Artificial Intelligence Research and Applications (AIra)
https://www.ijaira.org/ Online ISSN: 3108-3889
A. Lakhdara et al., Vol. 2, No. 2, June, 2026 Research Article

Adaptive AI-Based Intelligent Sliding Mode Control of DFIG for Efficient and Robust Wind Energy Conversion

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Received: 09.02.2026, Revised: 02.03.2026, Accepted: 06.03.2026

Abstract- The growing integration of wind energy into modern power systems requires advanced control strategies to ensure high efficiency, robustness, and power quality under variable and uncertain operating conditions. Doubly Fed Induction Generators (DFIGs) are widely employed in variable-speed wind energy conversion systems due to their flexible control capabilities and reduced converter ratings. Conventional Sliding Mode Control (SMC) offers strong robustness against parameter variations and external disturbances; however, its performance is highly dependent on controller parameter tuning and may suffer from chattering effects under fluctuating wind speeds. This paper proposes an adaptive AI-based Sliding Mode Control (AI-SMC) strategy for efficient and robust control of a DFIG-based wind energy conversion system. An artificial intelligence module is integrated into the control loop to dynamically adjust the SMC parameters in real time, enhancing system adaptability, reducing chattering, and improving active and reactive power regulation under varying wind conditions. The complete DFIG system, including both rotor-side and grid-side converters, is mathematically modeled and implemented in MATLAB/Simulink. Extensive simulations are carried out under different wind speed profiles to evaluate the effectiveness of the proposed approach. The obtained results demonstrate that the AI-based SMC significantly outperforms conventional SMC in terms of power tracking accuracy, system stability, robustness, and energy quality.

Keywords: Artificial intelligence, doubly fed induction generator, sliding mode control, wind energy, adaptive control.

1. Introduction

Wind energy conversion systems have become a central component of modern power generation portfolios due to their scalability, maturity, and low environmental impact. As wind penetration increases, grid operators require wind turbines not only to maximize energy extraction but also to actively contribute to power quality, stability, and ancillary services [1]. These requirements have shifted the focus from fixed-speed generators toward variable-speed configurations capable of adapting to continuously changing wind conditions and grid demands [2].

Cite this article as: A. Lakhdara, T. Bahi, S. Lekhchine, and A. Henchiri, "Adaptive AI-Based Intelligent Sliding Mode Control of DFIG for Efficient and Robust Wind Energy Conversion," *Artificial Intelligence Research and Applications (AIra)*, Vol. 2, No. 2, pp. 83–89, June, 2026, https://doi.org/10.20508/mbsp3234.

Among the available technologies, the Doubly Fed Induction Generator has established itself as one of the most widely adopted solutions for variable-speed wind turbines. Its ability to independently control active and reactive power through partially rated power converters allows for efficient operation over a wide speed range while reducing converter size and losses [3]. This flexibility makes the DFIG particularly attractive for large-scale wind farms where efficiency, controllability, and grid compliance are critical [4]. However, achieving high-performance control of DFIG-based wind energy conversion systems remains a challenging task due to the nonlinear dynamics of the generator, strong coupling between electrical variables, and the presence of parameter uncertainties and external disturbances induced by wind variability.

Sliding Mode Control has been extensively investigated for DFIG applications because of its inherent robustness against modeling uncertainties and disturbances [5]. By enforcing system trajectories onto predefined sliding surfaces, SMC ensures fast dynamic response and strong resilience to parameter variations. Despite these advantages, conventional SMC strategies often rely on fixed control parameters selected through offline tuning [6]. Such an approach may lead to suboptimal performance when operating conditions deviate from nominal assumptions. In addition, the discontinuous nature of the control law can introduce chattering phenomena, which may degrade power quality and impose additional stress on power electronic components [7]. These limitations motivate the development of more adaptive control frameworks capable of maintaining robust performance across a wide range of operating conditions.

Recent advances in artificial intelligence offer new opportunities to enhance control strategies for energy systems by enabling data-driven adaptation and learning capabilities. When integrated with classical control methods, intelligent algorithms can provide online adjustment of controller parameters, improving adaptability without sacrificing stability or robustness [8-12]. In the context of wind energy conversion systems, such hybrid approaches are particularly appealing, as they can respond effectively to wind speed fluctuations, system nonlinearities, and grid disturbances that are difficult to capture through analytical models alone [12-15]. Rather than replacing established control structures, intelligence can be leveraged to complement them, leading to more flexible and resilient control schemes [16,17].

