

Classical vector, first-order sliding mode control (SMC) of a wind turbine permanent magnet synchronous generator (PMSG) system: A comparative study

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ABSTRACT

This paper presents a comparative analysis of various control strategies for a wind energy conversion system. Its goal is to ensure a robust control strategy that delivers strong performance despite external disturbances. The system under study includes a wind turbine, a permanent magnet synchronous generator, and an AC/DC converter connected via a DC bus. A conventional vector control using a proportional-integral (PI) controller is applied to the system. Due to the sensitivity of the PI controller to external disturbances, a control strategy utilizing first-order sliding mode control (SMC) has been proposed. This approach offers enhanced performance by being less affected by system non-linearity. Additionally, MATLAB/Simulink simulations demonstrate that the proposed sliding mode control strategy outperforms the conventional proportional-integral control.

I. Introduction

The environmental effects of traditional energy production and the rising expense of fossil fuels have contributed to the recent increase in wind turbine power output [1]. Although utility-scale wind power systems have been the subject of the majority of prior research, interest in small-scale wind energy conversion systems is growing. These more compact systems are turning out to be a very viable option for isolated places or those without access to the grid. For power generation in remote locations typically rely on two primary generator types for electricity: induction generators (IGs) and permanent magnet synchronous generators (PMSGs) [1], [2].

PMSG is favored over IG due to its numerous advantages. This machine does not require an external power source and connects directly to the wind turbine without the need for a gearbox, recent research into PMSG design highlights their high torque-to-current ratio, impressive power-to-weight ratio, excellent efficiency,

superior power factor, and overall robustness [3]. To extract the most energy from the varying wind, the wind-turbine generator must operate at a variable speed. This requires precise control to ensure optimal power efficiency across a broad range of wind conditions [4]. The PI control law remains widely used in industrial controllers as it provides a simple and practical solution to control issues [5], [6]. Nonetheless, tuning the parameters of the PI controller is a crucial task during control system testing to achieve the desired responsiveness and performance. However, linear control has significant limitations; achieving optimal tuning of PI controllers can be challenging for nonlinear systems that may operate across multiple points. SMC was initially developed as part of variable structure system (VSS) theory, which involves dynamic switching between different control structures. Over the past two decades, SMC has gained significant attention due to its robustness against model uncertainties and external disturbances, making it a highly effective nonlinear control strategy [3], [6]. Sliding mode variable structure control offers several advantages, including insensitivity to changes in system parameters and load disturbances. It is known for its robustness, rapid response, and ease of implementation. As a result, applying SMC to the control of Permanent Magnet Synchronous Motors (PMSMs) is expected to yield a high-quality control strategy [4]. For sliding mode controllers, the Lyapunov stability method is used to maintain control over nonlinear systems, providing a fast and precise dynamic response while ensuring the system remains unaffected by parameter variations and load disturbances.

In this paper, a comparative study of two control strategies for a wind turbine PMSG system is conducted with the aim of ensuring robust control performance under external disturbances. The system configuration is shown in Figure 1 [6]. The study evaluates the classical vector control approach using a proportional-integral (PI) controller, which is known for its sensitivity to external disturbances. To address this issue, a control strategy using first-order SMC is proposed. This sliding mode approach provides improved performance, including insensitivity to system nonlinearities [6], [8].

