

An Improved Sliding Mode Control Approach for the Enhancement of Wind Energy Conversion Systems Based on PMSG

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Abstract—Recently, researchers have increasingly focused on enhancing the quality of grid-supplied power while efficiently controlling wind energy conversion systems (WECS) under variable wind conditions. This study presents an improved control method to mitigate the chattering phenomenon often encountered in traditional approaches. By integrating maximum power point tracking (MPPT) with pitch angle control, the efficiency and performance of WECS utilizing permanent magnet synchronous generators (PMSG) are significantly improved. The primary objective is to regulate the generator and grid-side converter to precisely track the wind speed reference determined by the MPPT algorithm. The proposed sliding mode control (SMC) employs a unique, smooth, and continuous switching mechanism to address the chattering issue. Its stability is rigorously analyzed using Lyapunov's stability function. The control framework is straightforward to implement, and simulation results demonstrate its superior performance, achieving a total harmonic distortion (THD) below 2%, accurate current injection, and a near unity power factor. The MATLAB/Simulink based system is also validated through real-time hardware-in-the-loop (HIL) testing using an OPAL-RT simulator, confirming the model's effectiveness. Finally, the proposed method is benchmarked against existing schemes, highlighting its competitive advantages.

Index Terms—Hardware in the loop, maximum power point tracking, power converter, renewable energy, real-time simulator, sliding mode control, wind turbine.

I. INTRODUCTION

EFFORTS are being intensified to build a sustainable renewable energy infrastructure as a viable alternative to fossil fuels and to safeguard the environment [1]. Consequently, wind energy technology has attracted considerable interest recently because of its several benefits, such as reasonable cost, simple installation, and little maintenance requirements [2], [3]. Permanent magnet synchronous generators (PMSG) based wind energy conversion systems (WECS) are highly favoured

for their compact design, high power density, and excellent torque-to-inertia ratio, making them efficient, stable, and ideal for modern wind power generation. In addition, the internal structure of the PMSG, which includes very accurate gears and brushes, is less complex than that of the doubly-fed induction generator. Thus, WECS based on PMSG have emerged as a prominent area of study in wind generation of energy [4].

Nevertheless, the lack of consistency and predictability in wind speed makes it difficult for current studies on high-power wind generators to achieve their maximum production level. Consequently, they reduced the effectiveness of wind energy utilization and rendered the advantages of high-capacity wind turbines meaningless. Integrating large-capacity wind farms into the power grid can introduce challenges, as frequent wind speed fluctuations and the inherent variability of wind energy may disrupt the stability of the power system. Maximizing wind energy conversion efficiency is crucial for reducing the cost of wind power generation and boosting the overall productivity of wind farms. Consequently, it becomes equally important to enhance the control mechanism of the wind energy system. Modern WECS sometimes use the best characteristic curve to control maximum power point tracking (MPPT) at specified wind speeds. The generator dynamically adapts its mechanical output to match the wind turbine input under varying wind conditions. This enables the WECS to maintain an optimal blade-tip speed ratio (TSR) and maximize wind energy capture.

Wind turbines harness energy from the wind by optimizing key parameters such as airflow velocity, blade pitch angle, and wind wheel rotation speed, which are critical to maximizing energy capture. However, variations in wind patterns and energy losses within the WECS can disrupt system stability [5]. This makes wind-to-electric energy conversion a highly nonlinear process, often fraught with uncertainty and complexity. In response, recent decades have seen the development of advanced control strategies and innovative solutions to overcome these challenges in PMSG-based systems [6].

The main goals of the control system are to adapt reactive power to the grid's demands and maximize power extraction. Using the suitable voltage vector, these operations must run in parallel. Fig. 1 displays the simplified version of the schematic PMSG-based WECS. The proportional-integral (PI) control technique is a popular choice for enhancing the reliability of

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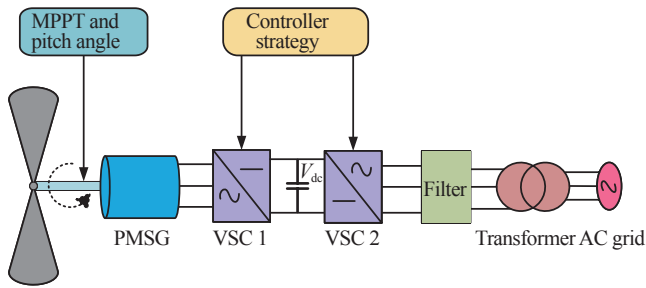


Fig. 1. Simplified version of schematic PMSG based WECS.

rotor-side and grid-side converters (GSCs) in PMSG wind turbines, valued for its simplicity, robustness, and ease of implementation. [7] highlights its effectiveness in optimizing the performance of PMSG wind turbines, even under dynamic wind conditions. Despite its simplicity and widespread use, the PI control scheme, as a linear method, falls short in addressing the nonlinear dynamics of PMSG wind turbine systems and the variability in wind speed and turbine parameters. To overcome these limitations and enhance power quality, advanced nonlinear control techniques have been developed and implemented, including fuzzy control methods [8], [9], backstepping control [10], [11], and direct power control (DPC). However, the implementation of fuzzy control in practical scenarios is challenging due to the need for substantial expertise and human consciousness, leading to a delayed reaction in return for achieving high standards of accuracy. While the DPC system offers an excellent transient response, it demands a rapid switching frequency to reduce torque and current fluctuations [12]. A drawback of backstepping control is that it can increase complexity, which reduces the controller's efficiency. Recent studies have focused on improving the control performance and power quality of grid-connected power electronic converters through advanced control strategies and modulation techniques [13]–[15].

In addition to the previously discussed nonlinear control systems, sliding mode control (SMC) has gained attention for its rapid response, ease of implementation, and robustness against parameter variations [16], [17]. Known for its simplicity and resilience, SMC is increasingly applied in WECS to optimize energy extraction, regulate DC link power, and control direct wind energy output. First-order SMC is employed to regulate the speed and power of PMSG-based WECS, as demonstrated in [18], [19]. This control system typically generates a voltage reference using pulse width modulation (PWM) technique. As a result, the PWM method struggles to accurately track the voltage reference when using the sinusoidal function due to chattering issues. In [20], [21] a continuous approximation and saturation function was used to design an SMC system with reduced noise for a PMSG system. However, using a saturation function introduces a finite steady-state error. [22] proposed a fractional order SMC to enhance the output power quality of a PMSG, emphasizing the need for accurate tuning of the fractional operator. Similarly, [20] introduced an adaptive second-order SMC method, effectively addressing model uncertainties, the nonlinear dynamics of WECS, and random wind

fluctuations. However, using differentiators in this approach requires careful consideration due to the influence of measurement noise.

The integral SMC method, developed for precise control of steady-state conditions, has been presented in the works referenced by [23], [24]. However, the controller gain must be meticulously calibrated to achieve a harmonious equilibrium between power and chattering dynamics. Second-order SMC is used with super-twisting algorithms (STA) [20]. Although STA may generate a rapid transient reaction with less steady-state error, it usually leads to high controller gains, which in turn causes system chattering. The primary drawback of SMC methods is the presence of chattering, which arises from the discontinuous control theory used in developing the SMC and the interactions of parasitic dynamics. Intermittent chattering can negatively impact the system by reducing control accuracy, causing higher heat dissipation in electrical circuits, and accelerating the wear and tear of moving mechanical components.