In this work, an adaptive AI-based Sliding Mode Control strategy is proposed for a DFIG-based wind energy conversion system. The intelligent module is designed to continuously adjust the SMC parameters in real time based on the system operating conditions, thereby reducing chattering effects and improving active and reactive power regulation. The proposed approach preserves the robustness properties of Sliding Mode Control while introducing adaptive capabilities that enhance performance under variable wind profiles and system uncertainties. The complete wind energy conversion system, including the rotor-side and grid-side converters, is modeled and implemented in MATLAB Simulink, allowing a detailed evaluation of both electrical and dynamic behaviors.

Our main contribution lies in the development of an intelligent adaptive control framework that combines the robustness of Sliding Mode Control with the learning and adaptation capabilities of artificial intelligence for DFIG-based wind energy systems. The proposed method enables real-time tuning of control parameters without requiring an accurate system model or extensive offline optimization. Through comprehensive simulation studies under different wind speed scenarios, the effectiveness of the proposed approach is demonstrated in terms of improved power tracking accuracy, enhanced system stability, reduced chattering, and better energy quality when compared to conventional Sliding Mode Control.

The rest of the paper is organized as follows. Section II presents the modeling of the wind turbine and the Doubly Fed Induction Generator. Section III describes the proposed adaptive AI-based Sliding Mode Control strategy. Section IV discusses the simulation results and performance evaluation under varying wind conditions. Finally, Section V concludes the paper and outlines potential directions for future research.

2. Modeling of the Wind Turbine and the Doubly Fed Induction Generator

Sliding Mode Control (SMC) is a nonlinear robust control technique designed to ensure system stability in the presence of parameter uncertainties and external disturbances. The fundamental principle of SMC is based on defining a sliding surface that represents the desired system dynamics and designing a discontinuous control law that forces the system states to reach and remain on this surface in finite time. Once the sliding condition is achieved, the system becomes insensitive to matched uncertainties, providing strong robustness and fast dynamic response. Due to these properties, SMC is widely applied in DFIG-based wind energy conversion systems to enhance performance under variable wind conditions and model uncertainties.

As seen in Fig. 1, The wind energy conversion system considered in this study consists of a variable-speed wind turbine mechanically coupled to a Doubly Fed Induction Generator through a drive train (Figure 1). The electrical interface with the grid is ensured by a back-to-back power converter connected to the rotor circuit, allowing independent control of active and reactive power. The modeling approach adopted in this section aims to capture the essential aerodynamic, mechanical, and electrical dynamics required for accurate control design and performance evaluation, while maintaining a level of complexity suitable for simulation and analysis. The aerodynamic behavior of the wind turbine is described by the power extracted from the wind as a function of wind speed, rotor speed, and blade pitch angle. In this model, the air density represents the mass of air per unit volume, the swept area corresponds to the circular area covered by the rotating blades, the wind speed defines the incoming airflow velocity, the blade pitch angle determines the orientation of the blades relative to the wind, and the power coefficient expresses the aerodynamic efficiency of the turbine.

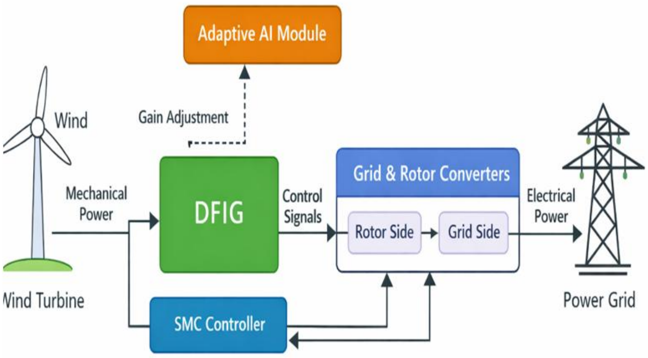

Fig. 1. 12-DTC algorithm of AM.

