Battery Energy Management System of a Hybrid Standalone PV-Wind-Battery Based Microgrid Utilizing Super-Twisting Sliding Mode Controllers

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ABSTRACT

The global community investigates strategies to harness renewable energy sources, aiming to address climate change and reduce reliance on non-renewable resources. Solar and wind power have gained widespread popularity. Nevertheless, the fluctuation and absence of regulation over wind speeds and solar radiation pose challenges. Therefore, the incorporation of an energy storage system is essential for maximizing the utilization of these energy sources by converting them into electrical power. Batteries are commonly utilized in medium power applications; therefore, a bidirectional DC to DC circuit is implemented to maintain a consistent voltage at the DC-link, regardless of varying operational conditions, by managing the charging and discharging processes of the battery in accordance with generation and load requirements. A novel control algorithm was created to ensure power quality at the 3-phase AC load bus and manage energy in the hybrid standalone system. The proposed control technique employs super twisting sliding mode controllers to improve system efficiency when compared to conventional controllers. The results of this study, conducted using Hardware-in-the-Loop (HIL) technology and two OPAL-RT modules, have been presented to assess performance in different scenarios.

Keywords-microgrid; PVS; standalone system; wind power generation; battery; super twisting sliding mode control

I. INTRODUCTION

Developing small-scale localized microgrids represents an effective strategy for delivering electricity to consumers in areas lacking access to utility grids. The Microgrids, which are fueled by sustainable energy sources, provide an eco-conscious answer to the current dilemma. By integrating various renewable energy sources, such as solar power utilizing the Photovoltaic (PV) technology and wind power utilizing the Permanent Magnet Synchronous Generator (PMSG) technology, these systems can reliably supply high-quality electricity to people residing in remote areas.

The power production is affected by changes in solar irradiance and wind velocity, leading to fluctuations in generation. Utilizing an energy storage device is essential for maintaining a stable power balance in a Hybrid Standalone Microgrid System (HSMS). Although batteries are commonly used for energy storage, they may not be suitable for prolonged high-power applications.

A Battery Unit System (BUS) is incorporated into the model through the utilization of a bidirectional DC-DC converter [1]. The BUS can quickly adapt to sudden changes while maintaining power equilibrium in stable conditions at a slower pace. During times of surplus generation and insufficient storage in Battery Energy Storage Units (BESU) relative to demand, load-shedding and deloading operations are implemented [2-4]. Utilizing BUS for short-term power provision and hydrogen for long-term storage improves the financial sustainability of the system. However, efficient energy management is crucial for sustaining the power quality in independent systems. Additionally, this report outlines the execution of an inverter control system designed to maintain consistent voltages at the load terminal, even when faced with unbalanced voltages, ultimately enhancing power reliability.

II. STANDALONE MICROGRID

The HSMS depicted in Figure 1 is derived from renewable energy sources. The HSMS, which exhibits comparable independent features, was examined in [5-16]. A power management approach was proposed to oversee the various components within the Microgrid [5, 17, 18]. The production of hydrogen through power conversion units utilizing renewable energy sources was demonstrated in [6]. A greenhouse utilizing renewable energy sources was established in [7]; however, the model was specifically tailored for single-phase applications. Authors in [8] showcased the generation of hydrogen through renewable energy sources; nevertheless, they failed to address issues related to power quality. Authors in [9, 19, 20] presented a DC Microgrid that utilized renewable energy sources to produce hydrogen. Furthermore, in [10], a microgrid energy management algorithm was created; however, it did not consider power quality concerns or scenarios involving imbalance. A comparative assessment was carried out on various energy management systems. This research paper discusses the objectives outlined during its creation, with specific emphasis placed on systems for standalone wind, PV, and wind conversion units.

1. A robust control coordination system has been established for the wind power conversion unit, the Photovoltaic System (PVS), and the Battery Storage System (BSS).
2. A novel control method has been developed for a bidirectional DC–DC converter, employed between the BSS and the DC-link, to efficiently manage the power distribution among various devices.
3. Efficient regulators have been implemented to oversee the voltage at the load terminal when there are fluctuations in wind or solar power generation and changes in the load.
4. Maintaining balanced voltages is crucial to ensure stable voltage levels at the bus load, especially when managing unbalanced currents within a three-phase system.
5. STSMCs are being designed to improve system performance when sudden changes occur in the HSMS as part of the proposed control method.