Although several techniques such as saturation functions and hyperbolic tangent-based approaches have been reported in the literature to mitigate the chattering effect in SMC, these methods often introduce a trade-off between chattering reduction and tracking accuracy. In contrast, the proposed smooth continuous switching-based SMC achieves a better balance between chattering suppression and dynamic performance. Compared with conventional approaches, the proposed method provides smoother control action, faster convergence to the sliding surface, and improved steady-state accuracy while preserving the inherent robustness of SMC. Furthermore, its integration with MPPT and pitch angle control makes it more suitable for WECS operating under highly variable wind conditions.

In this manuscript, the design of PMSG is examined using a smooth continuous switching controller. This work is unique in introducing an innovative controller architecture, distinguishing it from the commonly used SMC-based PMSG wind power generation system. The proposed system features an innovative sliding mode controller with a novel rate control approach, offering superior precision and adaptability through enhanced robustness and smoother transitions. The main contributions of this work are summarized as follows:

- 1) An improved SMC framework is developed for grid-connected PMSG-based WECS to mitigate the chattering phenomenon commonly observed in conventional SMC methods while preserving the robustness characteristics of SMC.
- 2) A smooth continuous switching function is incorporated into the SMC structure to reduce high-frequency oscillations in the control signal and improve the dynamic behaviour of the system under variable wind conditions.
- 3) A coordinated control strategy integrating MPPT and pitch angle regulation is implemented, enabling efficient wind energy extraction and stable operation of the wind energy conversion system.
- 4) The proposed controller improves the quality of grid-connected power, resulting in reduced current ripple and lower total harmonic distortion (THD) compared with the conventional SMC.
- 5) The effectiveness of the proposed control approach is veri-

fied through MATLAB/Simulink simulations and hardware-in-the-loop (HIL) testing, demonstrating improved dynamic response, system stability, and power quality.

This work is organized as follows: Section II discusses the wind turbine dynamic model of the WECS, including the MPPT technique and pitch control. Section III details the proposed SMC approach. Finally, Section IV provides a comprehensive analysis of the SMC performance results, comparing them with those of other control strategies.

II. WIND ENERGY CONVERSION SYSTEM MODELLING

A. Wind Turbine Model

The parameters determine how the turbine blades interact with wind energy, affecting the efficiency and performance of energy conversion. The equations that describe these parameters are derived from established aerodynamic and mechanical principles [25], [26]:

$$P_w = \frac{1}{2} \rho A V_w^3 \quad (1)$$

$$P_m = C_p(\lambda, \beta) \cdot P_w = \frac{1}{2} \cdot C_p(\lambda, \beta) \rho A V_w^3 \quad (2)$$

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda} - 0.4\beta - 4 \right) e^{\frac{-21}{\lambda}} + 0.0068\lambda \quad (3)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.008\beta} - \frac{0.035}{1 + \beta^3} \quad (4)$$

$$\lambda = \frac{\omega_r R}{V_w} \quad (5)$$

$$C_p^{\max} = \frac{16}{27} \quad (6)$$

where P_w , P_m , λ , C_p , A , ρ , β , and V_w are the wind power, mechanical power of wind turbine, tip-speed ratio power coefficient, area of the blade, air density, pitch angle and wind speed respectively.

B. Optimal Power Extraction

The MPPT control technique aims to maximize wind energy extraction by adjusting the wind turbine's rotational speed, ensuring the generator operates at its optimal speed for wind conditions below the rated value. The optimal condition is achieved when $\lambda_{\text{opt}} = 8$ and $\beta = 0^\circ$, as indicated in [5], [22], [26] and realize this, the MPPT technique is employed to estimate and control the electromagnetic torque. The PMSG then uses this torque to regulate the wind turbine's rotational speed precisely. The corresponding formulations are as follows [27], [28]:

$$T_m = \frac{P_m}{\omega_r} \quad (7)$$

$$T_{m(\text{Ref})} = \frac{1}{2 \cdot \lambda_{\text{opt}}^3} \cdot (\rho \cdot \pi \cdot C_{p_{\max}} \cdot \lambda_{\text{opt}} \cdot \omega_r^2) \quad (8)$$

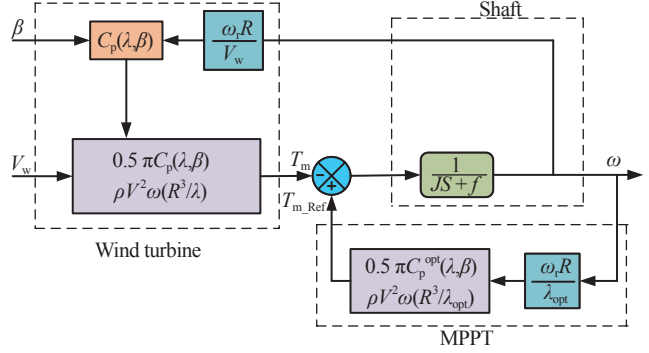


Fig. 2. Operating principle of the MPPT control.

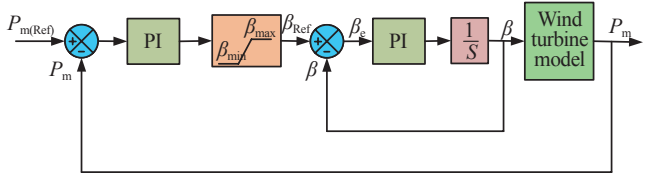


Fig. 3. Pitch angle control of wind turbine model.

where T_m and $T_{m(\text{Ref})}$ are the mechanical torque and reference mechanical torque developed by a wind turbine.

Fig. 2 demonstrates the operating principle of MPPT control, which provides a visual representation of how the MPPT command adjusts the system in response to changing conditions to maximize efficiency and power generation. The structure of the pitch angle control system is illustrated in Fig. 3. Pitch angle control is a widely used mechanical method employed to protect the wind turbine system and ensure that power output remains at its rated level. This system adjusts the blade pitch angle in response to changes in wind speed, limiting both output power and generator speed when they exceed 30% of the rated value [29], [30].

