

To satisfy the condition $S\dot{S} < 0$, the sliding mode controller is designed as:

$$u_{dqr}^{eq} = \sigma L_r (\dot{I}_{dqrDesired} + R_r I_{dqr}) \tag{16}$$

Ultimately, a discontinuous control term has been introduced to determine the sliding mode control law, as illustrated in Eq.(17) :

$$u_n = -k_1 \sqrt{|S|} \text{sign}(S) + \int (-k_2 \text{sign}(S)) dt \tag{17}$$

Where k_1, k_2 are strictly positive gains.

Consequently, the resulting control signal is formulated as follow:

$$u = u_{eq} + u_n = \sigma L_r (\dot{I}_{dqrDesired} + R_r I_{dqr}) - k_1 \sqrt{|S|} \text{sign}(S) + \int (-k_2 \text{sign}(S)) dt \tag{18}$$

III.2 FUZZY LOGIC ENHANCEMENT

To enhance the performance of the STSMC, a fuzzy logic controller (FLC) can be incorporated to dynamically adjust the gains k_1 and k_2 . The FLC uses system state information to modify these gains in real-time, improving the controller's adaptability and reducing residual chattering [14-16]. Input fuzzy membership functions, Our Fuzzy Logic Controller (FLC) uses input membership functions to establish a connection between the control decisions and the error signal. In Figure 4 [1], these membership functions are shown.

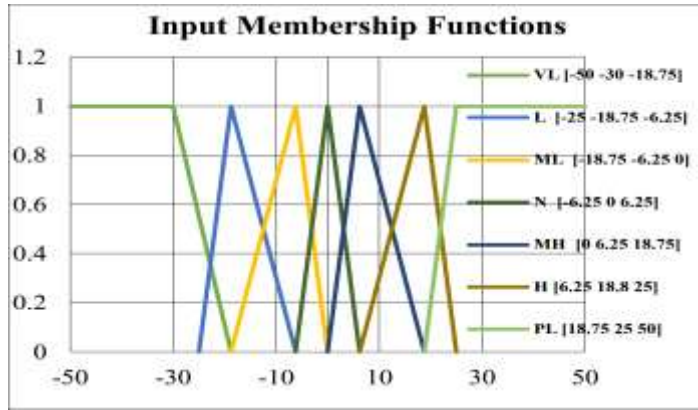


Figure 4: Input variables.
Source: Authors, (2026).

The linguistic variables are: "Very Low", "Low", "Moderately Low", "Neutral", "Moderately High", "High" and "Very High" error magnitudes.

– Output fuzzy membership functions

The FLC can precisely modify the gains k_1 and k_2 of the Super-Twisting Sliding Mode Controller (STSMC) due to these output membership functions. This improves the overall performance and stability of the DFIG-based wind turbine by allowing it to function at its best in a variety of wind situations.

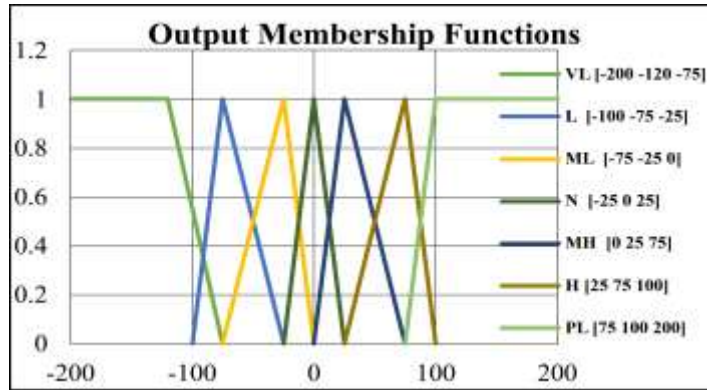


Figure 5: Output variables.
Source: Authors, (2026).

– Rules

These rules define how the FLC interprets input conditions and determines appropriate control actions, enabling it to mimic human-like reasoning and adapt to complex control scenarios.

Table 2: Fuzzy rules.

Output Input	VL	L	ML	N	MH	H	VH
VL	✓
L	.	✓
ML	.	.	✓
N	.	.	.	✓	.	.	.
MH	✓	.	.
H	✓	.
VH	✓

Source: Authors, (2026).

To create HFSTSMC, we replace the discontinuous sign function Sign(S) with a continuous fuzzy logic function Fuzzy(S). This modification helps to smooth out the control action and reduce chattering. The fuzzy logic controller dynamically adjusts the control signal based on the system's state.