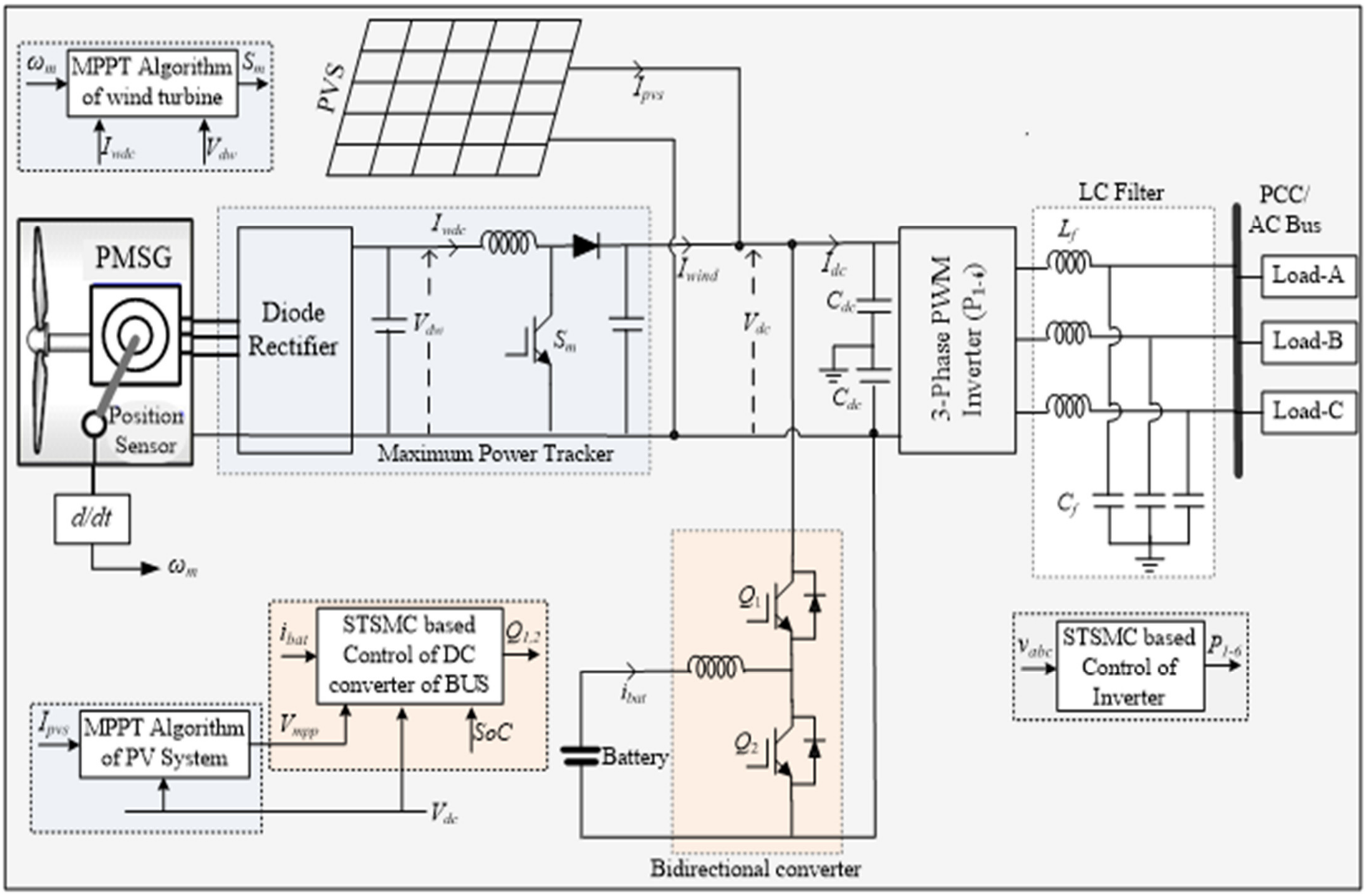


Fig. 1. Configuration of HSMS with battery, PVS, and wind power conversation unit.

III. DESIGN OF STSMCS

Super-twisting sliding mode controllers are a type of control system designed to handle uncertainties and disturbances in a more robust manner than traditional PID controllers. These controllers use a Sliding Mode Control (SMC) strategy that enables them to quickly adapt to system changes and maintain stability [21]. One of the key advantages of super-twisting sliding mode controllers is their ability to achieve a higher level of output accuracy in the face of unforeseen variations [22]. This is because they can rapidly adjust their control inputs in response to changes in the system, ensuring that the desired output is achieved even in the presence of disturbances.