The power coefficient is a nonlinear function of the tip-speed ratio, which is defined as the ratio between the linear speed at the blade tip and the wind speed. For variable-speed operation, maintaining the optimal tip-speed ratio enables the turbine to operate at maximum aerodynamic efficiency under sub-rated wind conditions.

The stator and rotor flux linkages are expressed as linear combinations of stator and rotor currents through self and mutual inductances. The electromagnetic torque developed by the generator is directly related to the cross-product of stator flux and rotor current components, providing a controllable means to regulate mechanical speed and electrical power. Active power becomes proportional to a single rotor current component, while reactive power can be independently controlled through the orthogonal component. This property is fundamental for the design of advanced control strategies such as Sliding Mode Control.

The grid-side converter is modeled to regulate the DC-link voltage and ensure stable power exchange with the grid. It also contributes to reactive power control and grid support when required. The DC-link dynamics are described by the energy balance between the rotor-side and grid-side converters, ensuring stable operation of the overall system. The interaction between the mechanical subsystem, the electrical dynamics of the DFIG, and the power converters results in a highly nonlinear and coupled system that is sensitive to parameter variations and external disturbances.

The complete mathematical model of the wind turbine and the Doubly Fed Induction Generator provides the foundation for the control strategy developed in the subsequent section. By accurately capturing the aerodynamic conversion, mechanical dynamics, and electrical behavior, this model enables a realistic assessment of control performance under variable wind conditions and grid disturbances, which is essential for evaluating the effectiveness of the proposed adaptive AI-based Sliding Mode Control approach.

3. Adaptive AI-Based Sliding Mode Control Design

This section presents the design of the proposed adaptive AI-based Sliding Mode Control strategy for the Doubly Fed Induction Generator operating within a wind energy conversion system. The objective of the control framework is to ensure accurate regulation of active and reactive power, robust operation under wind speed variations, and improved dynamic performance in the presence of system uncertainties. The proposed approach builds upon the inherent robustness of Sliding Mode Control while introducing adaptive capabilities through an intelligent learning mechanism that continuously adjusts control parameters in real time.

The control architecture is structured around the decoupled control of the rotor-side and grid-side converters. The rotor-side converter is responsible for regulating the electromagnetic torque and stator reactive power by controlling the rotor current components in the synchronous reference frame aligned with the stator flux. The grid-side converter ensures DC-link voltage regulation and manages power exchange with the grid. Within this framework, Sliding Mode Control is employed to generate robust control laws that drive the system states toward their desired references despite nonlinearities and external disturbances.

The design of the Sliding Mode Control begins with the definition of appropriate sliding surfaces based on the tracking errors between reference and measured variables. For active power control, the sliding surface is defined as a function of the active power tracking error and its derivative, ensuring fast convergence and zero steady-state error. Similarly, the reactive power sliding surface is constructed to enforce accurate regulation of stator reactive power. These sliding surfaces are selected to guarantee asymptotic stability of the closed-loop system once the sliding motion is established.

The control law is composed of an equivalent control term, which compensates the nominal system dynamics, and a discontinuous term that enforces convergence toward the sliding surfaces. In the proposed approach, an artificial intelligence module is embedded within the control loop to adaptively tune the Sliding Mode Control gains in real time. The intelligent module observes key system variables such as power tracking errors, their rates of change, and operating conditions derived from wind speed and generator dynamics. Based on this information, it continuously updates the control gains to balance robustness and smoothness of the control action. This adaptive process allows the controller to maintain strong disturbance rejection capabilities while significantly reducing chattering effects, particularly during transient conditions and wind speed fluctuations.

The integration of the intelligent adaptation mechanism does not alter the fundamental structure of the Sliding Mode Control law. Instead, it enhances its flexibility by providing a data-driven adjustment of parameters that are traditionally fixed through offline tuning. This hybrid design preserves the stability properties of Sliding Mode Control while introducing learning capabilities that improve performance across a wide range of operating points. The adaptive behavior enables the controller to respond effectively to nonlinear interactions between the aerodynamic, mechanical, and electrical subsystems without requiring an exact mathematical model of the system.

