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Improved Sliding Mode Control of a Wind Turbine System Based on a Developed Permanent Magnet Synchronous Generator

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ABSTRACT

Wind energy conversion systems (WECS) are emerging as among the most reliable alternative energy sources, requiring innovative control strategies to improve performance and reduce operating costs. The objective of this paper is the implementation of sliding mode control (SMC) for a permanent magnet synchronous generator (PMSG) to optimize the dynamical response and wind turbine system (WTS) stability. The control architecture comprises the PMSG, an AC-DC power converter, and a DC bus link, with a particular focus on extracting the optimum wind turbine power during variable wind speeds. A complete system model was developed and tested in MATLAB for a PMSG of 2 MW subjected to uncertain fluctuations in wind speed. The simulation results confirm that the SMC technique significantly improves speed-tracking accuracy, minimizes current ripple, and improves overall system stability. In addition, the proposed method ensures robust performance under non-linear and uncertain conditions, making it a viable solution for large-scale wind applications. These results highlight the potential of SMC to enhance the accuracy and efficiency of the WECS.

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1. INTRODUCTION

The rapid increase in energy demand, coupled with the need to minimize carbon dioxide emission, has led to a massive adoption of renewable energies in the power generation sector. Among these sources, wind power has come to dominate due to its inexhaustible potential, its relatively widespread availability, and its ability to make a significant contribution to decarbonizing the world's electricity grids (Chien Feng Sheng, et al., 2023). Small and large-scale WES are now widely deployed in many parts of the world, either as wind farms connected to distribution networks or in stand-alone mode in rural or remote areas. grids (Roy, Anindita, et al., 2019) However, the integration of WESs offers several technological solutions. The intermittency and unpredictability of the wind create difficulties in terms of grid stability and the reliability of electricity production. This variability requires the development of advanced control strategies for wind generators to guarantee stable production in line with grid requirements. In addition, the issues surrounding integrating wind power systems into the power system include power flow management, frequency and voltage regulation, and coordination with other energy sources, particularly when these also include renewable sources grids (Khalid Muhammad, et al., 2024, Belgacem, Moussa, et al., 2021). Energy management in wind power systems relies on the optimization of storage and distribution strategies, as well as the use of hybrid solutions integrating different energy sources to compensate for wind variability. The improvement of wind forecasting technologies and the development of new adaptive control approaches, such as the use of algorithms based on artificial intelligence, are promising avenues for overcoming current limitations (Barelli Linda, et al., 2020). Therefore, the objective of studying this area is to maximize wind power systems' contribution to the global energy transition while minimizing their negative effects on the environment and enhancing their performance. Since PMSGs have so many benefits over other generator types—like induction or separate excitation—they have emerged as the preferred technology in contemporary WESs, especially for offshore wind turbines and large-scale applications. One of their key strengths is the use of permanent magnets, which eliminates the need for an external excitation system. This not only simplifies the design but also improves overall energy efficiency by reducing excitation losses Mahmoud, Mohamed Metwally, et al., 2022, Podmiljšak, Benjamin, et al., 2024), thereby increasing system reliability. In addition, PMSGs are characterized by a higher power density, enabling the design of more compact and lighter machines. This is particularly advantageous for large offshore turbines, where weight reduction is crucial to minimize structural and maintenance costs while facilitating installation (Benhacine, Tarek Zine-eddine, et al., 2024). In addition, PMSGs offer better performance in variable conditions, being able to operate efficiently over a huge variety of speeds, which is important for making the most of wind energy in environments where wind speeds are unpredictable and fluctuate. Another important aspect is their ability to offer better integration with modern energy conversion systems, particularly variable frequency converters, which improves the energy quality injected into the power network. Unlike induction generators, which require constant support from the grid to maintain their magnetic field, PMSGs are completely autonomous in terms of magnetic field generation, reducing dependence on the grid and increasing system flexibility in microgrids or isolated systems. (El Attafi, Abdelhafid, et al., 2024, Hannan M. A., et al., 2023, Mayilsamy Ganesh, et al., 2023) Finally, the absence of mechanical friction associated with an excitation system reduces wear and tear and extends the life of the equipment, making PMSGs more cost-effective over the long term in terms of maintenance. PMSGs are the perfect answer to the rising needs of contemporary WESs because of their energy efficiency, compactness, robustness, and flexibility—especially in maritime areas where maintenance is costly and conditions are harsher. (Mseddi Amina, et al., 2024, Belabbes Abdallah, et al., 2024) However, integrating permanent PMSG into WESs poses complex control challenges because of the nonlinear, dynamic nature of these systems. PMSGs are often exposed to significant disturbances caused by rapid changes in wind speed and fluctuations in electrical load. These changes, if not properly managed, can lead to significant instabilities, a reduction in the quality of the power injected into the grid, as well as risks of disconnection of the wind systems (Raouf Amir, et al., 2023). To control electromagnetic torque and rotor speed, conventional control methods like proportional-integral (PI) control are frequently applied. However, these methods are not working well enough to deal with the variable uncertainties and non-linearities that come with WESs, especially when there are erratic and turbulent winds. (Mughees Neelam, et al., 2022, Nguyen Hoach The, et al., 2020). The non-linear behavior of WTSs equipped with PMSGs becomes particularly critical with the introduction of stochastic and intermittent variations in wind speed, which directly influence the rotation of the turbine blades, the speed of the generator, and, consequently, the production of electrical power. An effective control strategy must be able to adapt in real-time to fluctuations in wind speed while maintaining precise regulation of torque and power. The aim is to optimize energy capture and guarantee the system's operational stability. (Bonfiglio Andrea, et al., 2017, Milles Abdessmad, et al., 2024) Furthermore, control strategies must take into account several additional factors, such as uncertainties in the generator's internal parameters (stator resistance, inductance, magnetic flux, etc.) as well as external disturbances such as wind gusts or sudden changes in electrical load. These disturbances can lead to significant oscillations and, without a robust control method, compromise system performance Stiti, Chafea, et al., 2024). To meet these challenges, advanced control techniques like model predictive and adaptive controls and intelligent systems based on neural networks or optimization algorithms have been proposed. These methods aim to improve system robustness and responsiveness to PMSG uncertainties and non-linearities, while maximizing stability and energy efficiency (Chirantan Shaswat, et al., 2024, Stiti Chafea, et al., 2024). SMC is a widely employed nonlinear control technique for systems where robustness is essential, particularly in environments subject to large disturbances, such as wind power systems. Unlike linear control methods, which generally assume deterministic behavior and stable operating conditions, SMC is specifically designed to adapt to rapid and unexpected variations in the system's internal and external conditions. This allows for accurate and stable control even when there are significant parametric and dynamic uncertainties. The characterization of a sliding surface in state space serves as the foundation for the SMC concept. To ensure a quick and reliable response, the goal is to push the system's state to this sliding surface, where it is then pushed to "slide" toward the origin. Once on this surface, the system's behavior becomes independent of uncertainties and external disturbances, ensuring high robustness against these disturbances. The capacity of SMC to properly handle parametric uncertainty and external disturbances is one of its most significant advantages. This is especially important for wind power systems since changes in temperature, wind speed, and other external factors can cause operational conditions to alter quickly. SMC allows optimal performance to be maintained in real-time, even when the system model is not perfectly known or when certain characteristics are not modeled. However, despite its undeniable advantages, the classic SMC method suffers from a major drawback: the chattering effect. This phenomenon manifests itself in the form of high-frequency oscillations due to the rapid switching of the control law, caused by changes in the sign of the switching function. As well as degrading system performance, chattering can cause premature wear on mechanical and electrical components, reducing system (Mousavi Yashar, et al., 2022, Kelkoul Bahia, et al., 2021, Achar Abdelkader, et al., 2024, Bouguerra Zahira, et al., 2023). To overcome this problem, various variants of SMC have been proposed. The second-order SMC is one of the most common solution controls, which reduces the switching frequency while maintaining the robust properties of the SMC. Other approaches include the use of state observers and boundary band controllers to smooth the control without compromising accuracy (Ding Shihong, et al., 2020). These improvements not only significantly reduce the effect of chattering, but also maintain better control accuracy, particularly in high-dynamic applications such as wind power systems (Desalegn Belachew, et al., 2022), SMC remains a powerful and widely used technique, especially for systems facing large disturbances and uncertainties. Recent improvements have made it possible to overcome some of its limitations, in particular the chattering effect, while retaining its intrinsic characteristics of robustness and efficiency. Applications in in the field of renewable energies, including wind power systems, exemplify this approach's interest in highly variable situations (Herrera Marco, et al., 2020, Infield David, et al., 2020). In this research, we combine a second-order chattering minimization strategy with an SMC approach applied to a wind system with a PMSG. This paper's primary accomplishments are as follows:

