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Sliding Mode Control for Hybrid PV/Wind System Integrated to Power Grids

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Grid, wind power generation, solar generation, Battery, Bidirectional converter, SMC Controller.

ABSTRACT

This paper presents an advanced control strategy for integration of hybrid solar PV and wind energy systems into power networks, utilizing a Sliding Mode Controller (SMC) to address power fluctuations and improve grid stability. Renewable energy sources inherently suffer from environmental uncertainties, leading to intermittent power output and challenges in maintaining power quality. The proposed SMC approach offers a robust and dynamic response to these uncertainties, ensuring effective regulation of power flow and voltage levels within the system. By minimizing Total Harmonic Distortion (THD) and suppressing voltage oscillations in the DC link, the controller enhances the smooth delivery of power to the grid. Real-time simulations are performed to assess the performance of the SMC in comparison with conventional control methods. Results demonstrate a significant improvement in system reliability, reduced harmonic content, and enhanced dynamic stability across various operating conditions. The study highlights the effectiveness of SMC in supporting the reliable incorporation of hybrid renewable systems into modern power grids while maintaining high power quality and operational efficiency.

1. INTRODUCTION

The rising energy demands, environmental challenges, and limited availability of fossil fuels have driven a global transition toward renewable energy sources (RES) [1]. Among them, solar photovoltaic (PV) and wind energy are consider a most promising due to their abundance, sustainability, and zero-emission nature. However, the intermittent and unpredictable behaviour of these sources, caused by fluctuating solar irradiance and wind speed, creates serious challenges when integrating them into conventional power networks. This intermittency leads to instability in voltage, frequency, and overall power quality. To overcome these limitations, hybrid RES particularly combinations of solar PV and wind are increasingly deployed [2] [3]. These systems take advantage of complementary nature of solar and wind energy [4]: solar is typically available during day, while wind can be more prevalent at night or during cloudy conditions. Despite their improved continuity, hybrid systems still suffer from fluctuating output, which can affect grid stability and the quality of delivered power. Addressing these challenges requires intelligent control strategies that can maintain voltage regulation and reduce THD, especially when environmental parameters change rapidly.

In conventional systems, Proportional-Integral (PI) controllers are widely used for managing power electronic converters due to their simplicity and ease of implementation [5]. However, PI controllers are linear in nature and often fail to deliver optimal performance under non-linear and time-varying conditions typical of renewable energy environments. Their inability to adapt to sudden changes in load or input conditions results in delayed response, voltage dips, and high harmonic distortion. These drawbacks highlight the limitations of PI control in maintaining the dynamic stability and power quality required by modern smart grids. To address these challenges, this work proposes an advanced nonlinear control strategy using SMC to enhance performance of PV/wind system [6]. SMC is a variable structure control technique known for its robustness, fast transient response, and insensitivity to parameter variations and external disturbances. Unlike PI controllers, SMC dynamically adjusts its control action to maintain system states on a predefined sliding surface, ensuring accurate tracking and stability even under varying operating conditions.

The novelty of this work lies in the design and simulation of a hybrid solar PV and wind energy system controlled using SMC [7], implemented and validated under varying irradiance and wind speed conditions. The system comprises solar PV, wind rectifier, BES, a DC-link interface, and a voltage source inverter. The inverter is regulated using the proposed SMC to ensure high-quality AC output to both the load and grid. Simulation outcomes validate the SMC outperforms the conventional PI controller by reducing THD, stabilizing the DC-link voltage, and ensuring reliable power delivery. The PV system was designed for a nominal output of 200 W, and similar ratings were applied to other components to ensure system synchronization.

The results confirm the controller's superior performance in handling environmental uncertainty and maintaining power quality. The Sliding Mode Control strategy offers a significant improvement over traditional PI controllers in managing hybrid PV/wind systems. By effectively minimizing harmonic content, suppressing voltage oscillations, and enhancing dynamic response, the proposed method ensures smoother grid integration and higher reliability. This work contributes a simulation-based validation of SMC as a viable and scalable control approach for hybrid RES aimed at mitigating uncertainty in modern power networks [8].

The organization of the paper is as follows: Section II outlines the problem statement, Section III details the system modeling, Section IV explains the proposed methodology, Section V highlights the simulation results, and Section VI concludes with key findings and remarks

2. PROBLEM STATEMENT

Despite the growing deployment of hybrid renewable energy systems (HRES), especially solar PV and wind combinations, their integration into power networks continues to suffer from power quality degradation due to the unpredictability of environmental conditions [9]. Existing control strategies such as PI controllers are inadequate in responding to rapid fluctuations in source inputs,

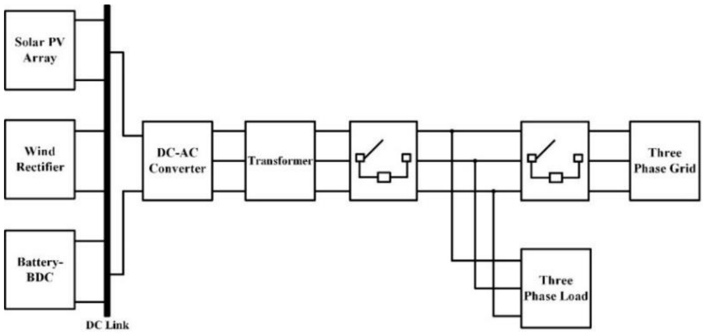


Figure.1 proposed block diagram of the system

leading to increased THD, voltage instability, and reduced grid reliability [10]. The core problem find in this study is lack of a robust and adaptive control mechanism that can dynamically stabilize the output of a hybrid PV/wind system under variable irradiance and wind speed, while maintaining low THD and consistent voltage at the grid interface. This work specifically investigates the implementation of a SMC as a solution to overcome these control challenges, with the aim of improving power quality and ensuring stable operation across different real-time operating scenarios.