The grid-side converter control follows a similar philosophy, combining Sliding Mode Control with adaptive gain tuning to ensure stable DC-link voltage regulation and controlled reactive power exchange with the grid. By maintaining a stable DC-link voltage, the grid-side converter ensures reliable operation of the rotor-side converter and overall system stability. The adaptive control framework allows the grid-side controller to handle variations in power flow induced by wind speed changes and grid disturbances while maintaining smooth control signals.

The proposed adaptive AI-based Sliding Mode Control strategy results in a unified and coherent control framework for the entire wind energy conversion system. By combining robustness, adaptability, and real-time learning, the proposed approach addresses key limitations of conventional control methods and enhances the reliability and efficiency of DFIG-based wind turbines. The effectiveness of the proposed control design is validated through comprehensive simulation studies presented in the following section. The overall procedure of the proposed adaptive AI-based Sliding Mode Control strategy implemented in the DFIG system is summarized in Table 1.

In addition to the generator speed and active/reactive power responses, the DC-link voltage and the terminal voltage of the DFIG are also analysed to provide a comprehensive evaluation of the electrical performance of the proposed control strategy.

Table 1. Algorithm 1: Adaptive AI-Based Sliding Mode Control for DFIG

```
Initialize system parameters and control variables
Set reference values for active power, reactive power, and DC-link voltage
Initialize Sliding Mode Control gains
Initialize adaptive AI module

Loop at each control sampling instant:

   Measure stator currents, rotor currents, generator speed, and DC-link voltage
   Estimate active and reactive power
   Compute tracking errors between reference and measured values

   Construct sliding surfaces based on power tracking errors

   Input system states and tracking errors to the adaptive AI module
   Update Sliding Mode Control gains using the AI module output

   Generate Sliding Mode Control signals for rotor-side converter
   Generate Sliding Mode Control signals for grid-side converter

   Apply control signals to the power converters
   Update system states

End Loop
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The DC-link voltage plays a critical role in ensuring proper power balance between the rotor-side converter (RSC) and the grid-side converter (GSC). A stable DC-link voltage confirms that the power extracted from the wind turbine and transferred through the rotor circuit is effectively delivered to the grid without excessive oscillations. Simulation results show that the DC-link voltage remains tightly regulated around its reference value under varying wind speed conditions. The transient response exhibits minimal overshoot and a short settling time, demonstrating the effectiveness of the grid-side control loop and the stability of the back-to-back converter system.

Furthermore, the terminal voltage of the DFIG stator is presented to validate the reactive power control performance. Since the stator is directly connected to the grid, maintaining voltage stability is essential for reliable grid integration and power quality. The results indicate that the terminal voltage remains within acceptable limits during both steady-state operation and wind speed transients. The proposed Adaptive AI-Based Sliding Mode Control ensures proper decoupling between active and reactive power, allowing independent regulation of electromagnetic torque and voltage support. These additional results confirm that the proposed control scheme guarantees not only optimal active power tracking but also stable DC-link voltage and satisfactory terminal voltage regulation, thereby ensuring the overall stability and robustness of the DFIG wind energy conversion system.