The modified control law becomes:

$$u = \sigma L_r (\dot{i}_{dqrDesired} + R_r I_{dqr}) - k_1 \sqrt{|S|} Fuzzy(S) + \int (-k_2 Fuzzy(S)) dt \tag{19}$$

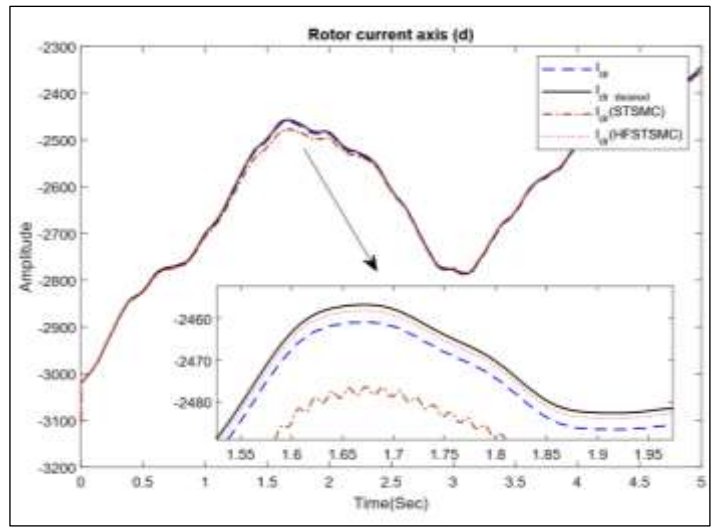
IV. RESULTS AND DISCUSSIONS

A Matlab simulation environment was used to assess the efficiency of the examined control techniques [17-19]. The main topics of the simulation were parameter fluctuation and reference tracking. The research made use of a Doubly Fed Induction Generator (DFIG) running at a nominal system voltage of $V_s = 398/690V$, with parameters shown in Table 1.

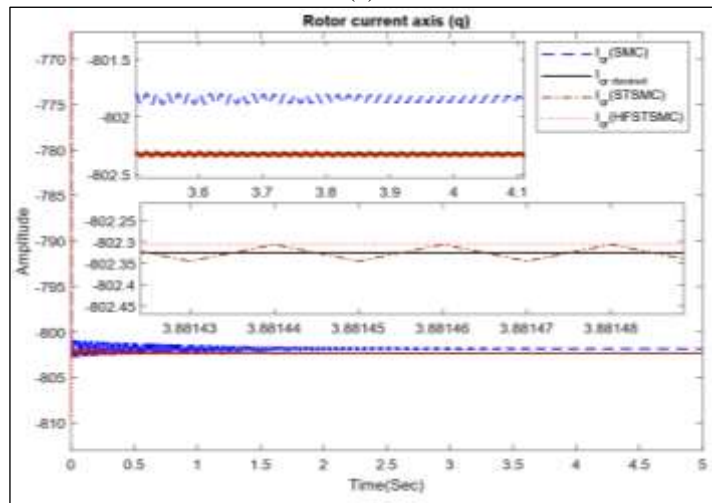
IV.1 TRACKING THE REFERENCE SIGNAL

The reaction of the Hybrid Fuzzy Super Twisting Sliding Mode Controller (HFSTSMC) to changing conditions in the environment was tested using a realistic wind speed profile. In order to maintain a unit power factor, the reference for reactive power ($Q_{sref} = 0$) was set to zero and the reference for active power (P_{sref}) was added using the MPPT technique. The performance of the Hybrid Fuzzy Super-Twisting Sliding Mode Control (HFSTSMC) was compared against the conventional Sliding Mode Control (SMC) and the Super-Twisting Sliding Mode Control (STSMC) to evaluate its effectiveness in controlling a DFIG-based wind turbine. Figure 6 clearly demonstrates that the HFSTSMC exhibited significantly less error compared to both SMC and STSMC. This indicates that the hybrid approach, incorporating fuzzy logic, effectively enhances the accuracy of the control system by dynamically adjusting the control gains in response to varying system states. The reduced error translates to more precise tracking of the desired rotor current, which is crucial for maintaining optimal performance in fluctuating wind conditions.

Figure 7 highlights a critical advantage of the HFSTSMC over the STSMC. The HFSTSMC successfully mitigated the chattering effect, which is a common issue with conventional sliding mode controllers. Chattering can lead to excessive mechanical wear and reduced efficiency. By integrating fuzzy logic to smooth the control actions, the HFSTSMC provides a more stable and efficient operation, minimizing the adverse effects of chattering observed in STSMC. The speed response of the control systems, depicted in Figure 8, showcases the superior performance of the HFSTSMC. The HFSTSMC achieved an extremely fast response with a settling time of $0.05\ ms$, which is ten times faster than the other control strategies. This rapid response is essential for the DFIG-based wind turbine to quickly adapt to changes in wind speed and maintain optimal power output. The significant reduction in settling time underscores the effectiveness of the fuzzy logic-enhanced super-twisting algorithm in improving the dynamic response of the system.

