

Application of Higher Order Sliding Mode Control for Doubly Fed Induction Generator for Chattering Reduction in Wind Turbine System

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ABSTRACT

Chattering mitigation in wind turbine-based Doubly Fed Induction Generators (DFIGs) is a critical issue to ensure stable and efficient operation. This paper presents the design of a higher-order sliding mode control (HOSMC) technique for mitigating chattering and improving the performance of DFIGs in wind turbine applications. The proposed control strategy leverages the benefits of sliding mode control, known for its robustness against uncertainties and disturbances, while addressing the chattering phenomenon that can cause high-frequency oscillations and undesirable effects on the system. The HOSMC design involves the use of higher-order sliding surfaces to achieve smooth and precise control. A mathematical model of the DFIG system is developed, and the control scheme is designed to regulate both the rotor-side and grid-side converters, enabling optimal power extraction and grid synchronization. Simulation studies are conducted to evaluate the performance of the proposed control technique under different operating conditions and in the presence of disturbances. The results demonstrate the effectiveness of the higher-order sliding mode control in mitigating chattering, reducing system oscillations, and improving the dynamic response of the DFIG system. The proposed control strategy shows great potential for enhancing the overall performance and stability of wind turbine-based DFIGs, contributing to the advancement of renewable energy generation systems.

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INTRODUCTION

Electrical energy has become a vital feature and a key element in our modern society's social and economic development (Adamu Abubakar et al., 2019; Hocini et al., 2020). Wind is a renewable energy source that is also one of the most popular energy sources (Abdulwahab et al., 2022; Safwat, 2020). Renewable energy sources, such as solar, wind, and water, are regarded to be the most frequent sources of clean energy (Abubakar 2018; Alhazmi, 2015). Wind energy is regarded as one of the cleanest renewable energy sources for electricity (Abdulwahab et al., 2021; Sun et al., 2018). Because of the abundance of this clean and free energy in recent years, it has attracted much interest and research is being conducted to

improve the efficiency and the quality of energy delivered (Hocini et al., 2020). Doubly Fed Induction Generators (DFIG) are widely utilized due to their variable speed operation, which allows 20%-30% of the power rating to pass through a power electronic converter (Musbahu et al., 2021). In the last decade, the use of DFIG has proven to be most preferred in wind turbine generating systems due to it providing the control of active and reactive exchange with the network and them having high efficiency, low cost, and flexible control (Abubakar & Sha'aban 2019; Musbahu et al., 2021).

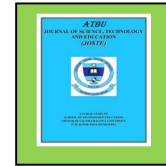
Due to the fast integration of wind power compared to other renewable energy sources has become a critical element in the modern power

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network (Liu et al., 2017). To maintain proper operation and increase the power quality, this calls for active control techniques on Wind Turbines (WT) (Ezzat et al., 2013).

Some factors of wind power plants are Uncertainty, nonlinearity, and robustness. Therefore, it makes it difficult to capture wind because of its randomness, nonlinearity, and uncertainty of the generator set (Sun et al., 2018). To achieve optimal conversion of wind power system, Nonlinear control techniques like fuzzy logic, feedback linearization, backstepping control, and neural networks are employed. Sliding mode control is a nonlinear robust control method that has been applied to doubly fed wind turbine system (Sun et al., 2018). The technique is highly regarded, accepted, and it has proven to be a preferable option in optimal conversion of wind energy. Therefore, it is needed to develop a technique for eliminating this effect in sliding mode control (SMC). Higher Order SMC with right design of parameter gain is a consequently needed control technique which is capable of eliminating the chattering phenomenon (Patnaik et al., 2016). This work developed a Higher order SMC with excellent performance in mitigating chattering effect and to also regulate the pitch and torque control of DFIG under dynamic conditions.

LITERATURE REVIEW

Anas, (2019) worked on development of second order sliding mode control chattering scheme for doubly fed induction generator based wind turbine system. The work developed a SOSM control scheme for grid a connected WT to better the tracking performance as well as mitigating the chattering effect for maximum energy delivery. The results showed the effectiveness of the SOSM control techniques in achieving a better tracking performance of WT systems and significant chattering reduction. However, DFIGs are highly susceptible to second order sliding mode (SOSM) disturbances like grid voltage dip and swell.