C. Modeling of a Wind-Driven PMSG

The modeling of a wind-driven PMSG involves creating a detailed representation of how wind energy is transformed into electrical power, accounting for the turbine dynamics, drive train, and the generator's mechanical and electrical behavior. The d - q reference frame of the PMSG is expressed as [25], [31], [32].

$$\frac{di_{sq}}{dt} = - \left(\frac{R_s}{L_q} i_{sq} + \omega_e \frac{L_d}{L_q} i_{sd} - \omega_e \frac{\phi}{L_q} + \frac{v_{sq}}{L_q} \right) \quad (9)$$

$$\frac{di_{sd}}{dt} = - \left(\frac{R_s}{L_d} i_{sq} - \omega_e \frac{L_q}{L_d} i_{sq} - \frac{v_{sd}}{L_d} \right) \quad (10)$$

$$T_{em} = \frac{3p}{2} [(L_d - L_q) i_{sq} i_{sd} + \phi \cdot i_{sq}] \quad (11)$$

$$\frac{d\Omega_{\text{mech}}}{dt} = \frac{T_m}{J} - \frac{3p}{2J} i_{sq} \cdot \phi - \frac{B\Omega_{\text{mech}}}{J} \quad (12)$$

$$\psi_{sq} = L_q \cdot i_{sq} \quad (13)$$

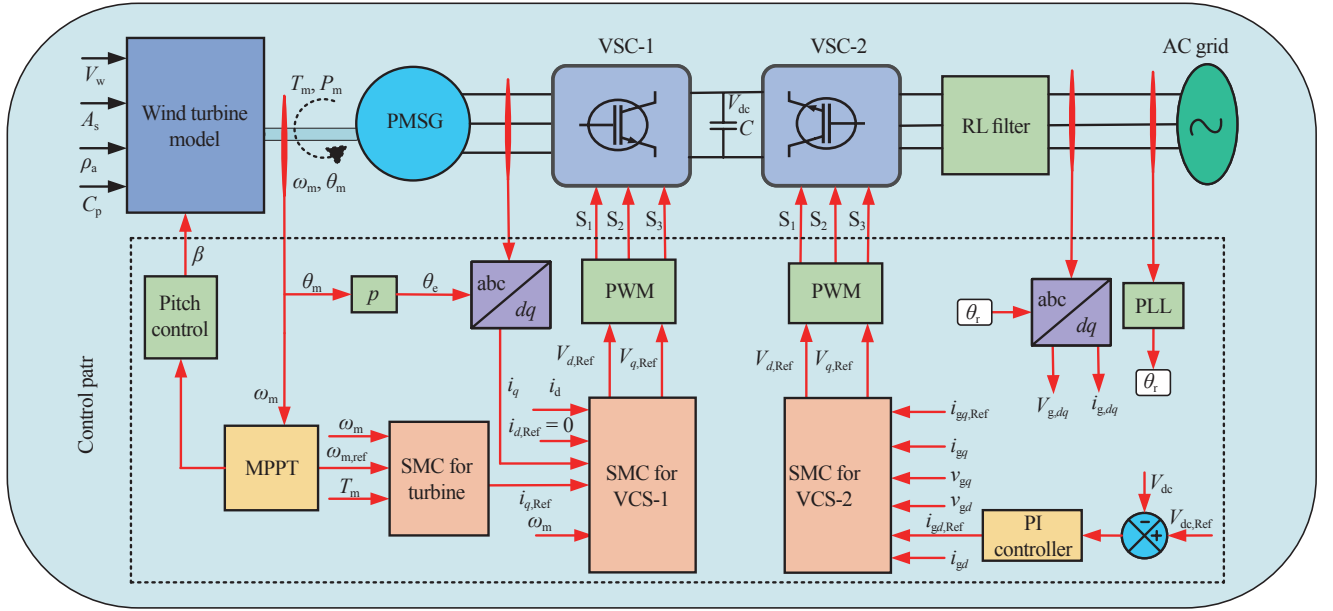


Fig. 4. The overall control mechanism of proposed PMSG based WECS.

$$\psi_{sd} = L_d \cdot i_{sd} + \phi \quad (14)$$

$$\omega_e = p \cdot \Omega_{mech} \quad (15)$$

$$P_{gen} = \frac{3}{2} (v_{sd} i_{sd} + v_{sq} i_{sq}) \quad (16)$$

$$G_{gen} = \frac{3}{2} (v_{sq} i_{sd} - v_{sd} i_{sq}) \quad (17)$$

D. Filter and Grid Modelling

A filter, comprising resistance (R_f) and inductance (L_f), is used to smooth the voltage and current waveforms in grid-connected systems. In grid mode, the system operates in synchronization with the grid, enabling stable power exchange. The d - q reference frame is formulated as (18) and (19) of the dynamic model of the grid side converter [33], [34].

$$\frac{di_{gq}}{dt} = \left(\frac{v_q}{L_f} - \frac{R_f}{L_f} i_{gq} - \omega_g i_{gd} - \frac{v_{gq}}{L_f} \right) \quad (18)$$

$$\frac{di_{gd}}{dt} = \left(\frac{v_d}{L_f} - \frac{R_f}{L_f} i_{gd} + \omega_g i_{gq} - \frac{v_{gd}}{L_f} \right) \quad (19)$$

The voltage component of the d - q axis of the inverter is v_d and v_q .

The grid real and imaginary powers are mathematically represented as:

$$P_{grid} = \frac{3}{2} (v_{gd} i_{gd} + v_{gq} i_{gq}) \quad (20)$$

$$Q_{grid} = \frac{3}{2} (v_{gq} i_{gd} - v_{gd} i_{gq}) \quad (21)$$

The generator-side converter (VSC-1) and the grid-side converter (VSC-2) are interconnected through a DC-link.

Considering the principle of power balance and assuming negligible converter losses, the DC-link voltage exhibits dynamic behaviour expressed as follows [35]:

$$P_{grid} = P_{gen} - \frac{1}{2} C \frac{dv_{dc}^2}{dt} \quad (22)$$

III. CONTROL SYSTEM DESIGN FOR WECS

The overall control mechanism of proposed PMSG based WECS is shown in Fig. 4. To achieve the desired control objectives in response to varying wind speeds, regulating the power and voltage parameters delivered to the grid is essential. The converter frequency is critical in controlling the active and reactive power and maintaining the grid voltage and frequency within acceptable limits [34], [35]. Consequently, the selection of the state vector and control vector is carried out as (23) and (24).

$$[Y] = (i_{sd}, i_{sq}, \Omega_{mech}, i_{gd}, i_{gq})^T \quad (23)$$

$$[V] = (v_{sd}, v_{sq}, v_{ld}, v_{lq})^T \quad (24)$$

A. Sliding Mode Controller Design

SMC aims to steer a system to a predefined sliding surface within a finite time and keep it there despite uncertainties such as varying wind speeds or changes in system parameters, making it particularly effective for dynamic systems. This approach enables the system to switch between differentiators, utilizing a discontinuous control signal structure at any given moment. As a result, the system dynamics leverage the advantageous characteristics of each structure to achieve the desired performance [36]. However, SMC is prone to issues such as chattering and instability during the reaching phase [35]. Thus, a control strategy for SMC has been proposed to address the typical SMC

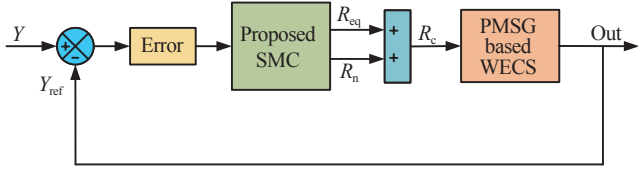


Fig. 5. The overall framework of the SMC.

requirements and enhance the performance of the system [37].