In contrast, conventional PID controllers may struggle to maintain accuracy when confronted with unexpected variations in the system. This limitation arises because PID controllers rely on a fixed set of parameters that may not adequately account for dynamic changes. Hence, super-twisting sliding mode controllers [23] offer a more robust and accurate control solution for systems subject to uncertainties and disturbances. By swiftly adapting to system variations, these controllers can enhance the overall performance and stability of a wide range of control systems. A basic model of the STSMC block is shown in Figure 2.

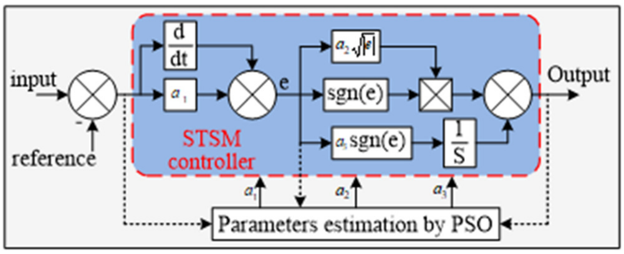


Fig. 2. A model of the STSMC.

IV. PROPOSED CONTROL METHODOLOGY

The DC-link of the BSS includes a built-in bidirectional DC–DC circuit. This circuit employs a control technique to manage the charging and discharging of the BSS while maintaining a stable DC-side voltage, as depicted in Figure 3. The proposed control output acts as the reference BSS line current, resulting in the creation of a hysteresis loop that generates the required PWM signals for switches Q1 and Q2 in the converter, as displayed in Figure 1. The bidirectional circuit controller incorporates the State of Charge (SoC) to prevent both the overcharging and over-discharging of the BESS. Once the BESS SoC reaches its maximum, any excess power is minimized by implementing deloading from the MPPTs of the PVS and wind system. Similarly, in steady-state conditions, when the SoC drops to its minimum, load shedding is applied. Establishing efficient control coordination among all elements within an independent model is essential to ensure consistent DC-side voltage despite fluctuations. Figure 3 illustrates the appropriate control mechanisms for the buck circuit. The DC–DC converter controllers are configured to enable the BESS to promptly respond to sudden load changes. When the SoC falls to 0.2% and Q2 of the DC–DC circuit is engaged (with Q1 turned off), the fuel cell stacks begin generating the required load power, while the battery backup system preserves its state throughout the DC-link. The system's energy management is depicted in Figure 4.

The optimization of power extraction from the turbine relies on [24]. The PVS is directly connected to the DC-bus, eliminating the need for an additional device to operate as an MPPT circuit. Instead, the PVS employs an MPPT mechanism in combination with a DC–DC circuit, which serves as the MPPT circuit for the PVS.

Imbalanced current flows through the three phases due to the operation of several single-phase loads in the power distribution system. During the operation of unbalanced loads, the DC-link voltage exhibits a second-harmonic oscillating component. The presence of this harmonic can induce oscillations in the turbine shaft, which may reduce its lifespan due to fatigue. To mitigate the effects of the second harmonic, the active filter on the DC side [12] is integrated with the control mechanisms of the BESS DC–DC converter. The direct current (DC) component, denoted as ($V_{dc}^{'}$), is separated from V_{dc} with a low-pass filter, while the alternating component ($V_{dco}^{'}$), is obtained from $V_{dc}^{'}$ and V_{dc} .The primary STSMC employs ($V_{dc}^{*}-V_{dc}^{'}$) as the error input to generate a reference signal for voltage regulation, while the secondary STSMC uses ($0-V_{dco}$) as its error input. The second STSMC utilizes a reference signal of zero to effectively eliminate the oscillating component in the DC voltage. By combining the outputs of both STSMCs, the final reference current is achieved.