Allam & Djeriri, (2019) presented a sliding mode control for wind energy conversion system (WECS) based on DFIG. In the proposed technique, a power transfer between the stator and the network is achieved acting on the rotor

signals through a bidirectional converter. The simulation results test on a 10 kW DFIG system confirms effectiveness and robustness of the proposed controller during variation of parameters and disturbances. However, the use of robustness of the controllers can be justified by the high performance required by DFIG.

Dida et al., (2020) designed and presented a control design and Analysis of High performance DPC strategies of Grid-connected Doubly Fed Induction Machine (DFIM). Simulation results test on a 1.5 MW grid connected DFIM proved the following points: firstly, the implementation of the FOC is simple but problematic to decide the optimal PI gains, Lastly, FOC gives a good performance in the normal operating conditions. However, it completely loses its tracking capability in the parameter variation conditions.

Wang et al., (2021) proposed a multivariable super-twisting control scheme of DFIG based wind energy conversion system (WECS) to achieve MPPT. The proposed method applies the adaptive algorithm to suppress the parametric uncertainty and external perturbations effectively without the information of upper bounds in advance. The proposed controller is able to achieve smooth regulation for both active and reactive powers quantities to track the optimal powers in finite time. However, this control method is sensitive to wind speed changes due to significant turbine speed control errors led by large gusts.

Amina et al., (2021) proposed a high-order sliding mode control (HO-SMC) with supertwisting (ST) algorithm for maximum power point tracking (MPPT) and grid-connected wind energy conversion system (WECS) based on squirrel-cage induction generator (SCIG). The main attractive feature of the strategy is robustness against external and internal disturbances which is encountered by the wind power system. Simulation was carried out using SimPower systems of MATLAB/Simulink to prove the performance of the conventional and that of fuzzy logic PI controllers and the results obtained gives good stability and dynamic performance.

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However, system performance may lead to instability.

METHODOLOGY

- A. Development of a baseline controller (PI) for 2MW WT system as benchmark controller in MATLAB environment.
 - i. Adoption of the linearized model from the work of (Bayat and Torun, 2017)
 - ii. Design of a torque controller using MATLAB
 - iii. Design of a pitch controller using MATLAB
- B. Development of First order sliding mode control using MATLAB
- C. Development of Second order sliding mode control for 2MW using MATLAB
- D. Development of higher order sliding mode control for 2MW WT using MATLAB to replace the conventional SMC for the feedback outer loop.
 - i. Adoption of the linearized model in (1), item (i) above.
 - ii. Design of sliding surface using in MATLAB environment
 - iii. Design of control law to hold the trajectory on the sliding surface in MATLAB environment.
 - iv. Design of higher order for Chattering-free implementation
- E. Implementation of the developed SOSM controller on a standard 2MW WT and comparison with baseline controller in order demonstrate its effectiveness in reducing chattering phenomenon.

However, the increase in drive train load at 8m/s for HOSM was as a result of the variation in wind speed value. Also, at (10m/s) SOSM recorded 40.7802% and 20.5617% reduction in chattering and drive train load. The research therefore, shows the use of classical baseline controller as control strategy for WT system degrade over time with inefficient tracking performance due to abrupt changes in wind speed. Thus, the work shows the effectiveness of HOSM control techniques in achieving a better tracking performance of WT systems and significant chattering reduction. The HOSM was shown to outperform baseline PI controller when implemented on a 2MW WT system.

RESULTS

A. Optimal Gain Parameters of Baseline Controller

The gains used for tuning baseline controller at the inner loop are as shown in Table 4.1, where K_p and K_i represent the proportional and integral gain of the PI controller used in the baseline controller.

Table 1: Parameter of inner loop baseline controller

Inner loop parameter gain	Value
K_p	5
K_i	0.1

B. Wind Speed Model

The effective wind speed model produced for baseline controller and higher order sliding mode at 8 m/s is shown in Figure 4.1. In comparison to a wind speed model at a stationary site, the model's effective wind speed is smoother and exhibits the dynamic nature of wind at maximum and minimum speeds of 9.2 m/s and 7.5 m/s, respectively. And 7.5 m/s, respectively.