In the proposed SMC scheme, the selected sliding surface is defined as

$$S(Y) = \left(\frac{d}{dt} + \alpha \right)^{n-1} e(y) \quad (25)$$

where n denotes the system order, α is a constant, and $e(y)$ represents the tracking error, defined as the difference between the desired signal y_{ref} and the state variable y . By setting $n = 1$, the tracking error dynamics associated with this sliding surface can be described as:

$$S(Y) = e(y) = y_{ref} - y \quad (26)$$

Fig. 5 shows the overall framework of SMC which consists of two components, the equivalent control R_{eq} and the switching control R_n . The R_{eq} defines the system's behaviour when it remains on the sliding surface. At the same time, R_n is expressed as a discontinuous function, often using a sign function. It is utilized to fulfill the requirement of both physical appeal and stability [29], [38]. To achieve commutation across the surface of the proposed SMC, each component of the control strategy is determined by summing two terms derived from

$$R_c = R_{eq} - R_n \quad (27)$$

The switching signal R_n can be written as

$$R_n = k_n \cdot \text{sgn}(S_n) \quad (28)$$

The switching gain k_n is precisely chosen to achieve optimal performance and reduce dynamic system disruption. The mathematical function $\text{sgn}(S_n)$ is a discontinuous function that exhibits an inadequate switching leading to chattering of the control signal [40]. In order to mitigate these phenomena, a novel sliding current strategy (SCS) control has been introduced to achieve signal smoothing. The core idea of this approach is to replace the traditional discontinuous switching control function Sgn with a switching control function (SCF), as outlined in [39].

$$R_n = k_n \cdot N(S_n) \quad (29)$$

The smooth continuous function $N[S(y)]$ is defined as

$$N(\lambda', S) = \frac{S\lambda'}{|S\lambda'| + \zeta} \quad (30)$$

Here, ζ denotes a width of boundary value, while λ' is a constant used to adjust the function's tuning rate. This continuous function's steepness is determined by these two parameters (ζ ,

λ'). Moreover, the boundary layer ζ , which is dependent on the state, is designed as

$$\zeta = 1 - |N(\lambda', S)| + \delta_1 \quad (31)$$

1) VSC-1 control: In this approach, three SMCs are designed to regulate the d - and q -axis current components of the stator (i_{sd} , i_{sq}) as well as the mechanical speed Ω_{mech} , as shown in Fig. 4. The sliding surfaces are defined as follows:

$$S(i_{sq}) = e(i_{sq}) = i_{sq}^* - i_{sq} \quad (32)$$

$$S(i_{sd}) = e(i_{sd}) = i_{sd}^* - i_{sd} \quad (33)$$

$$S(\Omega_{mech}) = e(\Omega_{mech}) = \Omega_{mech}^* - \Omega_{mech} \quad (34)$$

Here, i_{sd}^* and i_{sq}^* represent the reference values for the direct and quadrature stator currents, respectively, while Ω_{mech}^* denotes the reference for the mechanical speed. Differentiate (32) – (34), we can get:

$$\dot{S}(i_{sd}) = \dot{i}_{sd}^* + \left(\frac{R_s}{L_d} i_{sd} - \omega_e \frac{L_q}{L_d} i_{sq} - \frac{v_{sd}}{L_d} \right) \quad (35)$$

$$\dot{S}(i_{sq}) = \dot{i}_{sq}^* + \left(\frac{R_s}{L_q} i_{sq} + \omega_e \frac{L_d}{L_q} i_{sd} + \omega_e \frac{\phi}{L_q} - \frac{v_{sq}}{L_q} \right) \quad (36)$$

$$\dot{S}(\Omega_{mech}) = \dot{\Omega}_{mech}^* + \frac{B}{J} \Omega_{mech} + \frac{3p}{2} \phi \frac{i_{sq}}{J} - \frac{T_m}{J} \quad (37)$$

When the invariance criteria of the sliding surface are fully satisfied, $\dot{S}(Y) = 0$ and $v_{sd,qn} = 0$, a sliding mode appears on the sliding surface. Consequently, (35) and (36) can be used to obtain the control expression $v_{sd,qn}$ for each axis.

$$v_{sd,eq} = L_d \left(\dot{i}_{sd}^* + \frac{R_s}{L_d} i_{sd} - \omega_e \frac{L_q}{L_d} i_{sq} \right) \quad (38)$$

$$v_{sq,eq} = L_q \left(\dot{i}_{sq}^* + \frac{R_s}{L_q} i_{sq} + \omega_e \frac{L_d}{L_q} i_{sd} + \omega_e \frac{\phi}{L_q} \right) \quad (39)$$

The switching control variables $v_{sd,n}$ and $v_{sq,n}$ can be write as

$$v_{sd,n} = k_d \cdot N[S(i_{sd})] \quad (40)$$

$$v_{sq,n} = k_q \cdot N[S(i_{sq})] \quad (41)$$

Here k_d and k_q must be grater than zero.

To develop the VSC-1 controller can be structured by adding (38) with (40) and (39) with (41), then we get

$$v_{sd,ref} = L_d \left(\dot{i}_{sd}^* + \frac{R_s}{L_d} i_{sd} - \omega_e \frac{L_q}{L_d} i_{sq} \right) + k_d \cdot N[S(i_{sd})] \quad (42)$$

$$v_{sq,ref} = L_q \left(\dot{i}_{sq}^* + \frac{R_s}{L_q} i_{sq} + \omega_e \frac{L_d}{L_q} i_{sd} + \omega_e \frac{\phi}{L_q} \right) + k_q \cdot N[S(i_{sq})] \quad (43)$$

2) VSC-2 control: In order to maintain a consistent DC-link voltage, a PI controller was implemented to automatically adjust the measured V_{dc} voltage to match its reference $V_{dc,ref}$ as

shown in Fig. 4. Additionally, two sliding mode controllers are built to control the d - and q -axis current components (i_{gd} , i_{gq}) of the VSC-2 to regulate the grid current frequencies and obtain a unit power factor [42]. In this regard, the sliding surfaces can be written as:

$$S(i_{gq}) = e(i_{gq}) = i_{gq}^* - i_{gq} \quad (44)$$

$$S(i_{gd}) = e(i_{gd}) = i_{gd}^* - i_{gd} \quad (45)$$

Here, i_{sd}^* and i_{sq}^* represent the reference values for the d - and q -axis stator currents respectively.

The controller design for the VSC-2 will follow the same methodology as the VSC-1 control, and will appear as:

$$v_{id,ref} = v_{id,eq} + v_{id,n} \quad (46)$$

$$v_{iq,ref} = v_{iq,eq} + v_{iq,n} \quad (47)$$

$$v_{id,eq} = L_f \left(\dot{i}_{gd}^* + \frac{R_f}{L_f} i_{gd} - \omega_g i_{gq} + \frac{v_{gd}}{L_f} \right) \quad (48)$$

$$v_{iq,eq} = L_f \left(\dot{i}_{gq}^* + \frac{R_f}{L_f} i_{gq} + \omega_g i_{gd} + \frac{v_{gq}}{L_f} \right) \quad (49)$$

$$v_{id,n} = k_{id} \cdot N[S(i_{id})] \quad (50)$$

$$v_{iq,n} = k_{iq} \cdot N[S(i_{iq})] \quad (51)$$

where k_{id} and k_{iq} must be greater than zero. The reactive power Q_g^{ref} , which keeps zero to achieve unity power factor control, which determines I_{gq}^* in this case. Meanwhile, the DC-link voltage controller generates I_{gd}^* , as seen in Fig. 4.