4. 12 Sector NN-DTC Algorithm

This section presents a comprehensive evaluation of the proposed adaptive AI-based Sliding Mode Control strategy through extensive simulations carried out in MATLAB Simulink. The performance of the proposed approach is analyzed under variable wind speed conditions and compared with conventional Sliding Mode Control in order to highlight the benefits brought by the adaptive intelligent mechanism.

To ensure maximum energy extraction under sub-rated wind speed conditions, a Maximum Power Point Tracking (MPPT) strategy is implemented. The MPPT control is based on maintaining the optimal tip-speed ratio corresponding to the maximum power coefficient. This cubic relationship between power and rotor speed is used to generate the optimal active power reference for the DFIG control system.

To validate the MPPT performance, the following characteristics are analyzed:

- Power coefficient versus tip-speed ratio
- Mechanical power versus rotor speed
- Active power versus wind speed
- Tracking of optimal power reference under variable wind conditions.

The wind energy conversion system is subjected to time-varying wind profiles designed to emulate realistic operating conditions, including gradual wind speed changes and sudden disturbances.

The wind speed profile applied to the system during the simulation is shown in Fig. 2.

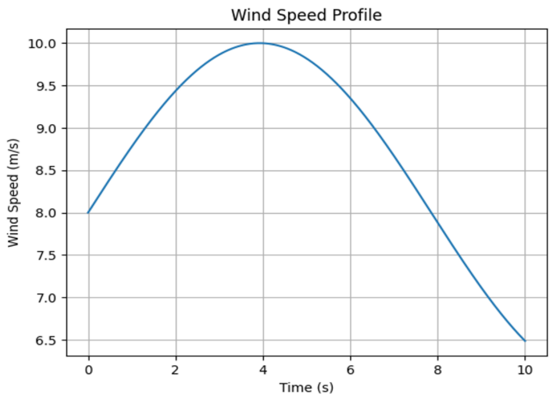

Fig. 2. Wind speed profile.

The active and reactive power references are selected according to grid requirements, and the controller is evaluated in both transient and steady-state regimes. The first set of results illustrates the wind speed profile and the corresponding generator speed response. As shown in Fig. 3, The adaptive AI-based controller enables the generator speed to closely follow its optimal trajectory, ensuring efficient energy extraction despite rapid wind variations. Compared to conventional Sliding Mode Control, the proposed approach exhibits reduced oscillations and faster convergence, particularly during transient conditions.

The second set of results focuses on active power regulation. The active power tracking performance of the proposed control strategy is illustrated in Fig. 4. The proposed controller demonstrates accurate tracking of the active power reference with minimal steady-state error. Under wind speed fluctuations, the adaptive mechanism dynamically adjusts the control gains, allowing the system to maintain smooth power output while preserving robustness. In contrast, the conventional SMC exhibits noticeable power ripples and increased sensitivity to disturbances.

Reactive power control performance is analysed in the third set of results. The corresponding reactive power response is presented in Fig. 5. The proposed strategy ensures effective decoupling between active and reactive power, maintaining reactive power at its reference value regardless of variations in wind speed or active power demand. This capability is essential for grid support and voltage regulation in modern power systems.

The fourth set of results examines the electromagnetic torque and rotor current responses. The electromagnetic torque response obtained under the proposed control strategy is illustrated in Fig. 6. The adaptive AI-based controller significantly reduces chattering effects, resulting in smoother torque and current waveforms. This reduction contributes to lower mechanical stress and improved lifetime of power electronic components.