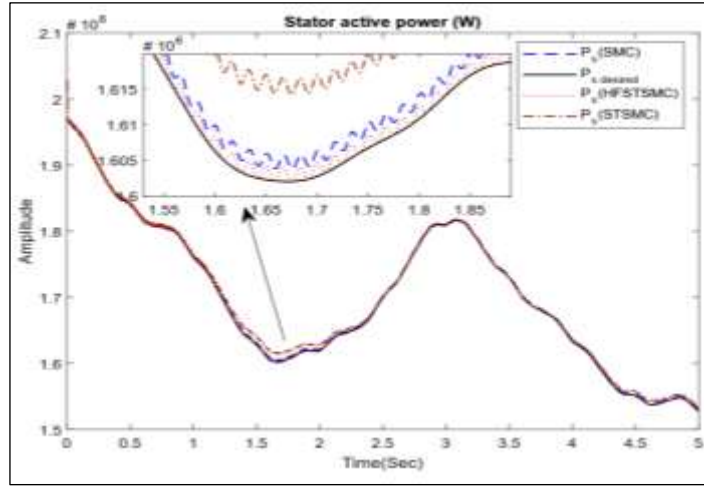


(a)

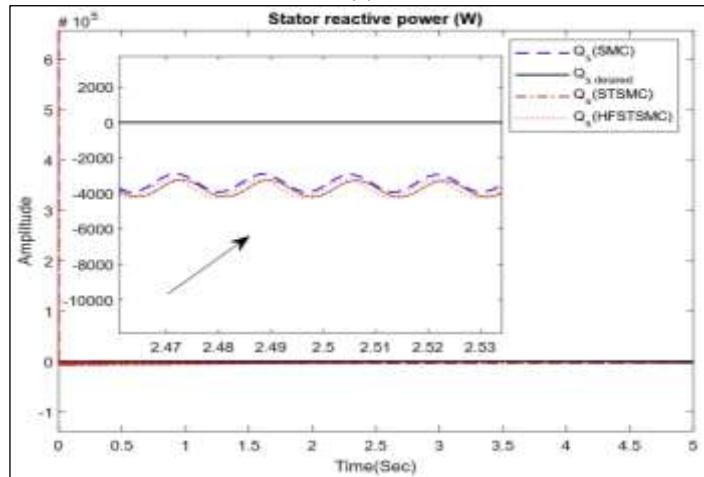


(b)

Figure 6: (a) behavior rotor current along d-axis; (b) behavior current along q-axis. Source: Authors, (2026).



(a)



(b)

Figure 7: (a) behavior of stator active power; (b) behavior of stator reactive power.
Source: Authors, (2026).

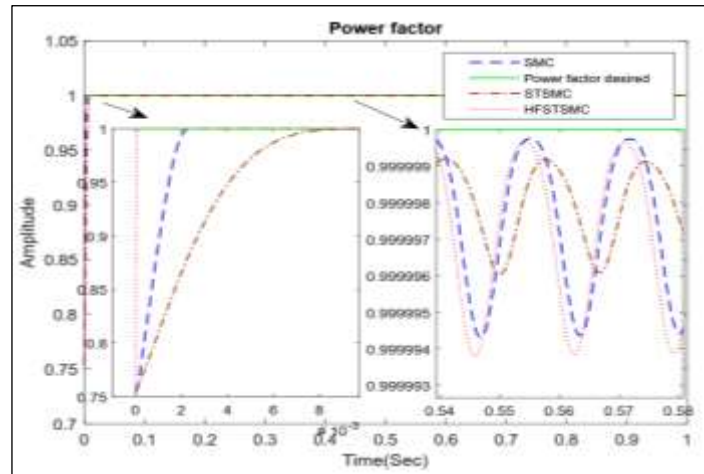


Figure 8: Power factor.
Source: Authors, (2026).

IV.2 ROBUSTNESS

In this section, we evaluate the robustness of the proposed control strategies by altering the reference value of reactive power. This assessment aims to determine how well each control method can adapt to changes in reactive power demands. Additionally, a stepped wind profile is employed to simulate realistic and challenging wind conditions, further testing the resilience and stability of the control systems. This robustness analysis is crucial for ensuring the reliability of DFIG-based wind turbines under varying operational scenarios. Figures 9 and 10 illustrate that the Super-Twisting Sliding Mode Control loses precision when subjected to parameter variations. The control system's ability to accurately track the desired reactive power reference diminishes, highlighting its sensitivity to changes in system parameters.