3. SYSTEM MODELLING

The designed hybrid renewable system comprises three primary sources: a solar PV array, a wind energy unit connected through a rectifier, and a BESS. These sources are integrated through a shared DC link, which acts as the central node for balancing energy flow within the system, as illustrated in Fig. 1. This arrangement ensures a reliable and uninterrupted power supply to both utility grid and the connected load, even when environmental inputs like sunlight and wind vary significantly.

A. Solar PV Integration

The solar PV subsystem in the proposed hybrid configuration is responsible for converting solar irradiance into DC power. In the system's block diagram, the solar PV array is connected to the DC link via a unidirectional converter. The PV module is constructed by arranging several solar cells in both series and parallel combinations to deliver desired levels of voltage and current to the system. [11].

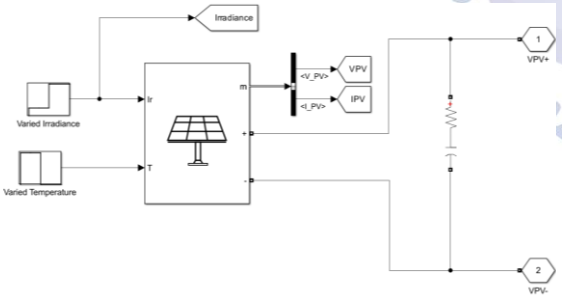


Figure.2 Solar block diagram

In this system, a rated power output of 200 W is assumed from the PV subsystem under standard test conditions, ensuring compatibility and synchronization with other subsystems [12]. To accurately model the solar output, the single-diode equivalent circuit is utilized, which captures nonlinear I-V characteristics of PV cell. The governing equations are:

Basic PV Output Current Equation:

$$I = I_{ph} - I_D - I_{SH} \ldots\ldots.. (1)$$

Expanded Current-Voltage Relationship:

$$I = I_{ph} - I_0\left(e^{\frac{V+IR_s}{mV_T}} - 1\right) - \frac{V+IR_s}{R_{SH}} \ldots\ldots (2)$$

Where:

I_{ph}: Photo generated current

I_0: Reverse saturation current

R_s: Series resistance

R_{SH}: Shunt resistance

V_T: Thermal voltage

m: Ideality factor

This formulation allows dynamic analysis of PV output under changing environmental conditions. In the simulation model, irradiance and temperature are set as time-varying inputs to reflect real-time behaviour. As observed in the results, the PV output current is more sensitive to irradiance changes, whereas the voltage shows stronger dependence on temperature fluctuations. The MATLAB/Simulink model of the PV system as displayed in the figure.2 incorporates a controlled current source and voltage-dependent output. This setup facilitates integration with the overall hybrid system and aids in the analysis of PV characteristics such as P-V and I-V curves under multiple scenarios. These characteristics are essential in tracking the Maximum Power Point (MPP) for optimal energy harvesting.

Furthermore, disturbances in PV output such as voltage dips or current spikes due to cloud cover or temperature variation were mitigated more effectively using the proposed controller compared to conventional PI-based methods. The smooth voltage and current responses establish the benefit of enhanced control strategy in maintaining power quality.

B. Wind Energy Integration

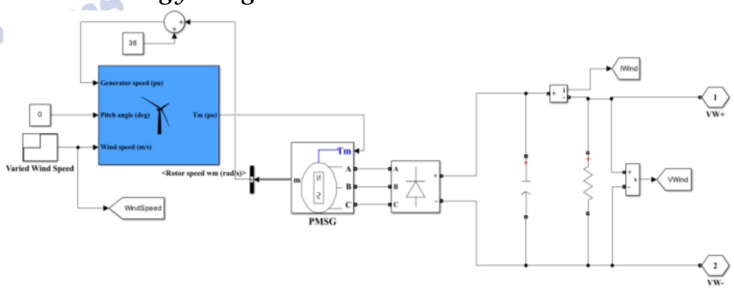


Figure.3 Wind system

The wind energy subsystem serves as an effective complement to solar power, particularly during periods of low sunlight or at night. In this hybrid configuration, the Wind Energy System includes a wind turbine, a Permanent Magnet Synchronous Generator (PMSG), and a three-phase uncontrolled rectifier, as illustrated in Fig. 3. The turbine converts wind's mechanical energy into AC electrical output through the PMSG, which is then rectified into DC and supplied to the shared DC-link to support system power flow.