1. WECS modeling at PMSG: Detailed system modeling, including generator dynamic equations and wind characteristics.

2. Construction of an SMC: The creation of an SMC technique that can lessen chattering while managing the wind's quick dynamic swings.

When compared to standard control approaches, the acquired findings demonstrate an improvement in the quality of power delivered and the stability of the system. Thus, our study shows that SMC is a reliable and effective method for controlling non-linear wind systems, especially when there are disturbances and dynamic uncertainties present. The remainder of the document is arranged as follows: In Section 2, relevant studies on SMC of a WTS based on a PMSG are presented. The mathematical modeling of the system is examined and explained. The SMC of the grid side converter is fully designed in Section 4. The effectiveness of the proposed technique is demonstrated by analyzing the simulation results in Section 5. In Section 6, the conclusion is discussed and a brief recommendation for additional research is made.

2. RELATED WORKS

Several research studies have dealt with SMC strategies for WTSs based on PMSG, each contributing valuable insights while also highlighting some limitations. In (Laabidine Nada Zine, et al., 2021), a SMC design for a wind power generation system was proposed; however, it faced challenges related to robustness under varying operating conditions. In (Valenciaga F, et al., 2008), high-order sliding control was explored, which improved performance but increased complexity in the implementation process. A PID-type terminal SMC was introduced in (Nasiri Mojtaba, et al., 2021), enhancing speed response but struggling with sensitivity to parameter variations. A robust SMC approach was presented in Zhuo Guangping, et al., 2016), effectively rejecting disturbances but not fully addressing transient response issues. SMC for variable-speed wind energy conversion was demonstrated in (Hostettler Jacob, et al., 2015), yet concerns about stability at low wind speeds were noted. Experimental validation was performed in (Benelghali, Seifeddine, et al., 2010), revealing the need for further refinements. Small-scale WTSs were focused on (Boudries Z. O. U. B. I. R, et al., 2019), although the findings indicated room for improvement in efficiency. Adaptive SMC for floating offshore wind turbines was investigated in (Zhang Cheng, et al., 2021), achieving good performance but encountering challenges in environmental adaptability. The study by (Valenciaga Fernando, et al., 2015) on multiple-input–multiple-output high-order SMC provided robust grid support but also increased the complexity of the control strategy. A variable gain real-twisting SMC was proposed in (Chirantan Shaswat, et al., 2024), which improved performance but highlighted the difficulty of tuning gains in practical applications. Adaptive for PMSG WTSs was addressed in (Ullah Ameen, et al., 2020), but this method required careful parameter selection. The integration of a high-speed SMC in grid-connected systems was studied in (Lee Sung-Won, et al., 2019), emphasizing the need for rapid response. Research on neural observers in dynamic SMC was discussed in (Tola, Omokhafe James, et al., 2022), showing potential improvements but introducing new layers of complexity. Furthermore, An enhanced sliding-model-adaptive system speed observer was highlighted in (Karami-Mollaee Ali, et al., 2024), which faced challenges in practical implementation. Recent work combining fuzzy logic with SMC demonstrated effectiveness in (Yan Jianhu, et al., 2013) but necessitated hybrid tuning methods. Non-linear extended state observer-based SMC was utilized in (YACHIR Amina, et al., 2024), yet this method raised questions about observer design robustness. A thorough SMC system for generator and grid control was created (Tang Yongwei, et al., 2019), although it required additional validation for various operational circumstances. Full-order sliding-mode current control was investigated by (Merabet, Adel, et al., 2016), which successfully rejected disturbances but necessitated sophisticated parameter tuning. Finally, an upgraded exponential reaching law-based SMC was developed (Wei Chun, et al, et al., 2022, Mozayan, Seyed Mehdi, et al., 2016), successfully minimizing chattering concerns but still posing difficulty in parameter tuning. Through addressing the issues raised in these earlier studies and putting forth a more straightforward strategy that preserves reliable performance in the face of varying wind conditions and system uncertainties, this paper seeks to enhance the SMC methodologies currently in use for WTSs based on PMSG. The full model was simulated in MATLAB using a 2-MW PMSG at variable wind speed. The simulation findings highlight the usefulness and importance of the proposed SMC in this system by showing high speed, accuracy, stable performance, and reduced output current variation.