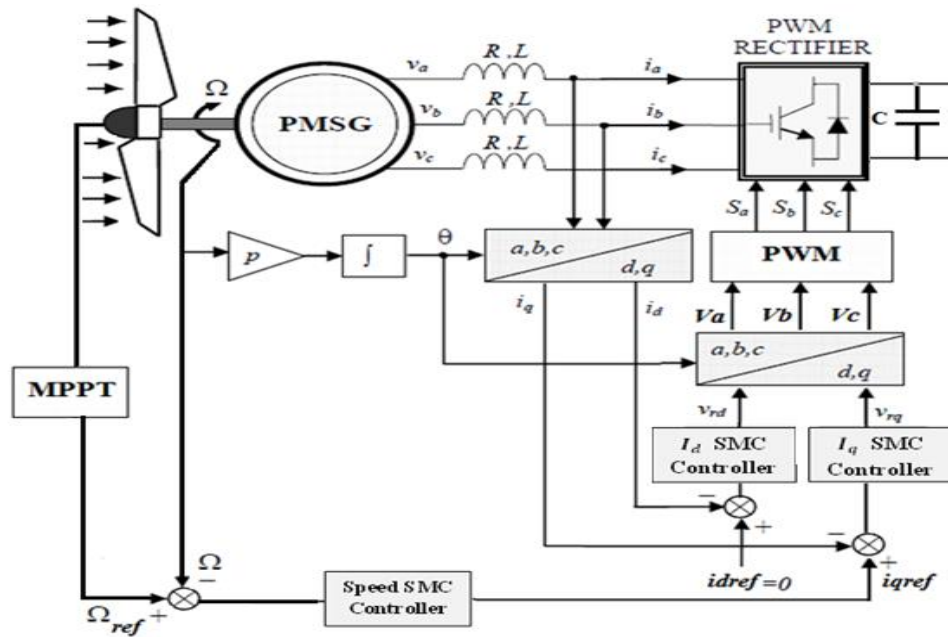


Figure 1. Schematic diagram of SMC-based control strategy.

II. Description and Modelling of the Wind Energy Conversion System (WECS)

II.1. Turbine model

Wind turbines capture aerodynamic power, which is merely a part of the total wind power (P_w) [3]. This

captured power is defined by the equation below:

$$P_{aer} = C_p P_w = \frac{1}{2} C_p (\lambda, \beta) \rho S V_v^3 \quad (1)$$

where P_{aer} denotes the aerodynamic power extracted from the wind (W), ρ is the air density in kg/m^3 , R represents the wind turbine rotor radius (m), C_p is the power coefficient, λ is the tip speed ratio, V_v is the wind velocity (m/s), and β refers to the blade pitch angle ($^\circ$). The power coefficient C_p defines the efficiency of aerodynamic power extraction from the available wind power. It is a function of both the tip speed ratio λ and the blade pitch angle β . The tip speed ratio is expressed by the following equation [6].

$$\lambda = \frac{\Omega R}{V_v} \quad (2)$$

where Ω denotes the rotational speed of the wind turbine (rad/s). The maximum power extracted using the maximum power point tracking (MPPT) strategy can be expressed as follows [5]:

$$P_{MPPT} = \frac{1}{2} \frac{\rho C_{p \max} R^5 \Omega^3}{\lambda_{opt}^3} \quad (3)$$

Accordingly, the mechanical torque C_m generated by the wind turbine is given by the following expression [5]:

$$C_m = \frac{P_{MPPT}}{\Omega} = \frac{1}{2} \frac{\rho C_{p \max} R^5 \Omega^2}{\lambda_{opt}^3} \quad (4)$$

II.2. PMSG model

Under standard assumptions typically employed in AC machine modeling, the electrical dynamics of the PMSG can be expressed in the (d,q) rotating reference frame as follows [7]:

$$\begin{cases} \frac{d}{dt} i_d = \frac{1}{L_s} (V_d - R_s i_{sd} + \omega L_s i_q) \\ \frac{d}{dt} i_q = \frac{1}{L_s} (V_q - R_s i_{sq} - \omega L_s i_d - \omega \phi) \end{cases} \quad (5)$$

The electromagnetic torque is related to the stator currents through the following expression [7]:

$$C_{em} = \frac{3}{2} p \phi i_q \quad (6)$$

The mechanical speed evolution of the PMSG is governed by the fundamental dynamic equation given below [9]:

$$J \frac{d}{dt} \Omega = C_m - C_{em} - C_{vis} = C_m - C_{em} - f \Omega \quad (7)$$

where J is the inertia time constant, f is the viscous friction, C_{em} and C_m denote the electromagnetic and mechanical torque respectively.

III. Classical Vector Control of Wind Generator

In this section, we will introduce a vector control approach using PI controllers to manage our conversion system. The goal of this approach is to demonstrate how sensitive PI controllers are to the broad range of wind speed variations and the nonlinearity of the system under study.

The control strategy of the wind generator relies on vector control applied to the PMSG to extract the maximum available wind power through MPPT. This approach involves setting the direct-axis current reference i_{d_ref} to zero, while the quadrature-axis current reference i_{q_ref} is regulated in proportion to the reference torque [5], [8].

IV. SMC strategy

SMC is a robust nonlinear technique that employs discontinuous control to drive system trajectories to a defined sliding surface. It is renowned for its resilience to model parameter uncertainties and external disturbances. The implementation of this control method requires mainly three stages [9], [10].