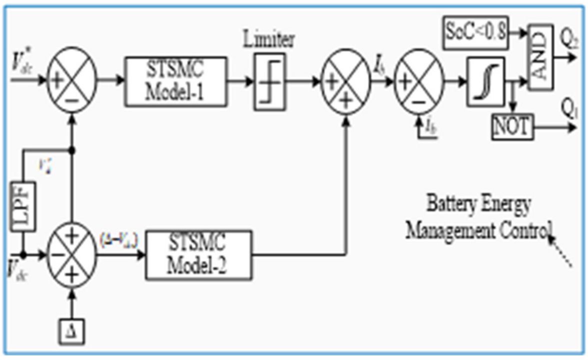


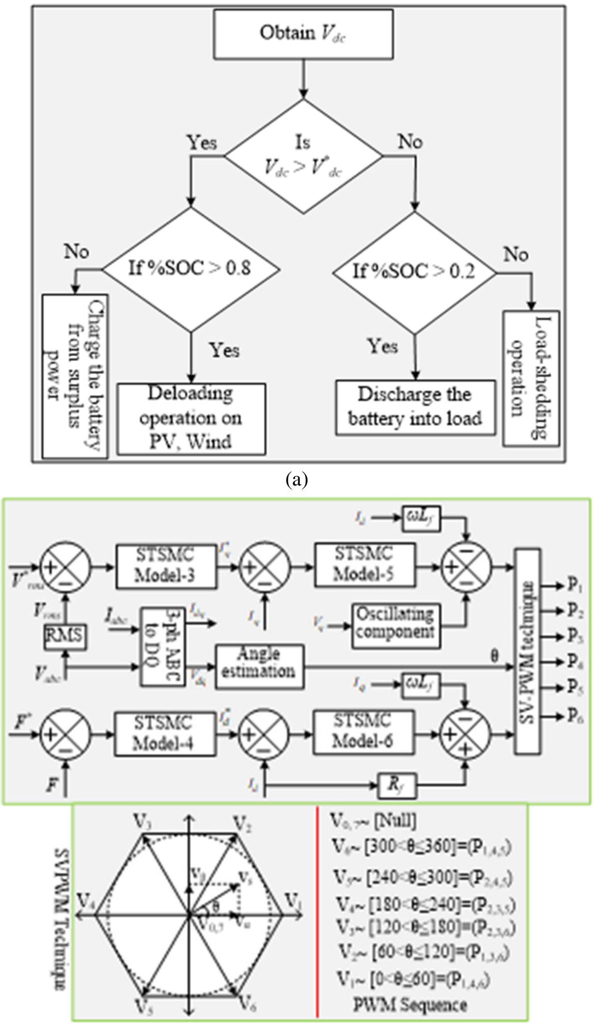
Fig. 3. Proposed BESU of the microgrid.

In a Hybrid Smart Microgrid System (HSMS), the conversion of DC power from renewable energy sources or storage systems into AC power suitable for distribution and consumption is a critical function, typically performed by Voltage Source Inverters (VSIs). A suitable and robust control system is essential for managing this DC–AC conversion process effectively, particularly under dynamic load and generation conditions [15, 16].

One of the major challenges during inverter operation is maintaining balanced three-phase voltages at the Point of Common Coupling (PCC), especially when the system is exposed to uneven or unbalanced load distributions. Imbalanced load conditions can cause asymmetrical voltage drops across the output filters of each inverter phase. Although these filters are designed to suppress high-frequency harmonics and smooth the inverter output, their impedance characteristics may vary across phases depending on loading and component tolerances. As a result, the inverter output voltages may become unequal, leading to poor power quality, equipment overheating, and inefficiencies in downstream devices. To address this issue, a distinctive control strategy has been developed, aimed at generating individualized modulation indexes for each inverter phase. This approach allows for adaptive compensation of the voltage imbalances by tailoring the modulation depth in each phase according to real-time operating conditions. The use of decoupled modulation indexes is a novel feature of the proposed control architecture, enabling the system to dynamically respond to load asymmetries while maintaining voltage symmetry at the PCC. The implementation of this control methodology is based on a synchronous reference frame transformation, also known as the dq0 transformation, which simplifies the analysis and control of AC variables by converting them from the three-phase stationary frame to a two-axis rotating frame. As shown in Figure 6, the inverter control loop leverages the dq0 model to regulate the system's dynamic behavior. In this transformed frame, the AC quantities become DC-like, allowing for easier manipulation and control through feedback mechanisms.

Once the DC-link voltage, which serves as the primary energy reservoir for the inverter is regulated to its reference value, the inverter's output voltage can be accurately determined using a Pulse Width Modulation (PWM) index. This modulation index determines the duty cycle of the switching signals applied to the inverter power electronics, thereby controlling the amplitude of the synthesized AC output. The overarching control structure that governs these operations is illustrated in Figure 5, where the implementation of Super-Twisting Sliding Mode Control (STSMC) is depicted. STSMC is chosen for its finite-time convergence properties, robustness to parameter uncertainties, and ability to maintain stability under high system nonlinearity, which are characteristic challenges in renewable-rich hybrid systems.