The wind turbine in the system is designed for a rated output of 500 W. Simulations were conducted for varying wind speeds between 6 m/s and 14.4 m/s, with peak performance observed at 12 m/s when pitch angle (β) was set to 0°. The rotor consists of five blades, each measuring 60 cm in length, and delivers a nominal voltage of approximately 12 V. The turbine's output power is influenced by its aerodynamic characteristics, which depend on wind speed and rotor design:

$$P_{wind} = \frac{1}{2}\rho A C_p(\lambda,\beta)V^3 \text{........ (3)}$$

The tip speed ratio is defined as:

$$\lambda = \frac{\omega_r R}{V} \text{....... (4)}$$

Where:

ω_r: Rotor angular speed

R: Radius of turbine blades

In the simulation model, performance coefficient C_p is calculated to evaluate power conversion efficiency under dynamic wind speed conditions. A capacitor filter is used at the output of the rectifier to reduce voltage ripples and ensure stable DC output. The load connected across the rectifier consists of 10 resistors, enabling measurement of power transfer performance [15].

Simulation results show that the voltage of the wind system varies from 2.91 V to 3.26 V as wind speed changes. The corresponding output current ranges from 0.04180 A to 0.04196 A, while the output power stabilizes near the rated 500 W mark under optimal conditions. These results validate the turbine's efficiency and its compatibility with the proposed hybrid system's power demands.

The wind subsystem contributes to the total power balance within the hybrid setup, and its variable nature is effectively managed by the centralized Sliding Mode Controller. This ensures a stable DC-link voltage and consistent power output, even during sudden wind speed variations. The smooth incorporation of wind energy into hybrid system enhances reliability and reduces dependence on a single renewable source.

C. Battery Energy Storage System (BESS)

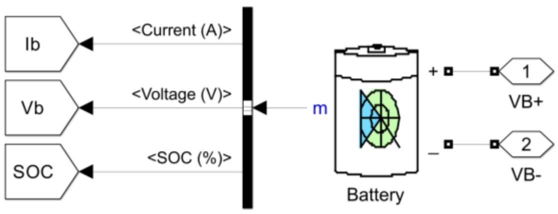


Figure.4 Simulation model of the battery

In the proposed hybrid renewable system, the BESS plays a vital role in maintaining energy stability. It helps manage the variability of solar and wind sources by storing excess energy when generation is high and supplying power during periods of low generation or unexpected increases in load. This ensures a steady and dependable supply of electricity to both the grid and connected loads, improving overall system reliability and performance. The simulation of the model is presented in the figure.4.

In this model, battery is connected to DC link via a Bidirectional DC-DC Converter (BDC) as presented in the fig.5. The converter ensures that the battery operates in both charging and discharging modes based on system requirements [17]. During high solar irradiance or strong wind conditions, excess energy charges the battery. When energy generation is insufficient, the stored energy discharges to maintain DC-link stability.

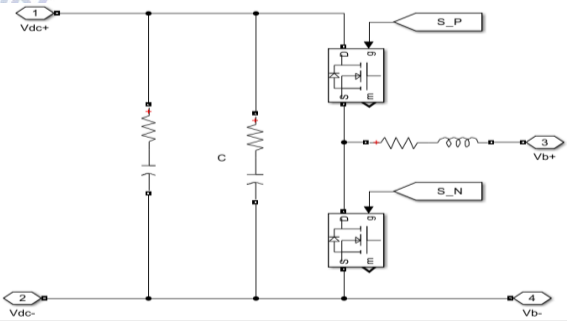


Figure.5 simulation model of the bidirectional converter

The battery also helps suppress DC voltage fluctuations, particularly during source transitions or sudden disturbances. This enhances the performance of the inverter and contributes to smoother AC output, thereby reducing voltage dips and harmonic content at the grid and load side.

The battery parameters used in simulation are chosen to match the scale of solar and wind subsystems, with nominal power rating and voltage range aligned with the 200 W PV and 500 W wind outputs. The State of Charge (SOC) of battery is continuously monitored, and charging/discharging control is implemented to avoid deep discharge and overcharging.

The power flow is governed by basic principles of energy conservation:

$$P_{bat} = V_{bat} \times I_{bat} \text{....... (5)}$$

Where:

P_{bat}: Battery power (positive when discharging, negative when charging)

V_{bat}: Battery voltage

I_{bat}: Battery current

Simulation results from the system confirm that the battery performs effectively under dynamic conditions. The SOC remains within safe limits, and battery current waveform demonstrates timely switching between charging and discharging. This behaviour ensures the DC-link voltage remains regulated and that the overall system stability is preserved.

By providing this energy balancing function, the BESS significantly enhances the robustness of the hybrid renewable energy system. When paired with the SMC, the battery's integration is even more impactful, ensuring that the system meets grid requirements even under environmental uncertainties.

D. Inverter and SMC Controller

The inverter stage in proposed hybrid system plays a crucial role in converting measured DC-link voltage into three-phase AC power suitable for both grid synchronization and load delivery. A VSC is employed for this purpose, interfaced between the DC-link and three-phase grid/load. The inverter is controlled using a SMC to ensure high power quality, minimal harmonic distortion, and enhanced stability under dynamic environmental conditions the SMC designing is presented in the fig.9. Conventional control strategies like the PI controller suffer from poor dynamic response, especially under fast-changing load or generation scenarios. Their linear behaviour is inadequate to handle the non-linear dynamics of power electronic systems integrated with renewable energy sources. To address this limitation, the SMC is adopted for its superior robustness, chattering mitigation, and adaptive control features.