B. Stability Assessment of the Proposed SMC

We introduce the Lyapunov stability function as the global stability criterion for the suggested SMC for the VSC-1 and VSC-2. The Lyapunov stability function is described in [43], [44].

$$v_{\text{vsc-1}} = \frac{1}{2} (S_{\text{isq}}^2 + S_{\text{isd}}^2 + S_{\text{w,mech}}^2) \quad (52)$$

$$v_{\text{vsc-2}} = \frac{1}{2} (S_{\text{igq}}^2 + S_{\text{igd}}^2) \quad (53)$$

Here the Lyapunov stability function is defined both $v_{\text{vsc-1}}$ and $v_{\text{vsc-2}}$ are picked for the VSC-1 and VSC-2, respectively.

The stability of SMC is ensured when the derivative of the Lyapunov function remains negative, as indicated in [45], [46].

$$\dot{v}_{\text{vsc-1}} < 0 \quad (54)$$

$$\dot{v}_{\text{vsc-2}} < 0 \quad (55)$$

Therefore, differentiate (52) and (53), then we get

$$\dot{v}_{\text{vsc-1}} = (S_{\text{isq}} \dot{S}_{\text{isq}} + S_{\text{isd}} \dot{S}_{\text{isd}} + S_{\text{w,mech}} \dot{S}_{\text{w,mech}}) \quad (56)$$

$$\dot{v}_{\text{vsc-2}} = (S_{\text{igq}} \dot{S}_{\text{igq}} + S_{\text{igd}} \dot{S}_{\text{igd}}) \quad (57)$$

Now, putting the value of (35), (36), and (37) in (56) and (57), we can get

$$\begin{aligned} \dot{v}_{\text{vsc-1}} = & S_{\text{isq}} \left(\dot{i}_{sd}^* + \frac{R_s}{L_d} i_{sd} - \omega_e \frac{L_q}{L_d} i_{sq} - \frac{v_{sd}}{L_d} \right) \\ & + S_{\text{isd}} \left(\dot{i}_{sq}^* + \frac{R_s}{L_q} i_{sq} + \omega_e \frac{L_d}{L_q} i_{sd} + \omega_e \frac{\phi}{L_q} - \frac{v_{sq}}{L_q} \right) \\ & + S_{\text{w,mech}} \left(\dot{\Omega}_{\text{mech}}^* + \frac{B}{J} \Omega_{\text{mech}} + \frac{3p}{2} \phi \frac{i_{sq}}{J} - \frac{T_m}{J} \right) \end{aligned} \quad (58)$$

$$\begin{aligned} \dot{v}_{\text{vsc-2}} = & S_{\text{igq}} \left(\dot{i}_{gq,ref}^* + \frac{R_f}{L_f} i_{gq} + \omega_g i_{gd} + \frac{v_{gq}}{L_f} - \frac{v_{id}}{L_f} \right) \\ & + S_{\text{igd}} \left(\dot{i}_{gd,ref}^* + \frac{R_f}{L_f} i_{gd} - \omega_g i_{gq,ref} + \frac{v_{gd}}{L_f} - \frac{v_{iq}}{L_f} \right) \end{aligned} \quad (59)$$

Now substituting (41), (42), (48), (49) into (58) and (59), we can get

$$\begin{aligned} \dot{v}_{\text{vsc-1}} = & -k_d S_{\text{isd}} \cdot N[S(i_{sd})] - k_q S_{\text{isq}} \cdot N[S(i_{sq})] \\ & - k_{\Omega_{\text{mech}}} S_{\Omega_{\text{mech}}} \cdot N[S(\Omega_{\text{mech}})] \end{aligned} \quad (60)$$

$$\dot{v}_{\text{vsc-2}} = -k_{id} S_{\text{igd}} \cdot N[S(i_{id})] - k_{iq} S_{\text{igq}} \cdot N[S(i_{iq})] \quad (61)$$

Furthermore, by substituting $N[S(Y)]$ with its corresponding equation, (60) and (61) are transformed as

$$\dot{v}_{\text{vsc-1}} = -k_{\Omega_{\text{mech}}} \cdot |S_{\Omega_{\text{mech}}}| - k_q \cdot |S_{\text{isq}}| \quad (62)$$

$$\dot{v}_{\text{vsc-2}} = -k_{id} \cdot |S_{\text{igd}}| - k_{iq} \cdot |S_{\text{igq}}| \quad (63)$$

where, $k_{\Omega_{\text{mech}}}$, k_d , k_q , k_{id} , and k_{iq} must be positive values and $v_{\text{vsc-1}}$ and $v_{\text{vsc-2}}$ must be negative values. Thus, the Lyapunov condition is met, and the primary goals of the proposed control approach are fulfilled.

The following equation is used to estimate the efficiency of the PMSG wind generation system [25].

$$\eta = \frac{\int_t^0 P_{\text{grid}}}{\int_t^0 P_m} \times 100\% \quad (64)$$

where η represents the system efficiency, P_{grid} denotes the grid power, and P_m signifies the theoretical mechanical power.

IV. RESULTS AND DISCUSSIONS

The proposed MPPT algorithm with an SMC scheme is designed for a 1.35 MW PMSG-based wind power conversion system. Its performance and effectiveness are evaluated under variable wind velocity profiles through MATLAB/Simulink 2022B simulations and verified via realtime testing on an OPAL-RT-based HIL test bench. The system parameters for the PMSG-based WECS are detailed in Table I.

For comparison among different control strategies, all the simulations and HIL experiments were performed under identical operating conditions. Specifically, the grid-side filter parameters and switching frequency of the GSC were kept

TABLE I
PARAMETERS OF THE SIMULINK MODEL

Component	Parameters	Value
Turbine parameters	Air density ρ_{air}	1.22 kg/m ³
	Power coefficient C_p	0.5
	Tip speed ratio λ	7
	Radius of turbine blade R	50 m
	Rated wind velocity V_w	8 m/s
	Moment of inertia J	900 kg • m ²
PMSG	Rated power P	1.35 MW
	Number of poles p	75
	Stator resistance R_s	6.25 mΩ
	Stator inductance L_a	4.3 mH
	Generator flux ϕ	11.15 wb
VSC	Switching frequency F_{sw}	5 kHz
	DC-link capacitor C_{bus}	60 mF
	DC-link voltage V_{dc}	5000 V
L-filter	Filter inductance L_f	10 mH rad/s

TABLE II
PARAMETERS OF THE SIMULINK MODEL

Controllers	Gain symbols	Gain value
PLL	$K_{\text{i,PLL}}$	8025
	$K_{\text{p,PLL}}$	126.92
DC-link voltage	$k_{\text{i,vdc}}$	5921.8
	$k_{\text{p,vdc}}$	66.633
	$k_{\text{i,idr}}$	246.74
	$k_{\text{p,idr}}$	3.332
Generator side converter	k_{id}	16.695
	k_{pd}	0.369
	k_{iq}	16.695
	k_{pq}	0.369
MPPT	K_{pv}	9.87×10^6
	K_{iv}	4.86×10^7
Grid side converter	$K_{\text{i,Qr}}$	0.0195
	$K_{\text{p,Qr}}$	0.2
	$K_{\text{i,iqr}}$	246.74
	$P_{\text{p,iqr}}$	3.332

the same for all control strategies. The switching frequency of the GSC was fixed at 5 kHz, and the same L-filter parameters were used throughout the study. Therefore, the improvement in THD is mainly attributed to the enhanced current control performance of the proposed SMC strategy rather than changes in the hardware configuration.