IV.1. Sliding surfaces

The sliding surface is selected to ensure that the controlled variable converges to its reference value. For an n th-order system, a time-varying sliding surface is typically chosen as follows

$$S = \left(\frac{d}{dt} + \lambda \right)^{n-1} (x_{ref} - x) \quad (8)$$

where n is the system order, λ is a positive constant, and $(x_{ref} - x)$ is the error of the controlled variable. In this paper, three sliding surfaces are defined in relation to the control objectives as follows

$$\begin{cases} S(\Omega) = \Omega_{ref} - \Omega \\ S(i_d) = i_{d,ref} - i_d \\ S(i_q) = i_{q,ref} - i_q \end{cases} \quad (9)$$

IV.2. Conditions of convergence

To ensure that the system's dynamic behavior remains on the sliding surface, the sliding mode control law must meet the condition of convergence defined by the Lyapunov equation [9].

$$\dot{s}s \leq 0 \quad (10)$$

IV.3. Controller design

A controller's structure is divided into two sections: one that deals with exact linearization and the other that stabilizes [9].

$$u(t) = u_{eq}(t) + u_n \quad (11)$$

$u_{eq}(t)$ represents the equivalent control proposed and is calculated based on the system's behavior along the sliding mode, as indicated by [7], [11].

$$\dot{s}(x, t) = 0 \quad (12)$$

$$u_n = -K_x \text{sign}(s(x)) \quad (13)$$

Where : $K_x > 0$, K_x is the gain of the SMC

$$\text{sign}(s(x)) = \begin{cases} 1 & s > 0 \\ 0 & s = 0 \\ -1 & s < 0 \end{cases} \quad (14)$$

In the following sections, we will develop the control law associated with each sliding surface.

1) Speed control design

For $n = 1$, the speed control manifold equation can be derived from (8) as follows:

$$\dot{s}(\Omega) = \dot{\Omega}_{ref} - \dot{\Omega} \quad (15)$$

The expressions of the continuous and the discontinuous components of i_{q_ref} are given by :

$$i_{q_ref}(t) = i_{q_eq}(t) + i_{q_n} \quad (16)$$

$$i_{q_eq}(t) = \frac{1}{1.5p\phi} \left(-J \frac{d\Omega_{ref}}{dt} - f\Omega + C_m \right) \quad (17)$$

$$i_{q_n}(t) = -K_{\Omega} \text{sign}(s(\Omega)) \quad , K_{\Omega} > 0 \quad (18)$$

2) Quadrature current control

For $n=1$, the quadrature current control manifold equation can be obtained from equation (8) as follow:

$$\dot{s}(I_q) = \dot{I}_{q_ref} - \dot{I}_q \quad (19)$$

The expressions of the continuous and the discontinuous components of v_{q_ref} are given by :

$$v_{q_ref}(t) = v_{q_eq}(t) + v_{q_n} \quad (20)$$

$$v_{q_eq}(t) = L_s \dot{I}_{q_ref} + R_s i_q + \omega L_s i_d + \omega \phi \quad (21)$$

$$v_{q_n}(t) = -K_{i_q} \text{sign}(s(i_q)) \quad , K_{i_q} > 0 \quad (22)$$

3) Direct current control

For $n = 1$, the direct current control manifold equation can be obtained from equation (8) as follow

$$\dot{s}(I_d) = \dot{I}_{d_ref} - \dot{I}_d \quad (23)$$

The expressions of the continuous and the discontinuous components of v_{d_ref} are given by :

$$v_{d_ref}(t) = v_{d_eq}(t) + v_{d_n} \quad (23)$$

$$v_{d_eq}(t) = L_s \dot{I}_{d_ref} + R_s i_d - \omega L_s i_q \quad (24)$$

$$v_{d_n}(t) = -K_{i_d} \text{sign}(s(i_d)) \quad , K_{i_d} > 0 \quad (25)$$

V. Simulation results

A dynamic system model was developed and simulated in MATLAB/Simulink, for the purpose to validate the control approaches proposed in this study and by using the parameters provided in Tables 1. The performance of the SMC has been compared with a PI controller. The simulation results are shown in Figure 2, Figure 3, Figure 4 and Figure 5. It can be seen from Figure 2 that the mechanical speed of the PMSG aligns with the reference speed derived from MPPT, ensuring optimal power point operation. It is evident that the PMSG speed closely follows the reference speed. Figures 4 and 5 illustrate the d and q components of the stator current, showing the d-component at zero while the q-component is non-zero to generate torque. Figure 5 also depicts the generator and wind turbine torque.

Figure 2 compares the rotor speed profiles under PI and SMC controllers. As shown in Figure 2(a), the PI controller provides smooth tracking with minor steady-state error but a slower dynamic response. In contrast, Figure 2(b) demonstrates that the SMC achieves faster convergence to the reference speed with improved transient performance. However, minor fluctuations around the reference may be observed, possibly due to chattering effects inherent to sliding mode control.