One of the core responsibilities of the inverter control system within an HSMS is to maintain frequency stability in the AC output. In isolated or weakly interconnected microgrids, frequency deviations can occur due to instantaneous mismatches between active power generation and consumption. When active power supplied exceeds or falls short of the load demand, the system's frequency may rise or drop, respectively. To mitigate these fluctuations, the STSMC framework processes the frequency error signal, which is the difference between the measured frequency and its reference (typically 50 or 60 Hz), and utilizes this to generate the reference component of the direct-axis (d-axis) current. This current component is then used to actively regulate active power flow, thereby stabilizing the system frequency. In parallel, voltage magnitude regulation is achieved by controlling the reactive power component, which is derived from the quadrature-axis (q-axis) current. Here, the RMS voltage of the output is compared against a defined reference value, and the resultant voltage error is used to calculate the reactive current reference. Both the active and reactive current references are combined to form a complete control signal for the inverter. To implement these control commands into the inverter hardware, a Space Vector Pulse Width Modulation (SVPWM) technique is employed. SVPWM provides superior DC bus utilization, lower harmonic distortion, and improved dynamic performance compared to traditional sinusoidal PWM methods. The SVPWM algorithm determines the optimal switching sequence and duration for the inverter switches based on the modulation index and vector location within the Clarke plane. The integration of SVPWM with the STSMC-based current control ensures that switching actions are both responsive and efficient. As portrayed in Figure 5, the coordinated execution of these control steps ensures that the inverter can simultaneously manage voltage balancing, frequency regulation, and power quality optimization. This is critical in HSMS applications, where system flexibility, resilience, and energy quality are paramount. Overall, the proposed inverter control framework provides a scalable and adaptable solution for reliable AC power delivery in modern hybrid microgrids.



(a)

(b)

Fig. 4. (a) Proposed BESU algorithm, (b) proposed control of the inverter.

V. RESULTS

Achieving performance levels comparable to real time is possible using Real-Time Simulator (RTS) modules with sufficient capacity to solve intricate power system equations, thereby mimicking the behavior of a physical network. Two RTS units have been developed by OPAL-RT Technologies for conducting HIL testing. The configuration, as shown in Figure 1, is divided into two primary parts: the plant, which includes all components, and the control unit, which houses all controllers. The plant model is in Module-1, while the control unit is situated in Module-2.

Each unit is equipped with both digital and analog cables to facilitate loop formation. The plant sends an analog signal to the control system, while the control system returns a digital signal to the plant. A comprehensive analysis is carried out on a dedicated computer to obtain detailed results. The HIL lab setup configuration, along with the corresponding connection cards, is demonstrated in Figure 6. Furthermore, a comprehensive block diagram depicting the HIL process of the proposed system, with color highlighting, is provided in Figure 7.

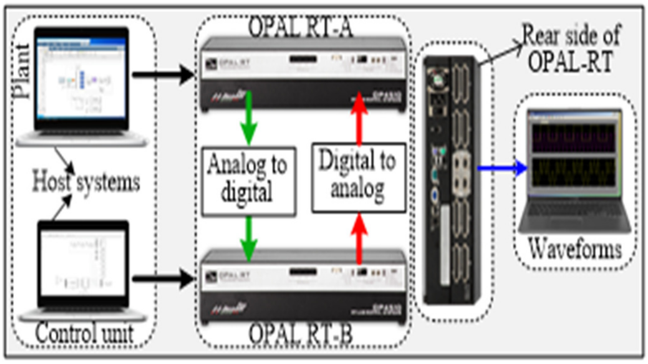


Fig. 5. HIL setup.