The controller gains were initially selected based on stability and sliding mode reaching conditions to ensure proper convergence and robustness. These parameters were then fine-tuned through simulation to achieve improved transient response, reduced oscillations, and stable DC-link voltage regulation. The final gain values used in the simulation and HIL studies are listed in Table II.

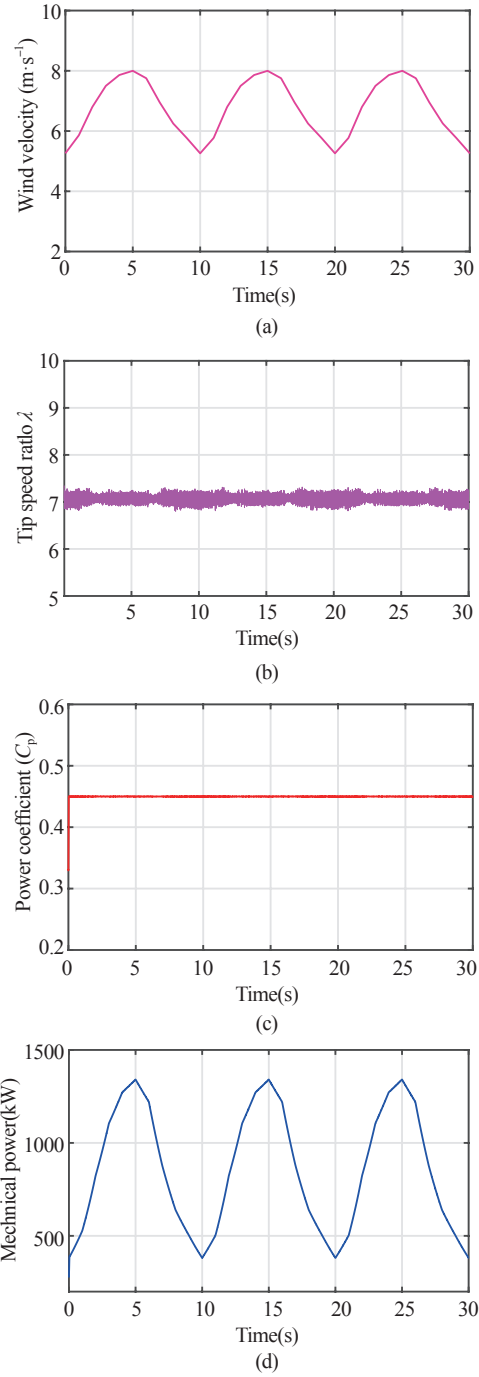


Fig. 6. Simulation results with system performance with the MPPT algorithm under variable wind velocity profile. (a) Wind velocity. (b) TSR. (c) Power coefficient. (d) Turbine mechanical power.

A. Simulation Results

This section presents the simulated results of the proposed system performance with the MPPT algorithm under a variable wind velocity profile. The wind velocity changes from 5.26 to 8 m/s as shown in Fig. 6(a). The TSR λ and power coefficient C_p of the wind turbine are shown in Fig. 6(b) and (c), respectively. The value λ and C_p near-optimal value can be observed. The turbine mechanical power output is shown in Fig. 6(d), which follows the same shape as wind velocity. The power de-