3. WIND ENERGY CONVERS SYSTEM MODELLING

3.1 Wind Turbine Model

Wind turbines convert wind energy from mechanical to kinetic energy, which can then be converted into electrical energy (Krumbein, S., et al., 2024, Bouddou Riyadh, et al., 2020) The fundamental principles governing the operation of wind turbines may be expressed using several different theoretical and mathematical models. The energy obtained from the wind can be stated as follows:

$$P_{tr} = \frac{1}{2} S v^3_{vent} C_p(\lambda, \beta) \tag{1}$$

The power coefficient is unique for each turbine; it is given as:

$$\begin{cases} C_p(\lambda,\beta) = 0.73.\left(\frac{151}{A} - 0.58\beta - 0.02\beta^{2.14} - 13.2\right) e^{\frac{18.4}{A}} \\ A = \dfrac{1}{\dfrac{1}{\lambda - 0.O2\beta} - \dfrac{0.003}{\beta^3 - 1}} \end{cases} \tag{2}$$

Aerodynamic torque: The instantaneous variation of wind kinetic energy captured by the aero turbine is transformed into mechanical power P_{tr} which develops a driving torque C_{tr}thus making the rotor rotate at a speed Ω_{tr}:

$$P_{tr} = C_{tr}.\Omega_{tr} \tag{3}$$

$$C_{tr} = \frac{P_{tr}}{\Omega_{tr}} \tag{4}$$

The mechanical torque produced by the turbine is stated as follows:

$$C_{tr} = \frac{1}{2} \rho \pi R^3 v_{vent}^2 C_q(\lambda, \beta) \tag{5}$$

The torque coefficient is expressed as follows:

$$C_q(\lambda, \beta) = \frac{C_p(\lambda, \beta)}{\lambda} \tag{6}$$

3.2 Mechanical Drive Train Model

In energy conversion devices like wind turbines, the mechanical drive train model is vital because it transfers the mechanical energy generated by the rotor to the generator. This model includes different components, such as the rotor, driving shaft, sprockets, and brake devices, to assess the overall efficiency and performance of the system. Since the three blades' designs are thought to be equal, they share the same turbine moment of inertia and generator moment of inertia. The speed's dynamic equation is provided by:

$$\begin{cases} C_{tr} - C_{em} = J.\dfrac{d\Omega_g}{dt} - f_v.\Omega_g \\ \Omega_{tr} = \Omega_g \\ J = J_t + J_g \end{cases} \tag{7}$$

The where is $C_{tr} and\ C_{em}$ is the mechanical and electrical torque respectively, Ω_g is the generator rotational speed, Ω_{tr} turbine rotational speed, and f_v is the damping coefficient, (Kim Dongmyoung, et al., 2024)

3.3 Model of PMSG

Used primarily in wind turbines, PMSGs offer an efficient solution for generating electricity from renewable energy sources. Their design is based on well-established physical principles, exploiting the properties of permanent magnets and the principle of electromagnetic induction. The operation of a PMSG is based on the rotation of the rotor, which is equipped with permanent magnets, within a magnetic field generated by the stator windings. As the rotor rotates, it induces an alternating voltage in the stator coils, generating electricity. This process is governed by the laws of electromagnetism, where the relative movement between the magnetic field and the conductors in the coils generates an electromotive force. (Zhang Jian, et al., 2020) The PMSG can be stated, in the reference frame d-q with synchronous rotation, by the following system equation,

$$\begin{bmatrix} \dfrac{dI_d}{dt} \\ \dfrac{dI_q}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{L_d} & w_e \dfrac{L_q}{L_d} \\ w_e \dfrac{L_q}{L_d} & -\dfrac{R_s}{L_d} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_d} & 0 & 0 \\ 0 & \dfrac{1}{L_q} & -\dfrac{w_e}{L_q} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ \varphi_f \end{bmatrix} \tag{8}$$

In this paper, the authors adopted a smooth pole $L_d = L_q$ of PMSG for the simulations of the offshore wind power system. The conversion of electrical energy into mechanical energy in synchronous machines is given by the following relationship:

$$\frac{d\Omega}{dt} = \frac{1}{J}\left(\frac{3}{2}p\left[\left(\left(L_d - L_q\right)I_d I_q\right) + \varphi_f I_q\right] - C_r - f_c\Omega\right) \tag{9}$$

3.4 Back-to-back converter modeling

The analytical model for the three-phase back-to-back converter (rectifier and inverter) is presented in this section. By Figure 1, the measured currents in the DC-bus can be expressed as shown in (10), where C represents the DC-bus capacitor, I_{ond} is the inverter input current, and I_{s1}, and $I_{s2}$are the rectifier input currents. The DC bus capacitor plays a crucial role in maintaining a stable voltage and filtering current ripples, reacting to variations due to load fluctuations or changes in the power source. In parallel, While the inverter, which is frequently driven by PWM, transforms the stored DC energy into AC form and modifies the duty cycle to obtain the required voltage and frequency, the rectifier must be modeled to comprehend its interaction with the power network. Optimizing energy conversion systems' performance in a range of operational conditions requires this modeling. He Yingjie, et al., 2024)

$$\begin{cases} I_{red} = s_a I_{s1} + s_b I_{s2+} s_a I_{s3} \\ \mathrm{C} * \frac{dV_{dC}}{dt} = I_{red} - \ I_{ond} \end{cases} \quad (10)$$

Three-phase PWM signals used by the inverter are represented by the symbols s_1, $s_2$and $s_3$in the analytical model of the inverter found in equation (11). V_{dc} is the DC-bus voltage.