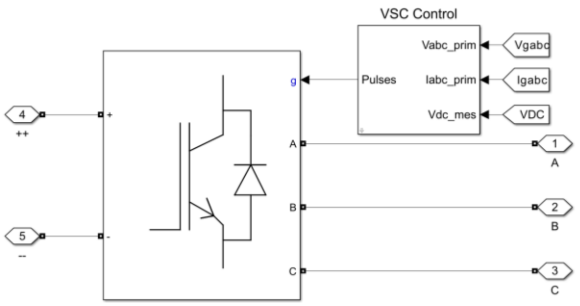


Figure.6 simulation model of three phase inverter with VSC control

The SMC is designed to force the inverter's output current to follow a reference trajectory defined by desired load/grid conditions. The key concept is to define a sliding surface, S (t), and apply control laws that maintain system dynamics on this surface:

$$S(t) = \frac{d}{dt}e(t) + \lambda e(t) \ldots\ldots.. (6)$$

$$u(t) = u_{eq} - K.sign\ (S(t)) \ldots\ldots.. (7)$$

Where:

$e(t)$: Error between reference and actual state

λ: Positive constant for convergence speed

u_{eq}: Equivalent control (nominal dynamics)

K: Gain to handle system uncertainties

This design ensures finite-time convergence to sliding surface, resulting in fast and accurate tracking. To further reduce high-frequency oscillations (chattering), boundary layer or saturation functions can be implemented instead of the sign function.

In the proposed system, the inverter is fed from the common DC-link, which receives power from PV, wind, and battery systems. The VSC-modulated inverter regulates voltage across the grid interface and load terminals, maintaining sinusoidal waveforms even during disturbances. The control objective is to suppress DC-link oscillations and maintain grid compliance by reducing THD. Simulation model of three phase inverter is shows in the fig.6 with the VSC control, the THD of grid voltage and current is significantly lower compared to PI-controlled system. The inverter output remains stable under variations in solar irradiance, wind speed, and load changes, validating the effectiveness of the proposed nonlinear control method.

E. Grid and Load Integration

The grid and load interface is a dynamic component of the HRES, allowing for dynamic interaction between distributed generation and utility grid [19]. In the proposed system, the inverter output is passed through a step-up transformer and connected to a three-phase grid and three-phase load through circuit breakers and switches for control and protection. This setup enables bi-directional energy exchange with the grid and supports local demand under varying supply conditions. The three-phase grid operates as a backup during low renewable

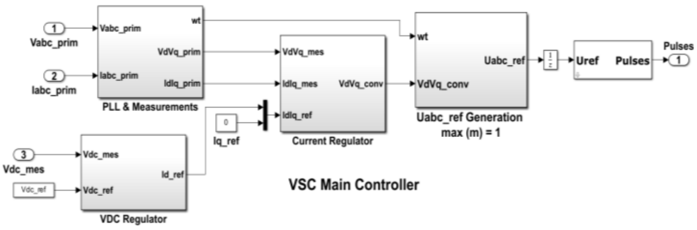


Figure.7 Voltage source controlling

generation periods and as a sink when excess power is available. The three-phase load receives energy directly from the inverter output, with priority given to fulfilling local load demands before exporting to the grid [20]. During simulation, both sources and loads are balanced dynamically, and switching mechanisms are used to route energy based on real-time conditions.

The simulation results indicate that under solar and wind fluctuations, the system maintains a stable sinusoidal voltage and current profile at the load terminals. This is a direct result of the SMC applied at the inverter stage, which ensures synchronization with grid frequency and limits the THD. The simulation shows grid voltage within 25 V, and grid current up to 3.5 A, with combined hybrid output power reaching 87.5 W.

The load side is designed to reflect typical residential or commercial three-phase demands, with voltage and current values measured for performance assessment. In the event of voltage dips or supply inconsistencies from PV/wind sources, the battery discharges to support the load, while the grid acts as a supplementary source. The parallel integration of PV and wind systems introduces a challenge due to their inherently different profiles. However, with proper control at the DC-link and inverter, smooth power delivery is maintained. The proposed configuration ensures grid compliance, improved power quality, and uninterrupted load operation, even during transients caused by environmental variations.

F. Controlling topologies

1. VSC Controller

The VSC Controller structure displayed in the figure.7 is responsible for generating precise gating pulses to control switching of the inverter in hybrid renewable energy system. Its primary function is to ensure that the AC output of the inverter remains synchronized with grid while maintaining the stability of the DC-link voltage and delivering high-quality power to both grid and load. The controller operates in synchronous *dq* reference frame and utilizes real-time measurements of voltages and currents to determine appropriate control actions.

The control process begins with the PLL & Measurements block, which receives the three-phase voltage (Vabc_prim) and current (Iabc_prim) signals from the inverter output. This block performs the Clarke and Park transformations to convert these time-domain signals into the rotating *dq* reference frame, producing V_d, V_q, I_d, and I_q components. It also includes a Phase-Locked Loop (PLL) that extracts the grid's phase angle ωt , ensuring that the controller remains synchronized with the grid voltage frequency.

The VDC Regulator block plays a critical role in maintaining the desired DC-link voltage. It compares the measured DC voltage (Vdc_mes) with a predefined reference value (Vdc_ref) and computes the error. This error is processed using a PI controller, which outputs a reference direct-axis current (Id_ref). This current reference signifies the amount of power that must be injected or absorbed by the inverter to stabilize the DC-link under varying power generation and load conditions.