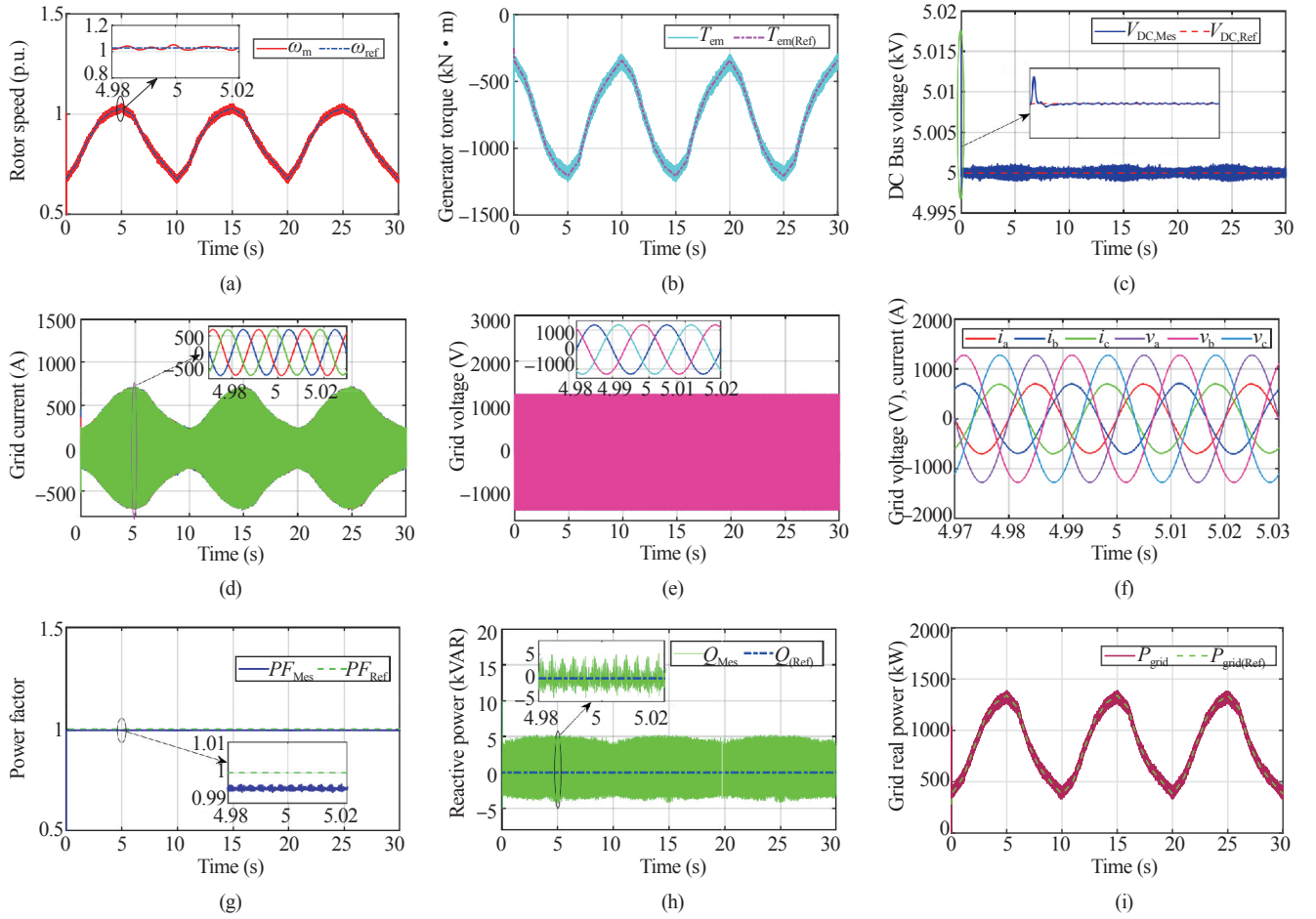


Fig. 7. Simulation results of proposed MPPT algorithm with SMC scheme under variable wind velocity profile. (a) Rotor speed. (b) Electromagnetic torque. (c) DC bus voltage. (d) Grid current. (e) Grid voltage. (f) Zoom grid voltage, current. (g) Power factor. (h) Grid imaginary power. (i) Grid real power.

veloped by wind turbines varies from 400 kW to 1.35 MW.

Fig. 7 presented the simulation results of proposed MPPT algorithm with SMC scheme under variable wind velocity profile. Fig. 7(a) shows that the rotor speed of PMSG can well track the wind turbine speed or reference speed by adopting the control system described in Section III-B. According to the principle of the proposed SMC depicted in Fig. 4, when wind velocity is low, then rotor speed is lower, and when wind velocity is high, then rotor speed is also high, as shown in Fig. 7(a). Further, Fig. 7(b) shows the electromagnetic torque, which tracks the maximum torque imposed by the MPPT algorithm. These results proved the MPPT control's performance, allowing the optimal utilization of wind energy to generate maximum electrical power, as discussed in Section II. Fig. 7(c) shows the DC bus voltage at starting spike as seen in zoom version of figure but after a few seconds V_{dc} is stable and changing according to wind variation. Fig. 7(d) shows the amplitude of the injected grid current alter with changes in wind velocity, maintaining a fixed frequency of 50 Hz. Under PSMC control, the current exhibits a more sinusoidal waveform and lower ripple compared to conventional sliding mode control (CSMC). Fig. 7(e) shows the grid voltage and current. We can observe from zoom version of Fig. 7(f) is voltage and current

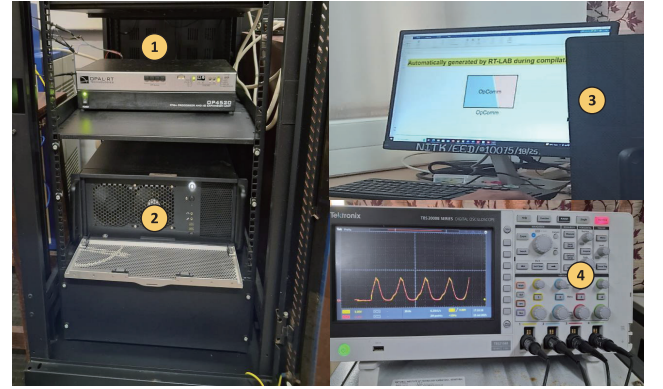


Fig. 8. HIL setup for real-time experiment: 1-OP4520 FPGA processor & I/O expansion unit. 2-Real-time simulator OP5033 XG. 3-Host PC. 4-Digital oscilloscope.

are in same phase. Fig. 7(g) shows the power factor which is almost unity. Fig. 7(h) shows the grid imaginary power (reactive power) which is improve from the previous literature. Fig. 7(i) illustrates the grid real power tracking the grid reference power, and it is evident that the proposed SMC demonstrates superior performance in terms of reduced oscillations, faster response time, and lower disturbance levels.

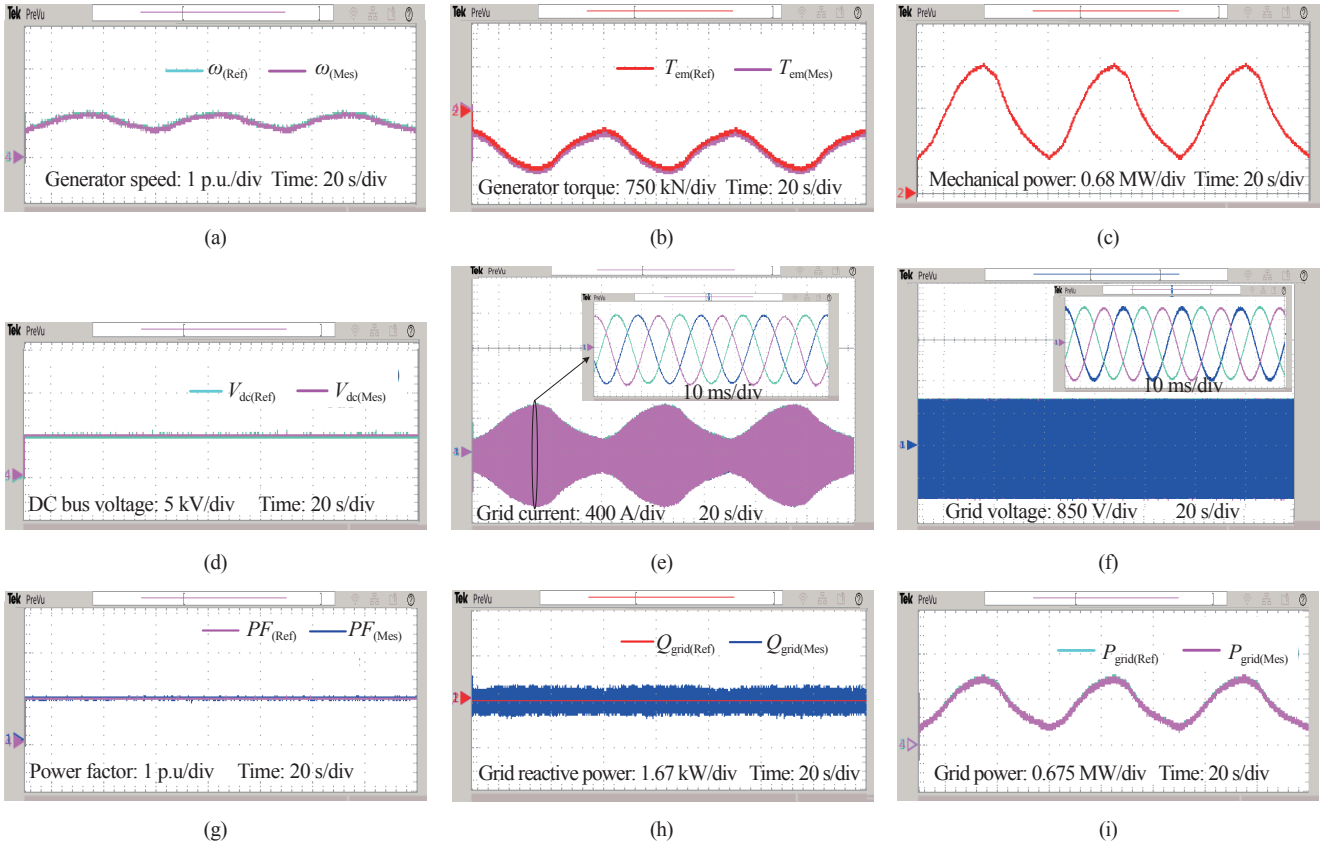


Fig. 9. HIL results of proposed MPPT algorithm with SMC scheme under variable wind velocity profile. (a) Rotor speed. (b) Electromagnetic torque. (c) DC bus voltage. (d) Grid current. (e) Grid voltage. (f) Power factor. (g) Grid imaginary power. (h) Grid real power.