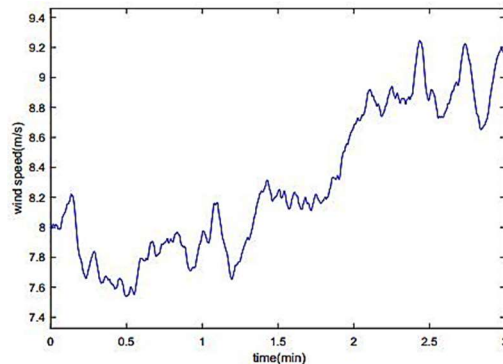


Figure 1: Effective Wind Speed at 8m/s

C. Response of Both Controllers.

Two baseline controllers and the HOSM control, acting as a feedback loop, made up the inner loop. The baseline responses of the inner loop were carried out in order to demonstrate the significance of the feedback control system.

i. Control loop response

In order for the controllers to track the reference speed, a wind speed of 8 m/s was applied as input. The system's response, however, reveals a small amount of arbitration at 65s, 144s, and 168s. The arbitrations during this time period were brought on by the rotor speed response. However, as demonstrated in Figure 2, HOSM recorded a superior tracking performance at an 8 m/s wind speed compared to 2OSM controller. This means that, Higher-Order Sliding Mode (HOSM) controller demonstrated better tracking performance at an 8 m/s wind speed compared to the Second-Order Sliding Mode (2OSM) controller.

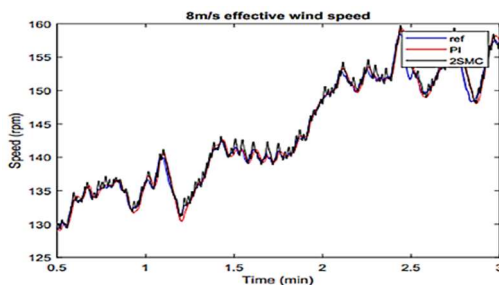


Figure 2: Tracking Response of Both Controller at 8m/s.

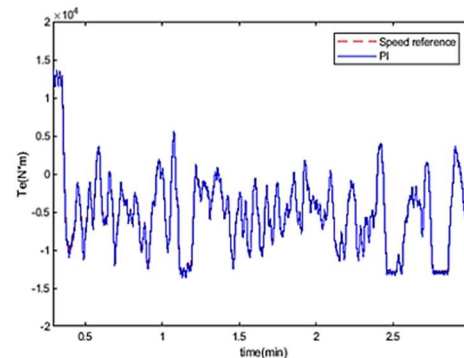
According to the HOSM data shown in Figure 2, the effective wind speed at 8 m/s is within 6.75 percent of its mean value and has less distortion and noise than the baseline controller. The magnitude is 10.57% and 8.75% below and above its mean value with noise distortion at the wind regime (10 m/s) in Figure 4.4. Additionally, it was discovered that the effective wind speed recorded throughout a 180-second period depended on its average wind speed with less noise than the baseline.

ii. Torque control

To check whether the obtained torque is equal to the anticipated torque, the baseline controller is simulated in MATLAB environment with a variable wind speed gradually raised from zero to operating wind speed of (0-8m/s). As seen in Figure 4.5, the baseline controller effectively

and with less distortion tracks the generator torque. However, the generator power coefficient (C_p) does not change. This is because torque control responds when the wind speed is lower than the system's operating speed.

Figure 3: Generator Torque as a function of time



for Baseline Controller at 8m/s

Generator torque refers to the torque applied to the generator of a wind turbine, which is responsible for converting the kinetic energy of the wind into electrical energy. The torque is an important control parameter as it affects the rotational speed and power output of the turbine. In the figure 3, the x-axis represents time, while the y-axis represents the generator torque. The graph illustrates how the torque varies over time during the operation of the wind turbine under the given wind speed of 8 m/s. The specific characteristics of the graph depends on the behaviour of the Baseline Controller. The shape of the curve may vary depending on the control strategy employed by the controller to optimize power output and system stability. The graph shows variations in generator torque due to changes in wind speed, control actions taken by the Baseline Controller, or adjustments made to optimize turbine performance.