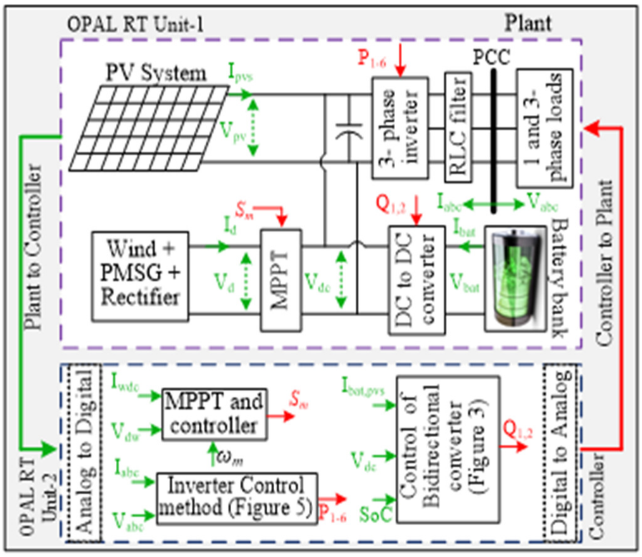


Fig. 6. HIL configuration of Figure 1.

A. *Case 1: Operation Under Power Variations*

In the presented hybrid renewable energy system, the cumulative power generated by multiple distributed sources is aggregated to simplify the analysis and enhance control implementation. Specifically, the power contributions from all PV arrays are summed to represent a single equivalent PV system. Similarly, the total power generated by the wind power conversion systems is aggregated and treated as the output of a unified wind power source. This method allows for a streamlined assessment of overall system dynamics, facilitating the evaluation of control strategies and energy balance mechanisms within the network.

Figure 8(a) illustrates the temporal variations in the power output from the PV and wind systems, along with the corresponding power demand at the AC bus. Due to their reliance on weather-dependent variables, i.e. solar irradiance and wind velocity, both PV and wind systems exhibit stochastic generation characteristics. Consequently, the power produced by these renewable sources is inherently variable, leading to frequent mismatches between supply and load demand. Figure 8(a) provides insights into these mismatches, highlighting the dynamic nature of both generation and consumption profiles. These fluctuations necessitate the inclusion of a compensating mechanism to ensure a balance between generation and load requirements.

To maintain this balance, a Battery Energy Storage Unit (BESU) is integrated into the system. The BESU acts as a power compensator that absorbs excess energy during periods of surplus generation and supplies power during deficits. The bidirectional nature of the BESU enables it to serve as a dynamic buffer, stabilizing the net power flow at the AC bus. In the adopted power flow convention, the negative values indicate battery charging, wherein surplus power is stored, and the positive values indicate discharging, when the BESU supplies energy to meet the load demands. This convention aids in interpreting the BESU's operational state and energy contribution at any given time.

Beyond compensating for power mismatches, the BESU plays a vital role in regulating the DC-link voltage. This voltage, present across the DC terminals interfacing various power electronic components (e.g., DC–DC converters and voltage source inverters), is critical for the system's operational integrity. Figure 8(b) presents the voltage profile of the DC-link under different load and generation conditions. The reference voltage for the DC-link is maintained at 710 V, and the observed variations in Figure 8(b) remain minimal despite the transient changes in power. These small deviations indicate the effective operation of the BESU in voltage stabilization, a crucial function in hybrid AC/DC microgrid configurations.

In addition to voltage regulation at the DC side, AC-side voltage stability is also essential for ensuring reliable power delivery to end users. Figure 8(c) displays the RMS voltages of the three-phase AC system under varying load and generation scenarios. These values reflect the system's ability to maintain balanced and regulated voltages across all three phases, even under conditions of fluctuating renewable input and load variation. The voltages remain well within acceptable operational limits, demonstrating that the combined control mechanisms ensure consistent power quality across the distribution network.

To achieve such robust control, the system employs a SMC strategy, with a focus on the STSMC variant. In renewable energy systems, where input variability is high, STSMC offers a reliable approach to maintaining desired performance metrics. The control strategy is designed to operate in real time, dynamically adjusting the BESU's operation to stabilize voltages and currents across the network. The effectiveness of the STSMC method is demonstrated by smooth and symmetrical three-phase load currents in Figure 9, confirming stable current quality and phase synchronization under fluctuating conditions. Together with the coordinated operation of renewable sources and the stabilizing role of the BESU, STSMC ensures efficient energy utilization, minimal voltage deviations, and reliable load compensation, which is essential for modern microgrid applications.