In contrast, the Hybrid Fuzzy Super-Twisting Sliding Mode Control demonstrates superior robustness. Both figures show that the HFSTSMC maintains its precision and performance even when the system parameters are varied. This indicates that the fuzzy logic component effectively adapts to changes, ensuring consistent control accuracy. Another critical aspect of robustness is the response time of the control system. The HFSTSMC not only preserves its fast response time but also shows no signs of chattering despite the parameter variations and stepped wind profile. This is a significant improvement over the STSMC, which exhibits degraded performance and increased chattering under the same conditions.

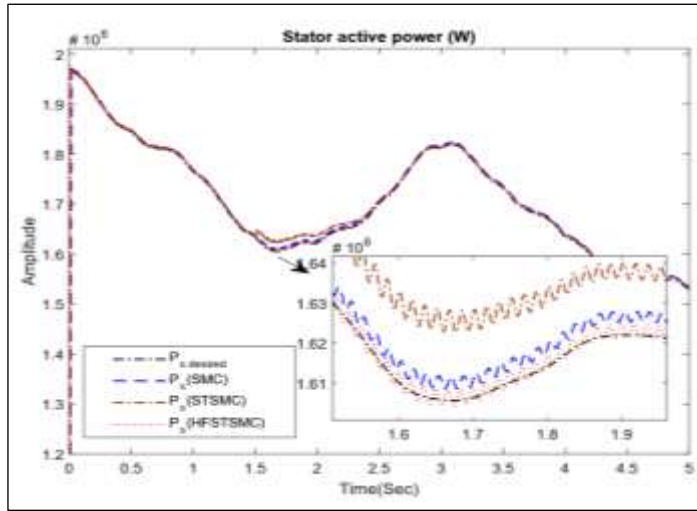


Figure 9: Behavior of stator active power with a 100% variation in R_r , 60% variation in L_r , and 10% variation in L_m .
Source: Authors, (2026).

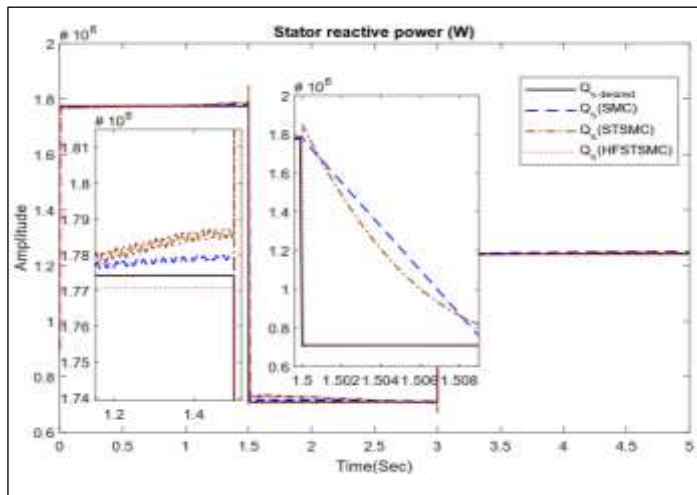


Figure 10: Behavior of stator reactive power with a 100% variation in R_r , 60% variation in L_r , and 10% variation in L_m .
Source: Authors, (2026).

V. CONCLUSIONS

This study presents a comprehensive analysis of advanced control strategies for Doubly Fed Induction Generator (DFIG)-based wind turbines, focusing on the development and implementation of a Hybrid Fuzzy Super-Twisting Sliding Mode Control (HFSTSMC) system. The primary goal was to enhance the robustness, accuracy, and efficiency of wind turbine operations under varying and challenging conditions. The HFSTSMC outperformed traditional Sliding Mode Control (SMC) and Super-Twisting Sliding Mode Control (STSMC) in several key aspects. The integration of fuzzy logic with super-twisting sliding mode control effectively reduced the chattering effect, improved control accuracy, and maintained rapid response times even under parameter variations and fluctuating wind conditions. Simulation results confirmed that the HFSTSMC provided superior performance in tracking the desired reactive power reference and exhibited remarkable resilience to changes in system parameters. These findings underscore the potential of HFSTSMC as a highly effective and reliable control strategy for DFIG-based wind turbines. By enhancing the precision and robustness of wind turbine control, this approach significantly contributes to the optimization of wind energy capture and the stability of renewable energy systems. The successful implementation of HFSTSMC highlights its importance in advancing the efficiency and reliability of sustainable energy solutions.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: A.F.
Methodology: Y.D.
Investigation: A.F.
Discussion of results: A.F, M.A.D.

Writing – Original Draft: A.F.

Writing – Review and Editing: A.F, M.A.D.

Supervision: L.F, A.B.

Approval of the final text: A.F.

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