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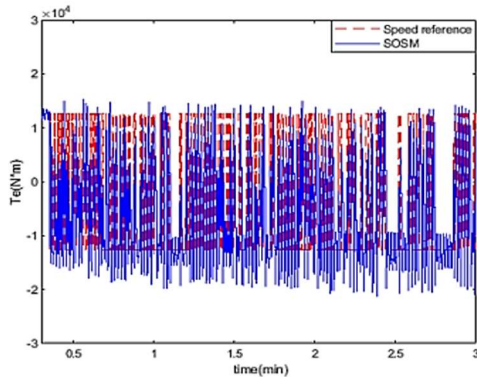


Figure 4: Generator Torque as a function of time for HOSM at 8m/s

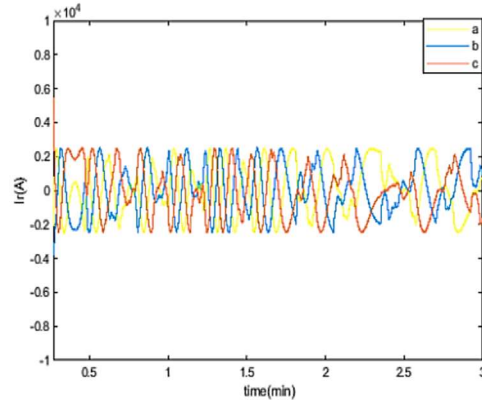


Figure 5: Rotor current as a function of time with baseline

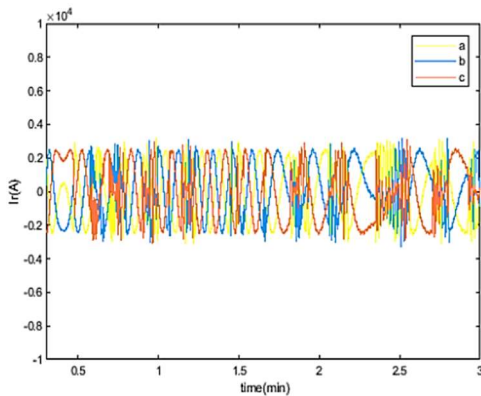


Figure 6: Rotor current as a function of time with HOSM

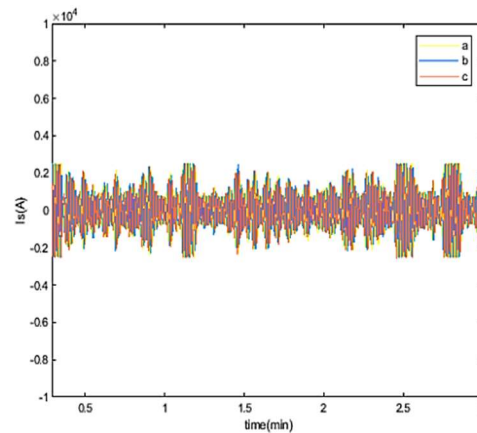


Figure 7: stator current as a function of time at 8m/s baseline

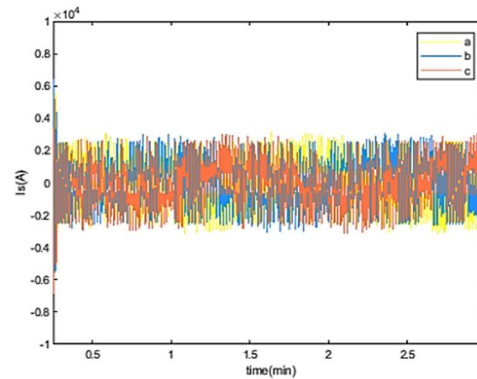


Figure 8: Stator current as a function of time at 8m/s HOSM

The tracking response at 8 m/s is represented by the stator current for the baseline controller in figures 4.11 and 4.12. According to the outcome, it achieves a tracking of 7.161×10^2 and 7.808×10^2 . When compared to the baseline, it appears that the HOSM shown in Figures 4.13-4.14 obtained a better response with maximum power tracking and chattering rejection of 1.269×10^3 and 1.949×10^3 , respectively. This demonstrated the HOSM's sturdiness and toughness in handling uncertainty even further.



This research work has presented the development of a higher order sliding mode control based chattering scheme for doubly fed induction generator WT system. The system comprises of two loops which are: inner loop and outer loop. The baseline controller was designed for inner loop. Thereafter, the outer loop of the system was designed with SMC and then replaced with HOSM for better tracking performance and chattering reduction. The developed controller has the ability to track the desired generator speed and output power within the region of WT operation. The tracking performance of HOSM was remarkable at wind speed of (8m/s) recording 37.7700% in chattering reduction compared to 2OSM.

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