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} \quad (11)$$

3.5 Electrical grid modelling

Power system modeling is a crucial aspect of power systems engineering, which involves creating a mathematical and computational representation of the electricity network. The grid is the backbone of modern society, delivering electricity from generators to consumers over vast distances. Effective modeling is essential to analyze grid behavior, optimize operations, improve reliability, and integrate renewable energy sources. (Oree Vishwamitra, et al., 2017) This section's objective is to create the perfect electrical grid model. The balanced three-phase system, with V_{res1}, V_{res2}, and V_{res3} coupled to the inverter via a transformer with a ratio of m, is taken into consideration to build this model. Based on Figure 1, the analytical model of the electrical grid is shown in (12), where e_1, e_2, and e_3, present the usual three-phase emf.

$$\begin{cases} V_{res1} - e_1 = R_{res} I_{1res} + L_{res} \frac{dI_{1res}}{dt} \\ V_{res2} - e_2 = R_{res} I_{2res} + L_{res} \frac{dI_{2res}}{dt} \\ V_{res3} - e_3 = R_{res} I_{3res} + L_{res} \frac{dI_{3res}}{dt} \end{cases} \quad (12)$$

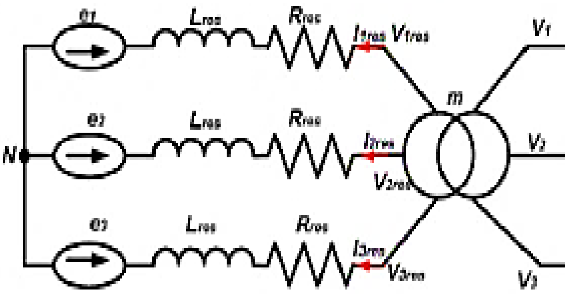

Fig 1. Ideal model of the electrical grid

3.6 Active and reactive power

The accurate calculation and management of active and reactive power are fundamental to the effective functioning of the electrical grid, influencing everything from individual device performance to the overall stability and efficiency of power systems. It is expressed in (13), where (V_{dres}, V_{qres}) and (I_{dres}, I_{qres}) are respectively the grid voltage and current in dq axis.

$$\begin{cases} P_{res} = \frac{3}{2}\left(V_{dres} I_{dres} + V_{qres} I_{qres}\right) \\ Q_{res} = \frac{3}{2}\left(V_{qres} I_{dres} - V_{dres} I_{qres}\right) \end{cases} \quad (13)$$

4. WES CONTROL STRATEGIES

Control solutions for wind systems are crucial for maximizing the output of renewable energy and guaranteeing a smooth integration into the electrical grid. Among these tactics, maximum power point tracking (MPPT) maximizes energy acquisition by constantly adapting wind turbine operation to fluctuations in wind speed. Furthermore, grid stability is maintained by adjusting energy output to maintain proper levels through voltage and frequency regulation. The incorporation of energy storage devices, such as batteries, provides flexibility and resilience by mitigating variations in output. Lastly, diagnostic devices monitoring wind turbine characteristics reduce downtime and foresee maintenance needs. When combined, these control techniques enhance WESs' sustainability, dependability, and efficiency, which is crucial for the switch to renewable energy sources. Figure 2 presents the technique of converting wind energy by applying synchronous permanent magnet generators. (Apata O, et al., 2020, De Siqueira, et al., 2021)

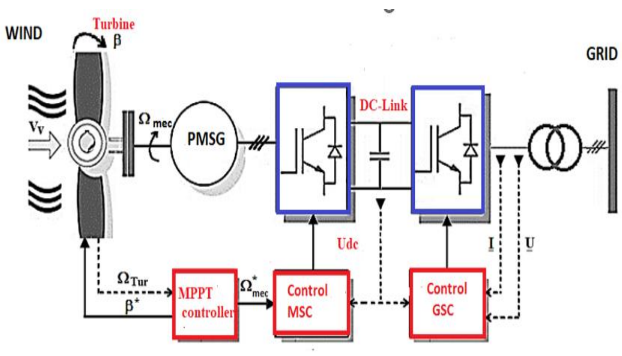

Fig 2. Technique for converting wind energy by applying synchronous permanent magnet generators

4.1 Proposed MPPT control strategy

The suggested plan offers a proportional-integral controller-controlled MPPT system that can be used with PMSG in variable-speed wind turbines. To effectively harvest the most electricity possible from wind turbines operating at changing speeds, several solutions have been devised. Because these MPPT systems make sure the turbine constantly runs at its optimum performance, they are essential to improving wind energy production regardless of changing wind conditions. Commonly used techniques include tracking algorithms based on wind speed variation, allowing the blade position to be adjusted and the angle of attack to be optimized to maximize energy capture. In addition, the use of advanced controllers, such as those based on adaptive control methods, has improved the responsiveness and accuracy of MPPT systems, ensuring optimal energy extraction even in fluctuating wind conditions. By integrating these approaches, the proposed scheme aims to improve overall system efficiency while reducing energy losses, which is essential for the sustainable exploitation of wind resources. Figure 3 present the ideal model of the electrical grid. (Rachedi Meriem Otmane, et al., 2020, Balbino Anderson José, et al., 2021).

The greatest power extracted and the coefficient of power conversion occurs at a specific tip speed ratio value known as the optimum tip speed ratio, or λopt. Because of this, $C_{pmax}(\lambda, \beta) = 0.45$is the maximum value of $C_p(\lambda, \beta)$.