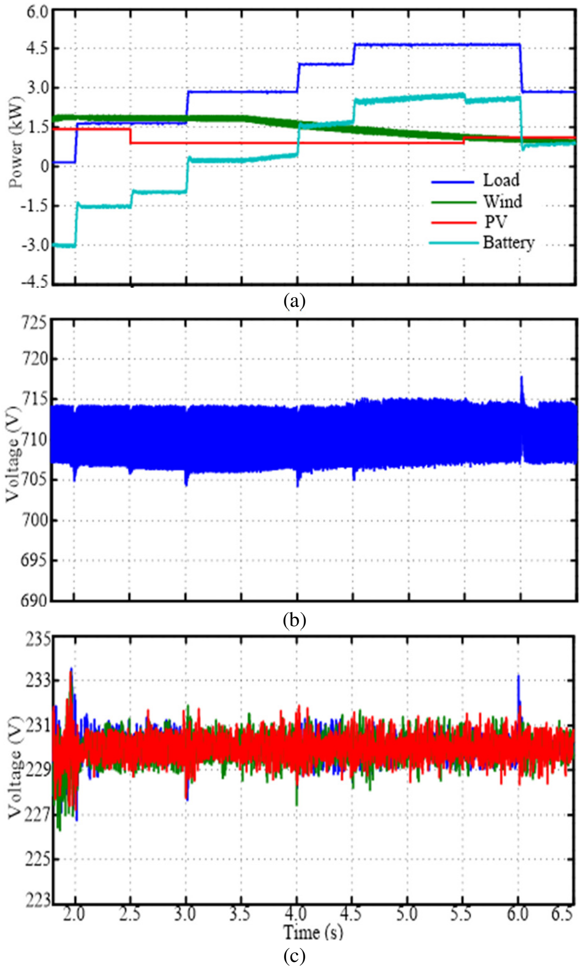


Fig. 7. (a) Output power, (b) DC-link voltage profile, (c) RMS voltage at the PCC.

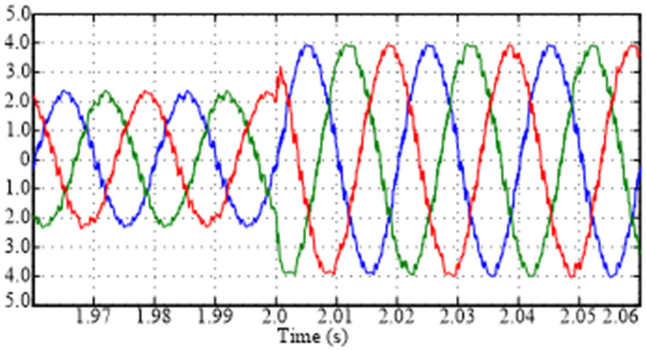


Fig. 8. Three phase currents.

B. Case 2: Unbalanced Scenario

The distribution system in residential properties predominantly operates with single-phase loads, causing asymmetry in the three-phase power supply and resulting in uneven voltages at the AC bus. Figure 10(a) illustrates the characteristics of the unbalanced three-phase current, while the performance of the proposed inverter controller is evaluated under the least favorable load profile. The regulation objective is to maintain consistent three-phase voltages at the PCC terminal, thereby improving power quality. The RMS voltages at the load point are shown in Figure 10(b). Although abrupt changes at the load bus cause variations in load current, the voltages eventually stabilize at the nominal value of 230 V. Unbalanced loads also induce secondary-frequency oscillations in the turbine shaft; however, the proposed approach effectively eliminates these fluctuations, as demonstrated in Figure 3.

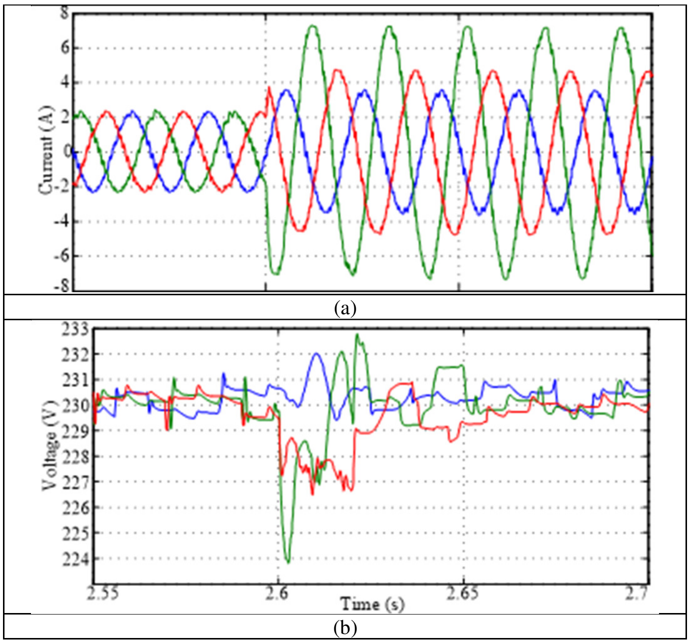


Fig. 9. (a) Currents, (b) voltages.