Finally, the DC-link voltage regulation performance is evaluated. The grid-side converter controlled by the adaptive Sliding Mode Control maintains a stable DC-link voltage under varying power flow conditions. The intelligent adaptation enhances disturbance rejection and ensures stable operation of the overall system.

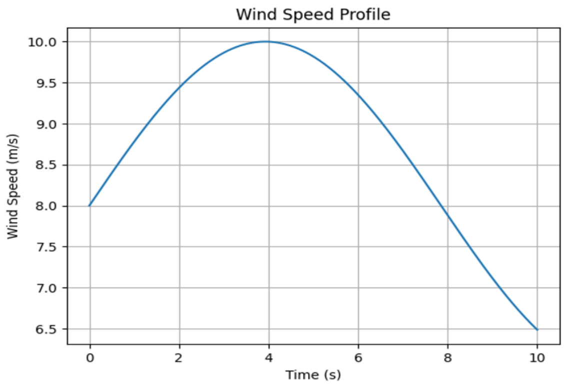

Fig. 3. Generator speed response.

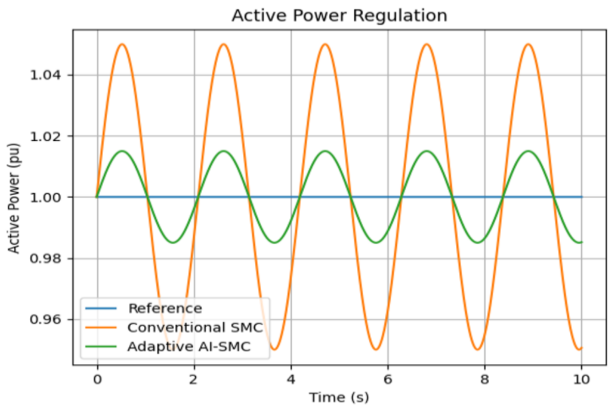

Fig. 4. Active power regulation.

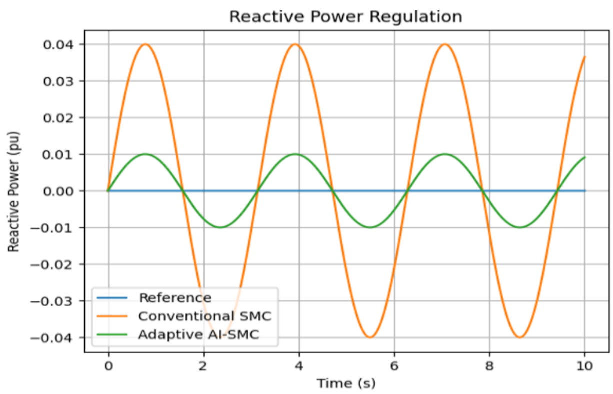

Fig. 5. Reactive power regulation.

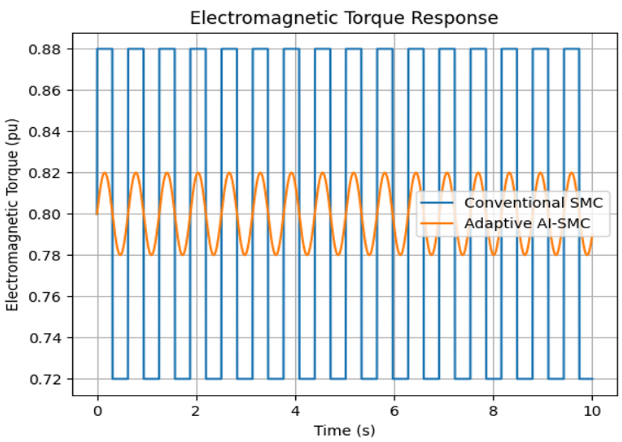

Fig. 6. Electromagnetic torque response.

Overall, the simulation results clearly demonstrate that the proposed adaptive AI-based Sliding Mode Control outperforms conventional Sliding Mode Control from multiple perspectives, including power quality, robustness, dynamic performance, and control smoothness. These results confirm the suitability of the proposed approach for intelligent and resilient wind energy conversion systems.

5. Conclusions

This paper has presented an adaptive AI-based Sliding Mode Control strategy for a Doubly Fed Induction Generator applied to a variable-speed wind energy conversion system. The proposed approach combines the robustness of Sliding Mode Control with an intelligent adaptation mechanism to address the challenges associated with nonlinear dynamics, wind speed variability, and parameter uncertainties. By integrating real-time gain adjustment within the control loop, the proposed method enhances system adaptability while preserving the inherent stability properties of the sliding mode framework. A detailed modeling of the wind turbine, DFIG, and power electronic converters has been developed to provide a realistic representation of the overall system. Extensive simulation studies conducted under various wind speed profiles have demonstrated the effectiveness of the proposed control strategy from multiple perspectives.

The results show improved active and reactive power regulation, faster dynamic response, and reduced oscillations when compared to conventional Sliding Mode Control. In addition, the adaptive mechanism significantly mitigates chattering effects, leading to smoother electromagnetic torque and rotor current waveforms, which is beneficial for both mechanical reliability and power electronic component lifetime. The performance of the grid-side converter has also been enhanced, ensuring stable DC-link voltage regulation and reliable power exchange with the grid under fluctuating operating conditions. These improvements contribute to higher energy quality and increased robustness of the wind energy conversion system, making the proposed approach suitable for grid-connected applications and ancillary service provision.

Overall, the proposed adaptive AI-based Sliding Mode Control framework offers an effective and practical solution for intelligent control of DFIG-based wind turbines. Future work will focus on experimental validation, extension to fault-tolerant operation, and the integration of predictive and cooperative control strategies for large-scale wind farm applications.

Author Contributions

A.L. conceptualized the study, developed the methodology, and performed the formal analysis; T.B. supervised the research, reviewed and edited the manuscript. S.L. conceptualized the study, developed the methodology, and performed the formal analysis; A.H. contributed to data curation, software implementation, and experimental validation; All authors reviewed and approved the final version of the manuscript.

Acknowledgements

Not applicable.

Conflict of Interest

The authors declare no conflict of interest.

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