The wind turbine speed reference, which controls PMSG speed, is written in (14), where v represents the wind speed. The MPPT technique is the source of this reference.

$$\Omega_{ref} = \frac{V.\lambda opt}{R_t} \tag{14}$$

Fig. 3 shows the PMSG speed control approach. The closed-loop analysis PI controller coefficients are represented in (15), where w_{nd} and T_{sd} stand for the system's dynamics and time constant, respectively.

$$\begin{cases} K_i = w_{nd}^2 * J \\ K_p = 2\xi w_{nd} * J \end{cases} \qquad w_{nd} = \frac{5.8}{T_{sd}} \tag{15}$$

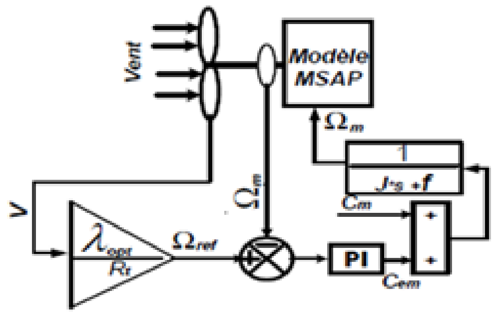

Fig 3. Ideal model of the electrical grid.

4.2 Theory of SMC

SMC is a variable structure control method that aims to stabilize non-linear systems by forcing them to evolve around a predefined sliding surface, representing the desired equilibrium state. Once the system's trajectory reaches this surface, it is maintained in its vicinity using appropriate switching logic, guaranteeing specific dynamics toward the equilibrium point. This approach is particularly advantageous because of its robustness to system disturbances and uncertainties, making it an effective method for complex environments. However, SMC can cause unwanted oscillations, known as chattering, due to the discontinuous nature of the control. To mitigate this, advanced techniques such as smooth SMC or adaptive approaches have been developed. In short, this method makes it possible to ensure system stability and performance while maintaining a high degree of tolerance to variations in conditions, particularly in critical applications. The system's transient dynamic reaction is determined by the state trajectory that leads to the sliding surface, which symbolizes the intended equilibrium state. (Wu Ligang, et al., 2021) Let a nonlinear system be in its canonical form:

$$\begin{cases} \dot{x}(t) = f(x,t) + g(x,t).u(t) + dt \\ y(t) = x(t) \end{cases} \tag{16}$$

Where the system's state, input, and output vectors are, respectively, represented by the vectors x(t) ∈ $\mathcal{R}$ n, u (t) ∈ $\mathcal{R}$ m, and y (t) ∈ $\mathcal{R}$ n; $f(x,t)$, and $g(x,t)$are non-linear functions; p(t) denotes the external disturbances, which are considered to be bounded. To cancel the tracking, which is indicated by the tracking errors, the goal is to create a control law (   )that forces the output $y(t)$ to follow the reference trajectories y*(t) in finite time from an arbitrary initial condition.

$$\boldsymbol{e}(t) = y*(t) - \boldsymbol{y}(t) = \dot{x}(t) - \boldsymbol{x}(t) \tag{17}$$

The following is the general equation that [15] suggested be used to find the sliding surfaces and guarantee that the variables converge to the desired value:

$$\boldsymbol{S}(x) = \left(\frac{d}{dt} + \lambda\right)^{r-1} . \boldsymbol{e}(x) \qquad (\lambda \rangle 0) \tag{18}$$

The relative degree, or r, is the quantity of output needed to cause the command to appear. The system enters the sliding mode if the convergence condition (19) is met with S(x)=0.

$$\boldsymbol{S}(x). \dot{S}(x) \langle 0 \tag{19}$$

When this requirement is met, the sliding surface becomes invariant and attractive, and the sliding mode with an infinite switching frequency is ideal. By combining two words, the control law is obtained in the following way:

$$\boldsymbol{u}_{smc} = \boldsymbol{u}_{equ} + \boldsymbol{u}_n \tag{20}$$

The equivalent control, or $\boldsymbol{u}_{equ}$, is a low-frequency term that affects how an object approaches the sliding surface. The discontinuous high-frequency term that affects the sliding mode by maintaining the system on the general form of discontinuous control is the $\boldsymbol{u}_n$, which represents the non-linear control.

$$\boldsymbol{u}_n = -\boldsymbol{k}. sign\,[\boldsymbol{S}(x)] \tag{21}$$

$\boldsymbol{k}$ is a diagonal matrix that allows for the desired dynamics to be adjusted and has constant positive coefficients. In actuality, there is no perfect sliding mode since there would need to be constant control changes. This is not feasible because of the time needed for the control computation and the restrictions on the inverter switches' switching frequency. As a result, rather than moving directly across the surface, the state trajectory tends to fluctuate. Chattering is a behavior that results in high-frequency oscillations caused by control discontinuities that produce control frequency oscillations. Talking is bad for the way things work. By stimulating dynamics that were overlooked in the modeling, it can weaken the system or harm the actuators from excessively high stresses.

4.3 SMC for generator

The PMSG control and the control of the DC-Link are based on the measurement not only of the rotational speed Ω_g but also the direct i d and quadrature I_d of the stator current of the PMSG. (Kelkoul Bahia, et al., 2021) From these measurements and the reference values of the current components I_d* and I_q*, the objective of control is to calculate the values of the direct V_d* and quadrature components V_q* of the stator voltage. Considering the PMSG model given by equations (8) and the control quantities V_d* and V_q*, we define that the system to be controlled is of unitary relative degree (r = 1), the control variables control variables appearing in the first derivative of the of the output variables. Therefore, the sliding surface S associated with the currents. Where, I_d and $I_q$can be chosen such that:

$$\boldsymbol{S}(I_d, I_q) = \boldsymbol{\lambda}. \dot{e}(I_d, I_q) + \ddot{e}(I_d, I_q) \tag{22}$$

Were,

$$S = \begin{bmatrix} S_{Id} \\ S_{Iq} \end{bmatrix} e = \begin{bmatrix} e_{Id} \\ e_{Iq} \end{bmatrix} = \begin{bmatrix} I_d^* - I_d \\ I_q^* - I_q \end{bmatrix} \text{et } \lambda = \begin{bmatrix} \lambda_{Id} & 0 \\ 0 & \lambda_{Iq} \end{bmatrix}$$