Next, the Current Regulator block uses both the reference currents (Id_ref and a set Iq_ref, typically zero for unity power factor) and the actual *dq* currents to calculate the required voltages in the *dq* frame. These voltages are then transformed back to the three-phase *abc* reference frame (Uabc_ref) using inverse Park transformation. The resulting signal represents the desired output voltage waveform for the inverter, ensuring it aligns with the grid voltage in phase and magnitude.

Finally, this output voltage signal is normalized and sent to the PWM generator, which creates the corresponding gate pulses for the inverter switches. These pulses ensure accurate switching that enforces the desired voltage and current waveforms, achieving both grid synchronization and power quality compliance. The VSC Main Controller integrates voltage regulation, current control, reference frame transformations, and synchronization in a cohesive structure to ensure stable and efficient operation of the inverter. It effectively coordinates with the Sliding Mode Controller (SMC) for enhanced robustness and THD suppression across various operating conditions.

2. VDC Regulator Controlling

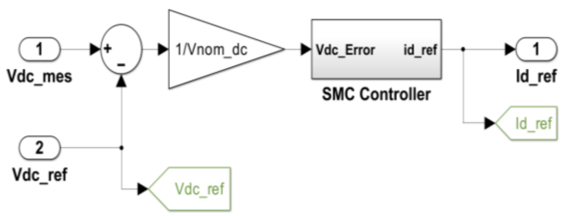


Figure.8 VDC regulator controlling

The VDC regulator controlling structure is displayed in the figure.8 is designed to maintain a stable DC-link voltage in the HRES. Variations in solar irradiance, wind speed, and load demand can cause the DC-link voltage (Vdc_mes) to fluctuate, which can affect the overall system stability and inverter performance. The regulator's goal is to continuously compare actual DC-link voltage with a predefined reference (Vdc_ref) and generate a corresponding current reference (Id_ref) to balance power flow.

The control begins with a subtraction block that calculates the voltage error by subtracting measured DC voltage (Vdc_mes) from the reference value (Vdc_ref). This error represents the deviation of the system from its intended operating point. The error signal is then passed through a normalization gain block, typically set to the inverse of the nominal DC voltage (1/Vnom_dc), to scale the error within a manageable range suitable for control processing.

The normalized error signal, now representing the Vdc_Error, is fed into the Sliding Mode Controller (SMC). The SMC block processes this error and generates the required direct-axis current reference (Id_ref) needed to either absorb or inject power through the inverter to regulate DC-link voltage. This reference is then passed to current controller of the inverter stage, where it influences PWM pulse generation for switching control.

Through this closed-loop configuration, the VDC regulator dynamically adjusts power flow based on real-time conditions, ensuring that the system maintains a constant and reliable DC-link voltage. The use of SMC in this control loop enhances robustness against environmental disturbances and improves the system's response speed compared to conventional PI regulators.

3. SMC Controller Controlling

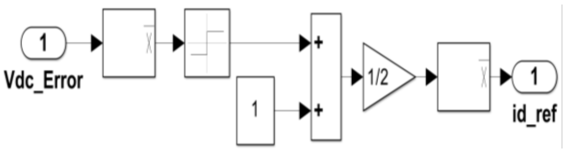


Figure.9 SMC controller controlling

The SMC control structure shown in the fig.9 is responsible for generating direct-axis current reference (id_ref) based on DC-link voltage error (Vdc_Error). This controller is part of a robust nonlinear control framework designed to respond effectively to rapid fluctuations and uncertainties common in HRES.

The control begins by taking the Vdc_Error the difference between the actual and reference DC-link voltages as input. The first block applies the sign function (represented as sign(x)), which extracts the sign (positive or negative) of the error. This step is essential in sliding mode control to determine the direction of corrective action.

The output of the sign function is then passed through a scaling stage, where it is added to a constant value (typically 1) and passed through a summing block. This creates a composite control signal that blends the system's discontinuous corrective effort with a fixed component to help improve convergence and reduce chattering. The result is then scaled down by a gain of 1/2, acting as a boundary layer control that smoothens the transition near the sliding surface, again helping to suppress high-frequency switching.

After this, the output passes through a saturation or limiting block, which ensures that the resulting id_ref remains within a safe operating range and prevents excessive current commands that could destabilize the system or damage the hardware. Finally, the id_ref is fed to the current control loop of the inverter, where it directly affects the PWM pattern and hence the inverter's output behaviour. This SMC control strategy ensures that DC-link voltage is tightly regulated by producing a robust and adaptive current reference. It offers significant advantages over linear controllers, particularly in terms of disturbance rejection, fast dynamic response, and reduced THD. This implementation allows the inverter to respond quickly to changing load or generation conditions while preserving system stability and power quality.

4. PROPOSED METHOD

The key contribution of this work lies in the integration of a SMC into the hybrid solar PV and wind energy system to enhance control robustness, power quality, and dynamic performance. The SMC is introduced at the inverter stage as a replacement for conventional controllers, specifically targeting the issues of instability, poor disturbance handling, and delayed system response during sudden environmental changes. In this proposed method, the SMC governs the operation of the voltage source inverter by generating reference control signals that respond rapidly to fluctuations in power generation and load demand. Unlike traditional linear controllers, the SMC operates based on system state feedback and applies switching logic to correct deviations in real time. This enables the controller to maintain smooth voltage profiles and balanced current waveforms even under challenging operating conditions, such as rapidly changing irradiance or wind speed.