B. HIL Validated Results

The HIL experiments were performed using the OP4520 FPGA-based OPAL-RT system. As depicted in Fig. 8, the real-time HIL setup consists of a host PC connected to the OP5033 XG real-time simulator via internet protocol, with processing handled by the FPGA-based OP4520. Data transfer between the RT lab and the real-time simulator is facilitated through a dedicated cable. At the same time, an oscilloscope is used to monitor signals from the analogue output of the FPGA processor. Fig. 9 shows that the HIL results closely agree with the simulation results, thereby validating and justifying the effectiveness of the proposed approach under real-time implementation. In Fig. 9(a), the rotor speed is represented with a scale of 1 p.u./div. Fig. 9(b) depicts the electromagnetic torque, with a scaling of -750 kN/div. Fig. 9(c) displays the turbine's mechanical power, with a scaling of 0.45 MW/div. Fig. 9(d) shows the DC bus voltage, which scale 5 kV/div and observed and compare with simulation results. it is more precise waveform that of Fig. 7(c). Injected grid current i_g and zoom current are illustrates in Fig. 9(e) with 400 A/div. It observed that injected current is precise and pure sinusoidal waveform and lower ripple. Fig. 9(f) shows the grid voltage and zoom v_g waveform with scaling of 850 V/div. It is also observed that in zoom v_g is precise and pure sinusoidal waveform and lower ripple. Fig. 9(g) shows the injected power factor to the grid with 1 p.u./div which almost unity. Fig. 9(h) shows the injected grid imaginary

power with 1.67 kW/div which is more precise results. Fig. 9(i) demonstrates that the grid powers with 675 kW/div which is accurately track their reference values and it is evident that the proposed SMC outperforms the CSMC in terms of reduced oscillations, faster response time, and lower disturbance rates.

The robustness of the proposed control strategy is validated through its performance under varying wind conditions and system disturbances. The simulation and HIL results demonstrate that the controller maintains stable DC-link voltage, accurate grid current tracking, and low THD under dynamic operating conditions. This behavior confirms the strong disturbance rejection capability of the proposed method. Furthermore, due to the inherent invariance property of SMC, the system remains insensitive to moderate parameter variations and external disturbances once the sliding condition is achieved. In particular, the proposed controller exhibits consistent performance under wind speed variations and disturbance scenarios, confirming its robustness in practical operating conditions.

C. Comparison With Existing Approaches

Table III compares the proposed SMC method with existing control techniques in terms of efficiency, THD, power factor, and robustness. The proposed approach achieves the highest efficiency (98.9%), the lowest THD (1.21%), and an improved power factor (0.996) compared to conventional and advanced methods reported in the literature. Moreover, it demonstrates

TABLE III
COMPARISON OF PROPOSED APPROACH WITH STATE OF ART IN PREVIOUS LITERATURE

Reference	Methods	Efficiency/%	THD/%	PF	Robustness
[29]	Classical PI	—	6.10	0.983	Moderately high
	RTO PI	—	3.21		
[13]	AFLC	93.10	—	—	Moderately high
	FLC	85.44	—		
[14]	SMC	91.14	—	—	High
[35]	Integral SMC	92.45	—	—	High
[25]	DTC system	90.95	—	0.983	Moderately high
	MPCS system	92.1	—		
[34]	ANN DPC	98.6	1.79	—	High
	C-DPC	—	2.95		
[15]	SMC	90	—	—	High
Proposed	PSMC	98.9	1.21	0.996	High

high robustness, indicating superior overall performance over state-of-the-art approaches.

In addition to conventional SMC, other control strategies such as classical PI control and higher-order sliding mode methods, including super-twisting sliding mode control (ST-SMC), have been widely reported in the literature. PI controllers are commonly used in industrial applications due to their simplicity, although their performance is sensitive to system parameter variations. On the other hand, ST-SMC provides improved chattering mitigation and robustness against disturbances. For example, the work in [50] demonstrates enhanced tracking performance and reduced torque ripple under uncertain conditions. However, these methods generally involve higher computational complexity and require careful parameter tuning, which may limit their real-time applicability. Compared to these approaches, the proposed method offers a simpler implementation while still achieving improved dynamic performance and power quality.

D. Harmonic Analysis

A harmonic analysis of the injected grid current was conducted, as depicted in Fig. 10, to evaluate the quality of the waveform supplied to the grid. The results in Fig. 10 demonstrate that the proposed SMC control effectively reduced the THD to 1.21%, a substantial improvement compared to the values outlined in Fig. 10.

V. CONCLUSION

This paper presents a novel smoothing continuous function-based SMC integrated with MPPT to address the chattering issues of traditional SMC. The proposed method significantly improves tracking performance by reducing chattering, enhancing the power factor, and minimizing harmonic distortion. The approach's effectiveness and robustness are validated through simulations and real-time HIL experiments under variable wind speed profiles. Stability analysis using the Lyapunov function confirms the system's stability. Comparative analysis, simulation, and HIL results show the superior performance of the proposed

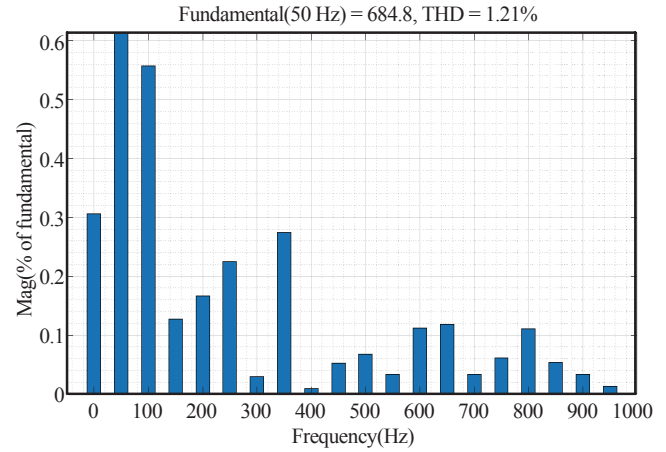


Fig. 10. THD value injected currents.

control strategy for a wind power system employing a PMSG with variable speeds. The method achieves a power factor of 0.997, an efficiency of 98.9%, and a THD of 1.21%, highlighting its high robustness and reliability.

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