Applying equation (22) to the machine model the following relationships are obtained:

$$\begin{cases} \dot{e}_{Id} = \dfrac{dI_d^*}{dt} + \dfrac{1}{L_d}.\left[R_s I_d - w_e L_q I_q\right] - \dfrac{V_d}{L_d} \\ \dot{e}_{Iq} = \dfrac{dI_d^*}{dt} + \dfrac{1}{L_d}.\left[R_s I_q - w_e L_q I_d + \varphi_f w_e\right] - \dfrac{V_q}{L_q} \end{cases} \tag{23}$$

The equivalent control is obtained by imposing an invariant sliding surface (St. $\dot{S} < 0$) and attractive ($\dot{S} = 0$), hence,

$$\begin{cases} V_{d\_equ} = L_d.\dfrac{dI_d^*}{dt} + \left[R_s I_d - w_e L_q I_q\right] \\ V_{q\_equ} = L_q.\dfrac{dI_q^*}{dt} + \left[R_s I_q - w_e L_q I_d + \varphi_f w_e\right] \end{cases} \tag{24}$$

The discontinuous control is then chosen in the following form:

$$\begin{cases} V_{d\_n} = K_{id} \times S(e_{Id}) \\ V_{q\_n} = K_{iq} \times S(e_{Iq}) \end{cases} \tag{25}$$

k_{id} and k_{iq} , being positive constants. The command $\boldsymbol{u}_{smc} = [V_d * \;\; V_q *]^T$ is the combined use of equivalent and discrete control. It is expressed as:

$$\begin{cases} V_d * = V_{d\_equ} + V_{d\_n} \\ V_q * = V_{q\_equ} + V_{q\_n} \end{cases} \tag{26}$$

Ultimately, the tracking errors of the stator currents tracking errors, i_d, and i_q, will converge exponentially to zero under the influence of the control voltages $V_d *$ and $V_q *$. The wind power system's SMC architecture is presented in Figure 4.

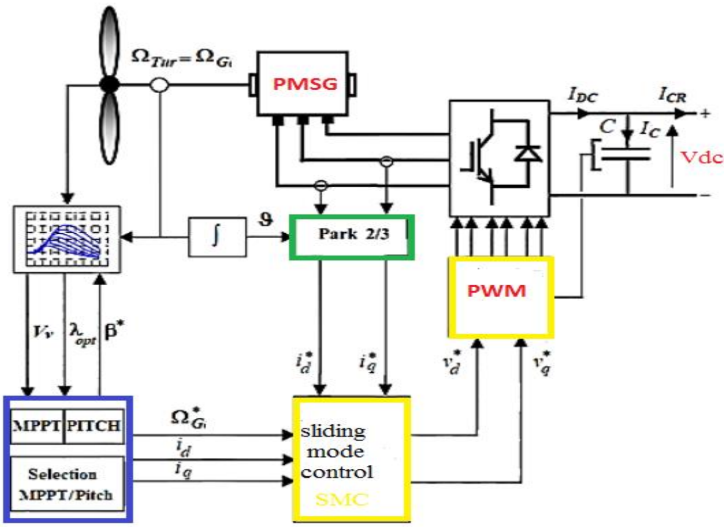

Fig 4. Structure of the SMC of the wind power system.

5. RESULTS AND DISCUSSION

This section assesses the performance of the suggested method for the entire system in the dynamic regime using MATLAB/Simulink simulation. Replicating realistic operating conditions for WESs is made possible by varying the wind speed for 15 seconds between 5 and 9 meters per second. This fluctuation in wind speed is used to examine how well the system responds and adjusts to abrupt or gradual changes. The outcomes of the simulation highlight various significant facets of the system's behavior. First, the Cp, stall angle (β), and peak speed ratio (λ) show how well the rotor converts energy as a function of wind speed. To maximize energy generation, one must be capable of maintaining an ideal tip-speed ratio. The PMSG mechanical speed displays how the machine behaves differently in response to differences in wind speed. At the same time, the Pmec delivered by the wind turbine varies proportionally, highlighting the importance of good synchronization between the rotor and the generator to optimize the conversion of mechanical energy into electrical energy. The Tem also fluctuates, indicating that the generator is adapting to variations in mechanical power. This rapid response ensures that the system runs smoothly and minimizes efficiency losses. The DC voltage regulation system is effective because the DC bus voltage stays constant despite changes in wind speed. Lastly, the smooth energy injection into the grid, which is necessary to prevent disruptions in the distribution system, is demonstrated by the amplitude of the grid voltage and current. These outcomes demonstrate the system's resilience in a range of dynamic scenarios while ensuring effective conversion and handling of the generated electrical energy. Throughout the simulation time, the Cp and specific speed (λ) essentially stay at their optimal reference values of 0.48 and 8, respectively, as seen by the findings exhibited in Figure 6. These results confirm that the system manages to maintain high energy efficiency, despite variations in wind speed. As for Figure 7, the mechanical speed (W) of the PMSG faithfully follows the wind speed profile, proving that the generator correctly adjusts to the reference speed imposed by wind variations. In addition, Figure 8 shows that the Pmec has a curve similar to that of the wind speed profile, reflecting the efficient conversion of kinetic energy into mechanical energy. Figure 9 In section 2, the Tem is shown in figure 9 to follow exactly the optimum torque imposed by the MPPT algorithm. This illustrates the efficiency of the MPPT control, which allows the maximum amount of wind energy to be exploited to produce the maximum amount of electrical energy. Figure 10 highlights that the DC bus voltage remains stable despite variations in wind speed, demonstrating the robustness of the voltage control system. Finally, as a function of wind speed, Figure 11 illustrates how the amplitude of the current injected into the grid changes. Additionally, the SMC produces a superior sinusoidal waveform with a reduced ripple rate at a fixed frequency of 50 Hz. Furthermore, it is discovered that the injected current and the grid voltage are in phase, indicating that the power factor is nearly one, ensuring the highest possible efficiency in the transfer of electrical energy to the grid. These outcomes support the evidence of the control system's excellent performance, which not only maximizes the utilization of wind energy but also maintains an ideal power factor while providing the stability of the injected current's voltage and waveform.