One of the standout features of the SMC is its ability to offer consistent performance without requiring fine-tuned gains or extensive manual retuning. This makes it highly suitable for renewable energy applications where source conditions are continuously changing. The controller adapts dynamically to mismatches and uncertainties, ensuring uninterrupted power flow and voltage support to both the load and the grid. Its design inherently suppresses disturbances, making the system more resilient to environmental noise and unpredictable generation spikes.

The inclusion of SMC significantly improved the inverter's ability to maintain synchronization with the grid while delivering high-quality, low-distortion output. The controller demonstrated excellent tracking of current and voltage references with minimal error, thereby enhancing overall power quality. It also enabled system to recover more quickly from sudden dips or surges in source power, which is critical in maintaining stable operation in hybrid configurations. Furthermore, the SMC minimized switching losses by reducing unnecessary fluctuations in the pulse generation process, leading to improved inverter efficiency. Its structure ensured that system states were driven steadily toward desired operating conditions without oscillations or overcorrections. Overall, the proposed implementation of the Sliding Mode Controller in this hybrid system proved to be a reliable and intelligent solution for handling the nonlinearity, variability, and uncertainty typical of renewable energy environments.

5. SIMULATION RESULTS AND DISCUSSION

This simulation results of the proposed HRES that integrates solar PV and wind sources, controlled by a SMC. The simulations were carried out using MATLAB/Simulink under dynamically changing environmental conditions, such as varying solar irradiance and wind speed. The system's performance is analysed in terms of voltage, current, and power behaviour for each subsystem, as well as overall power quality, with a special focus on THD. The figures referenced in this section correspond to labelled simulation outputs provided in the results documentation.

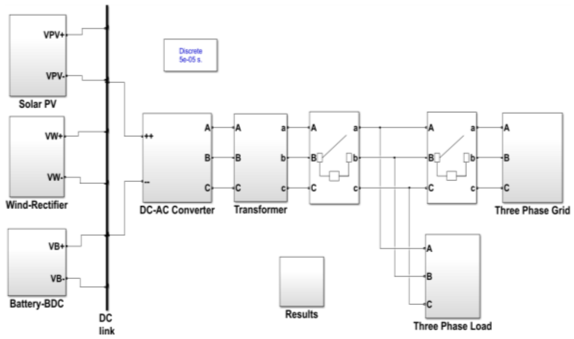
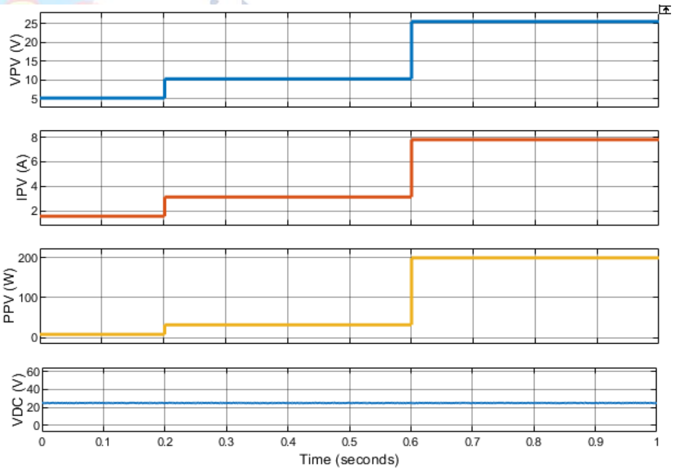


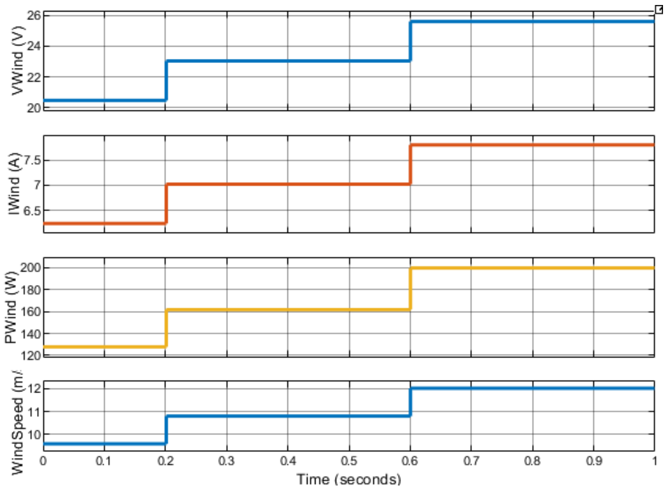
Figure.10 Simulink Model of Hybrid System

Figure 10 illustrates the complete Simulink model of proposed hybrid system. It includes all major subsystems: the solar PV array, wind energy conversion system with a rectifier, battery connected through a bidirectional DC-DC converter, a common DC link, and a VSC. The inverter is connected to both a three-phase load and the utility grid. The control units, including the VDC regulator and the Sliding Mode Controller, are embedded within this model to ensure voltage regulation, synchronization, and high power quality at the output.