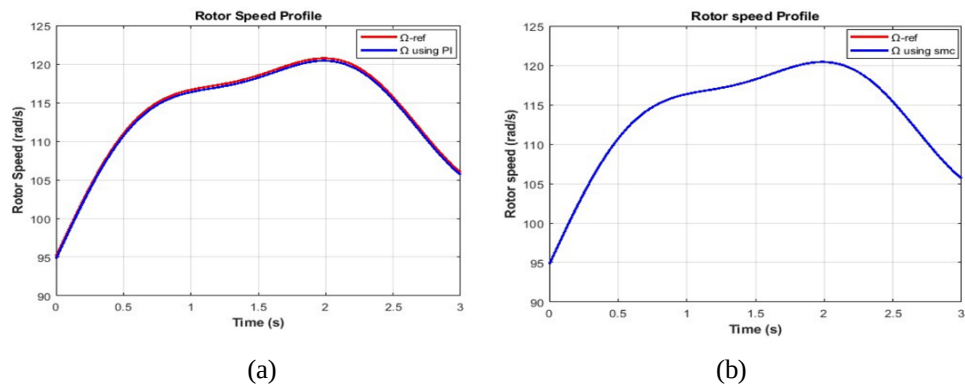


Figure 2. Rotor speed variation, (a) using PI controller, (b) using SMC

Figure 3 presents the direct-axis stator current (I_d) profiles under PI and SMC strategies. In Figure 3(a), the PI controller introduces a notable transient spike at the start, followed by a relatively smooth convergence to the reference value. In contrary, Figure 3(b) shows that the SMC effectively suppresses transient deviations and maintains the current close to zero throughout the simulation period. This reflects the superior transient response and disturbance rejection capability of the SMC strategy in regulating the I_d component.

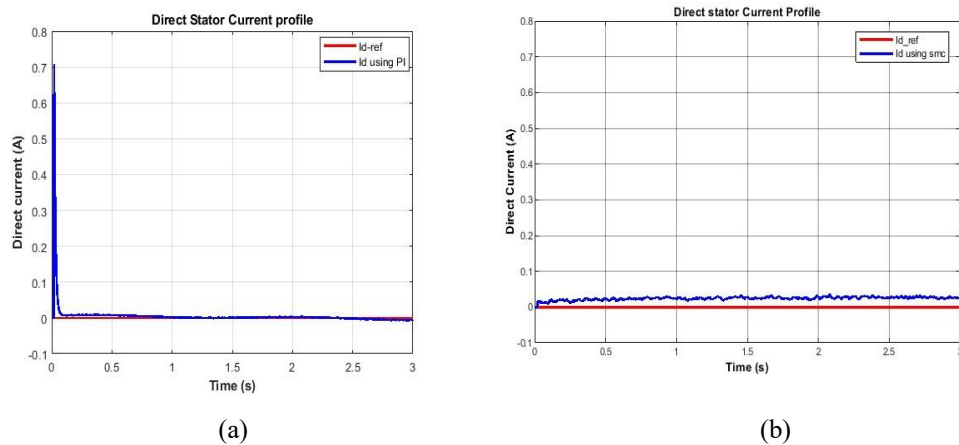


Figure 3. Direct axis current component, (a) using PI controller, (b) using SMC

Figure 4 illustrates the quadrature-axis current behavior. The PI controller in Figure 4(a) exhibits noticeable transient oscillations before settling near the reference. In contrast, the SMC in Figure 4(b) achieves faster and more stable tracking with reduced ripple, highlighting its superior transient response and control precision.

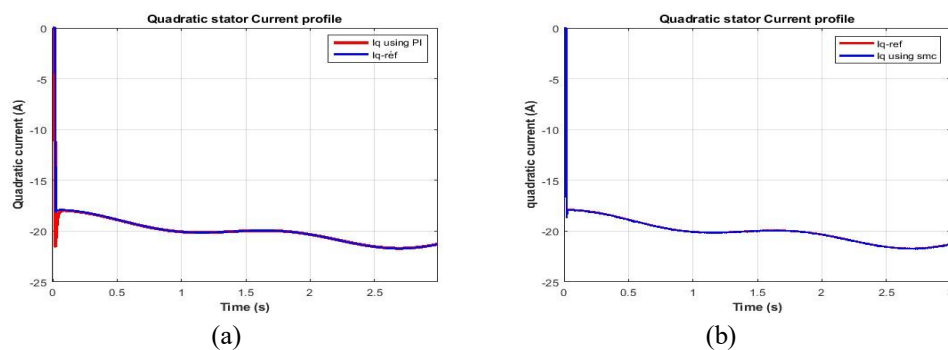


Figure 4. Quadratic axis current component, (a) using PI controller, (b) using SMC

Figure 5 compares electromagnetic torque responses. The PI controller (Figure 5a) results in higher torque ripple and delayed stabilization, while the SMC (Figure 5b) delivers improved torque tracking with reduced oscillations and faster convergence. This affirms the enhanced robustness and dynamic performance of the SMC method in torque control.