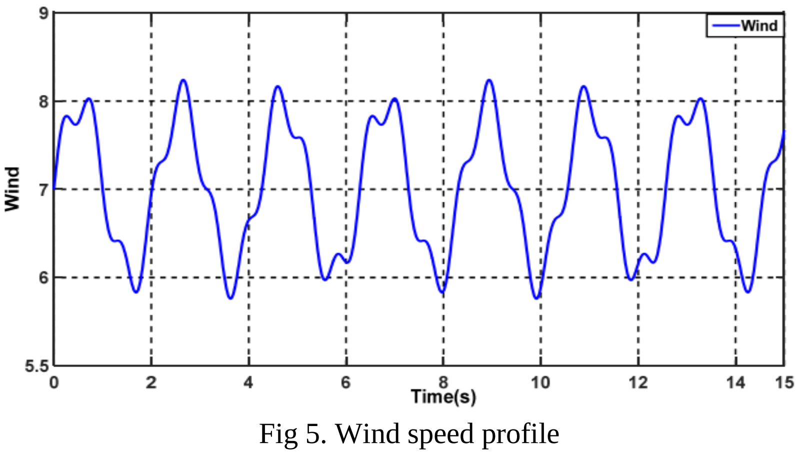

Fig 5. Wind speed profile

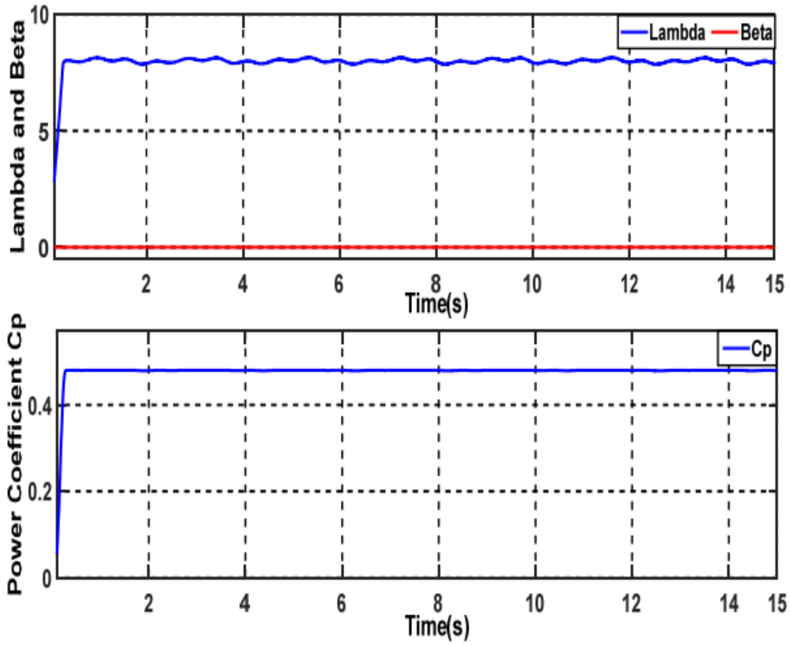

Fig 6. Tip speed ratio λ (lambda), Beta β and power coefficient (Cp)

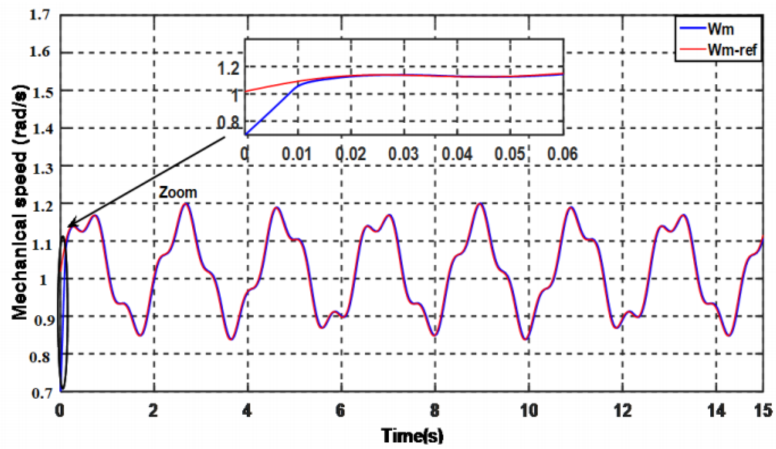

Fig 7. Mechanical speed (WMEC) of the PMSG

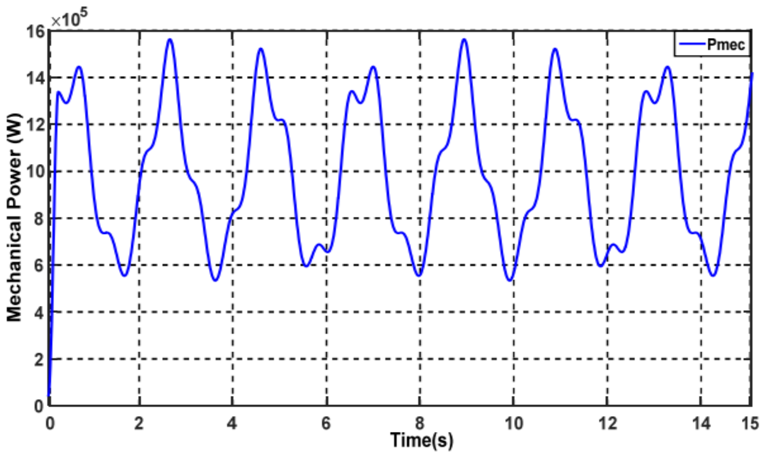

Fig 8. Mechanical power (Pmec)