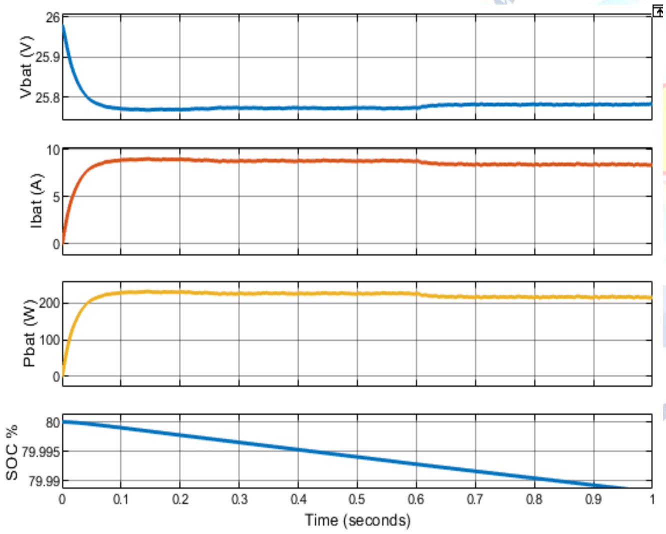
a) Solar PV Voltage, Current, Power

In Figure 11(a), the voltage, current, and power waveforms of solar PV system are depicted. The PV output remains stable despite variations in irradiance, confirming the model's robustness. A smooth voltage and current profile is observed, and the power reaches close to the 200 W mark under optimal conditions. This validates the effectiveness of MPPT and the controller's role in maintaining operational consistency.



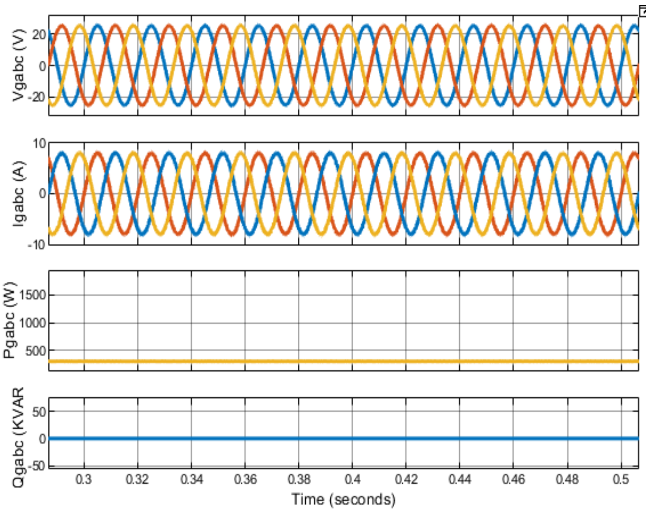
b) Wind Voltage, Current, Power, Wind Speed

Figure 11(b) illustrates the performance of wind energy system, showing wind speed, rectified voltage, current, and generated power. The results demonstrate a clear correlation between wind speed and power output, with consistent voltage and current observed at higher wind speeds. The rectifier output remained ripple-free, supporting clean DC integration into the hybrid DC-link.



c) Battery Voltage, Current, Power, SOC

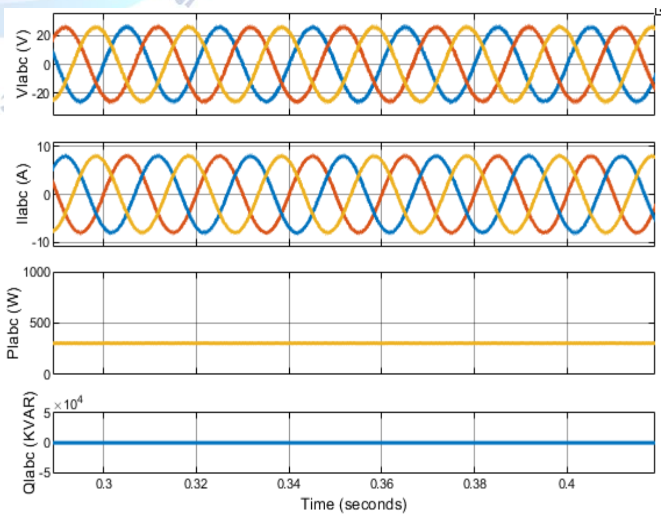
The behaviour of the battery system is presented in Figure 11(c), showing battery voltage, current, power, and SOC. The battery responds effectively to charging and discharging commands from the bidirectional converter based on system needs. The SOC is well maintained within safe limits, and the transitions between charging and discharging are smooth, confirming precise VDC regulation.



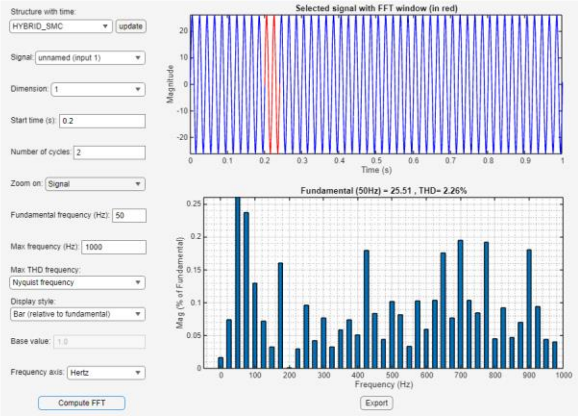
d) Grid Voltage, Current, Active and Reactive Power

Figure 11(d) shows the grid voltage and current waveforms, along with active and reactive power values. The system delivers well-balanced power to the grid, and the SMC ensures stable voltage synchronization. Active power flow is smooth, and reactive power remains near zero, indicating near-unity power factor operation.