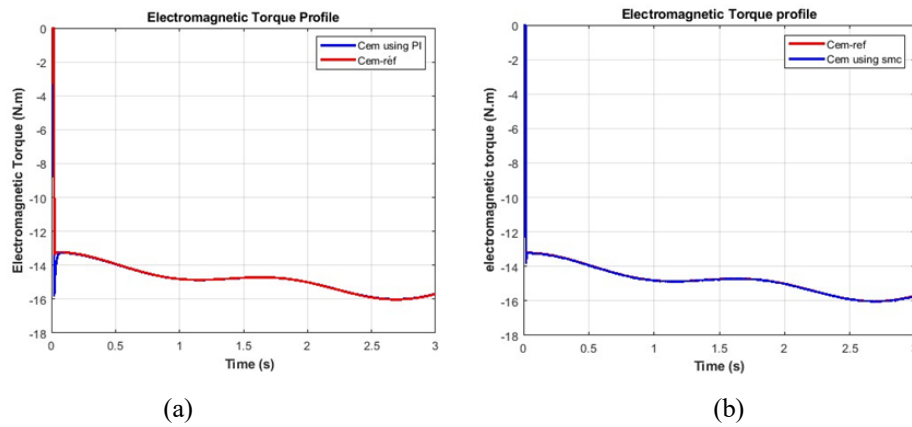


Figure 5. Electromagnetic torque, (a) using PI controller, (b) using SMC

VI. Conclusion

This paper presented a comparative study between classical PI control and first-order SMC for a wind turbine based on PMSG system. The performance of both controllers was evaluated in terms of rotor speed tracking, stator current regulation, and electromagnetic torque response. Simulation results confirmed that while both proposed controllers were able to follow the reference trajectories, the SMC achieved superior performance. For the rotor speed response, the SMC closely followed the reference with a maximum deviation less than 1 rad/s, compared to the PI controller which exhibited a slightly larger overshoot around 1.6 s. Regarding the direct-axis current, the PI controller displayed a transient spike reaching approximately 0.75 A, whereas the SMC maintained a smoother profile with peak values not exceeding 0.05 A, the same conclusion for the quadrature-axis current, this indicating better suppression of transients currents. Similarly, in the electromagnetic torque profiles, the SMC exhibited reduced oscillations. In the steady state the torque ripple under PI control varied by nearly ± 2 Nm, while the SMC limited the variation to approximately ± 1 Nm, highlighting its enhanced disturbance rejection capability. Overall, the results validate that SMC offers faster dynamic response, lower current ripple, and improved torque smoothness compared to the PI controller. Future work will focus on exploring higher-order or adaptive SMC approaches to further enhance control performance and mitigate chattering effects.

Table 1. Wind turbine,PMSG and DC bus parameters.

Parameter		Value
Wind Turbine	Number of blades	3
	Density of air	$\rho = 1.225 \text{ kg} \cdot (\text{m}^3)^{-1}$
	Radius of the wind turbine	$R = 3 \text{ m}$
	Optimal speed ratio	$\lambda_{\text{opt}} = 8.1$
	Maximum power coefficient	$C_{p_max} = 0.48$
	Viscous friction	$f = 0.017 \text{ (kg} \cdot \text{m}^2) \cdot \text{s}^{-1}$
Inertia time constant		$J = 0.48 \text{ Kg} \cdot \text{m}^2$
PMSG	Resistance of the stator	$R_s = 0.18 \Omega$
	Inductance of the stator	$L_s = 0.002 \text{ mH}$
	Pole pair number	$P = 4$
	Flux of the permanent magnet	$\Phi = 0.123 \text{ Wb}$
Moment of inertia		$J = 0.048 \text{ Kg} \cdot \text{m}^2$
DC bus	DC-link voltage	$V_{dc} = 700 \text{ V}$
	Capacitor of the dc-link	$C = 100 \mu\text{F}$

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