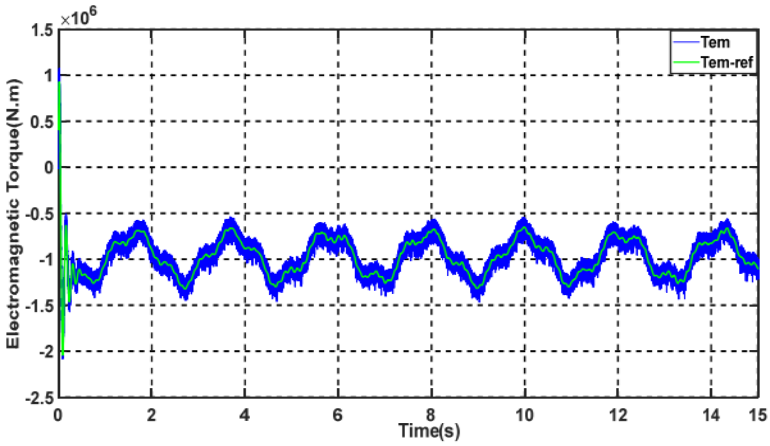

Fig 9. Electromagnetic torque (Tem)

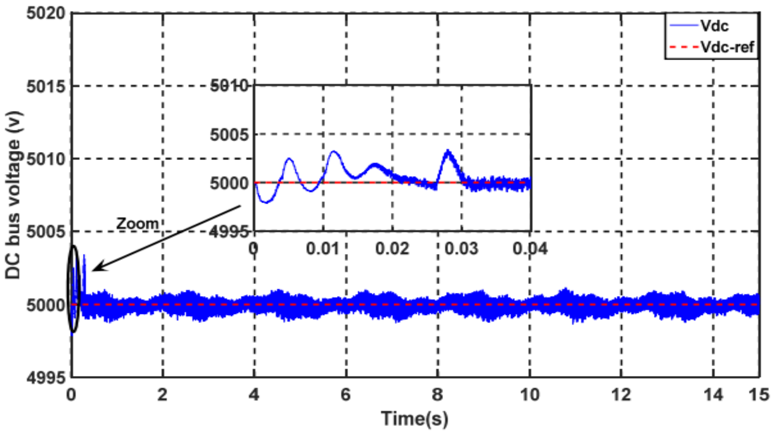

Fig 10. DC link voltage

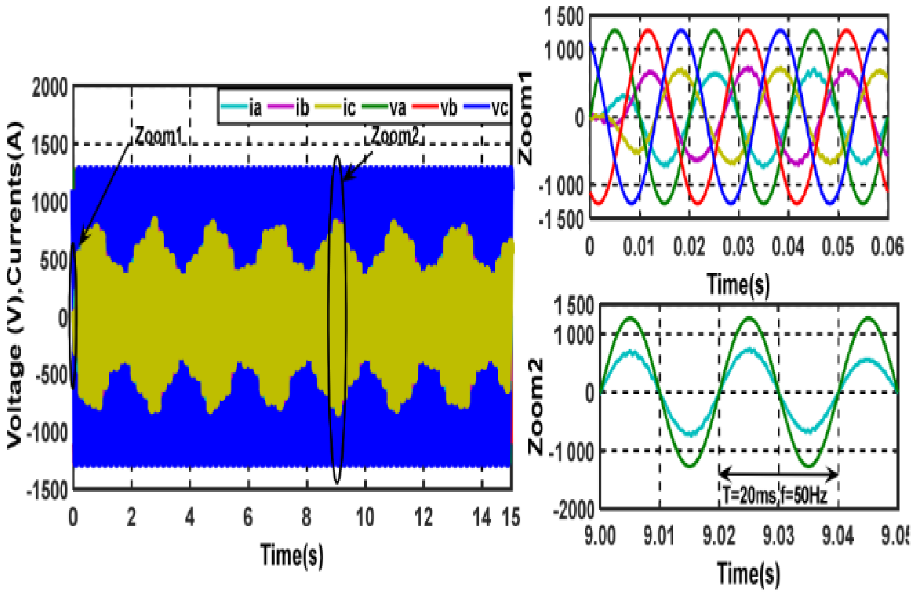

Fig 11. Grid voltage and current amplitude

6. CONCLUSION

With an emphasis on the integration of SMC for the PMSG, we have built and analyzed a comprehensive control strategy for a WECS in this work. The system, encompassing wind turbine aerodynamics, MPPT control, PMSG, AC/DC rectification, and DC connection, was exhaustively tested under varied wind conditions. The SMC method showed significant advantages in terms of robustness, fast dynamic response, and resilience to external disturbances, while effectively controlling the PMSG. In addition, a simple PI control loop was used to regulate the stall angle, ensuring efficient extraction of mechanical power. According to simulation results, the suggested system can effectively harvest the most power from the wind, use the rectifier to provide a steady and high-quality DC voltage and preserve the system's overall stability. These results highlight the relevance of combining SMC with traditional PI control for advanced wind power systems. The findings of this study pave the way for further exploration of advanced control strategies, particularly for large-scale WECS where non-linearity and uncertainty are ubiquitous. Future work could focus on expanding these control techniques for multi-machine configurations and grid-connected systems, improving the scalability and applicability of WECS in the renewable energy sector.

NOMENCLATURE

The nomenclature section is not numbered. Variables are listed alphabetically in Times New Roman, normal font, size 11.

(WECS)	Wind energy conversion systems	Pw	Output power (W)
(SMC)	Sliding mode control		
(PMSG)	Permanent magnet synchronous generator	Cp	Power coefficient
		ρ	The density of air (kg/m³)
		A	The surface swept by the turbine blades
		V	The wind speed (m/s)
	Wind turbine system	V_{dq}	The direct and quadrature mechanisms of the generator voltages
(WTS)	wind energy system		
(WES)			
(PWM)	Pulse width modulation	I_{dq}	The equivalent current of the 'd ' and 'q' axis
(Pmec)		ϕ_{dq}	The flux of the 'd ' and 'q' axis
(Cp)	The mechanical power	ϕ_f	The flux of the permanent magnets
(Tem)	The power coefficient	L_d,L_q	The inductances of the generator on the 'd ' and 'q' axis
	Electromagnetic torque	$w_e\varphi_f$	Electromotive force induced only on the "q" axis
		R_s	The stator phase resistance

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