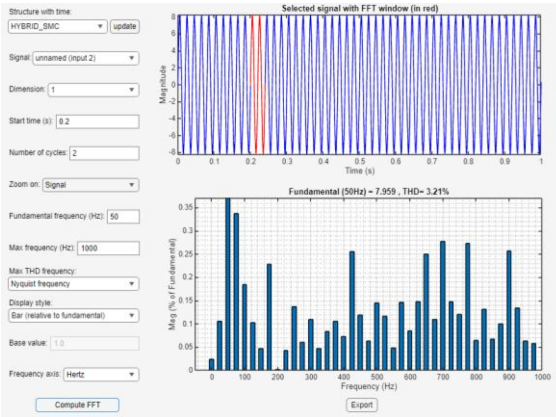
The load side voltage, current, and power are presented in Figure 11(e). Similar to the grid side, voltage and current remain sinusoidal with minimal distortion. Both active and reactive power profiles demonstrate the system's capability to serve dynamic load demand without degradation in power quality.



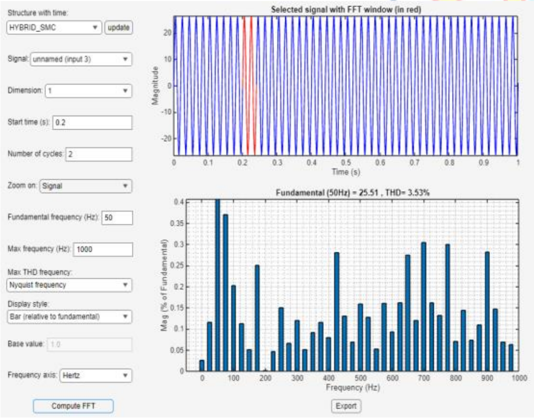
e) Load Voltage, Current, Active and Reactive Power.



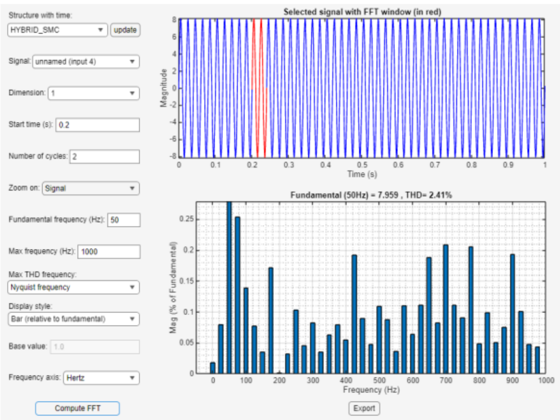
f) THD of Grid Voltage



g) THD of Grid Current



h) THD of Load Voltage



i) THD of Load Current

Figures 11(f) through 11(i) provide THD analysis of the grid and load voltages and currents. The THD of grid voltage (f) and grid current (g) are both significantly reduced, remaining well within IEEE 519 standards. Similarly, load voltage (h) and load current (i) show low distortion, confirming the effectiveness of the SMC in suppressing harmonics across all output terminals.

Figure: 11 Simulation Results obtained in Hybrid System

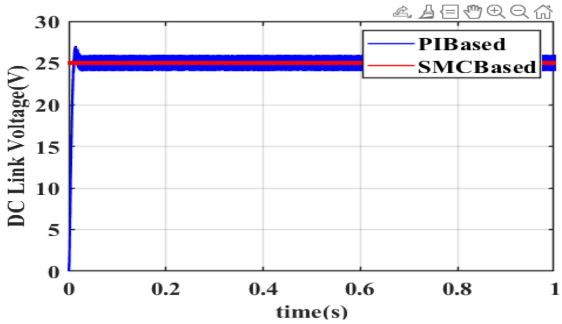


Fig.12 DC Link Voltage Comparison Waveform

Finally, Figure 12 compares the DC-link voltage performance with SMC and PI controllers. The waveform clearly shows that the SMC regulates voltage more effectively than conventional methods. Voltage oscillations are significantly suppressed, and the system stabilizes faster, especially during source/load transitions.

These results collectively validate the proposed SMC-based control strategy. The system delivers high-quality power with low THD, ensures dynamic voltage regulation, and provides smooth integration of intermittent renewable sources, even under changing environmental conditions. The coordinated control of the battery and converter further enhances system resilience and uninterrupted operation.

6. CONCLUSION

This paper presented a hybrid solar PV and wind energy system integrated with a battery storage unit and controlled using a SMC. The proposed control strategy was designed to address the limitations of traditional PI controllers in handling nonlinearity, environmental uncertainties, and fast-changing load conditions. The use of SMC at the inverter stage enabled robust tracking of current and voltage references, minimized THD, and improved system stability during source and load fluctuations. Simulation results demonstrated the successful regulation of DC-link voltage, effective synchronization with grid, and consistent power delivery to the load under dynamic irradiance and wind speed conditions. The system maintained high-quality sinusoidal output voltages and currents, even under disturbances. The coordinated operation of the VDC regulator, bidirectional converter, and battery ensured reliable energy balancing, further enhancing the system's resilience. Overall, the proposed SMC-based control strategy proved to be highly effective for grid-connected HRES, improving dynamic response, reducing THD, and providing superior power quality compared to conventional approaches.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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