In addition, a comparative analysis was conducted between the proposed STSMC and conventional PI and PID controllers to evaluate dynamic performance, as displayed in Table I. As evidenced, STSMC outperforms both alternatives across all metrics. It achieves a rise time of 0.35 s and a settling time of 0.55 s, considerably faster than PI (0.75 s, 1.40 s) and PID (0.60 s, 1.00 s). The overshoot is reduced to 2.1%, compared with 14.5% for PI and 8.2% for PID, ensuring greater stability and lower oscillations. Under a ±20% load disturbance, STSMC recovers in only 0.35 s, outperforming PI (0.90 s) and PID (0.60 s). Overall, STSMC enhances transient performance, improves robustness, and proves highly suitable for reliable microgrid operation.

TABLE I. COMPARATIVE DYNAMIC PERFORMANCE OF STSMC, PI, AND PID CONTROLLERS

Performance metric	**PI controller**	**PID controller**	**STSMC (proposed)**
Rise time (s)	0.75	0.60	0.35
Settling time (s)	1.40	1.00	0.55
Overshoot (%)	14.5	8.2	2.1
Steady-state error (%)	2.8	1.5	0.3
Disturbance rejection (recovery time, (s))	0.90	0.60	0.35

VI. CONCLUSION

An advanced Energy Management System (EMS) has been designed and implemented for a Hybrid Standalone Microgrid System (HSMS) integrating Photovoltaic (PV) arrays, wind turbines, and battery storage, with hydrogen production as a secondary energy carrier. The EMS is tailored for isolated environments without grid support, where precise energy coordination is required to ensure reliability, efficiency, and power quality. Its synchronized control strategy manages power distribution, regulates voltages at the Point of Common Coupling (PCC), and optimizes electrolyzer operation for efficient hydrogen production. Thus, the EMS improves energy conversion efficiency while reducing reliance on fossil-based backup systems.

To address challenges posed by unbalanced and nonlinear loads, especially prevalent in remote microgrids, the system incorporates Super-Twisting Sliding Mode Controllers (STSMCs). This advanced nonlinear control technique is known for its robustness, finite-time convergence, and ability to suppress the chattering effects, which are typical drawbacks of conventional sliding mode controllers. The STSMC-based control algorithm is specifically tailored to minimize second harmonic distortions, a common issue in inverter-fed systems under unbalanced loading conditions. This enhances the power quality by maintaining balanced phase voltages and reducing Total Harmonic Distortion (THD), thereby extending equipment life and improving end-user experience.

Furthermore, the EMS is designed to respond dynamically to real-world fluctuations in solar irradiance, wind speed, and load profiles. It ensures swift and accurate tracking of reference voltages and power commands, enabling real-time adaptation to unpredictable environmental and load conditions. The control strategies also include Maximum Power Point Tracking (MPPT) for both PV and wind subsystems, and SoC management for the battery system, ensuring operational safety and battery longevity. To validate the proposed EMS, comprehensive simulations were conducted in a Hardware-in-the-Loop (HIL) environment using industry-standard tools. HIL simulation provides a high-fidelity testing platform that replicates physical system dynamics in real-time, allowing for detailed performance evaluation under various fault scenarios and dynamic disturbances. The simulation results demonstrate the system's effectiveness in maintaining voltage and frequency stability, suppressing harmonic content, and managing energy flows under different loading and generation conditions. Extensive case studies, including partial shading, gusty wind, step load changes, and battery SoC limits, were analyzed to evaluate the robustness and adaptability of the proposed solution.

Moreover, a comparative analysis with traditional control techniques, such as PI and PID, revealed that the STSMC-based controller consistently outperforms conventional approaches in terms of speed of response, harmonic suppression, and robustness to parameter variations. The results of this analysis have been presented using clear quantitative metrics all of which confirm the superiority of the proposed system.

Overall, the developed EMS offers a comprehensive solution for energy coordination in standalone hybrid renewable systems. By integrating advanced control strategies with real-time simulation validation, the system ensures not only reliable energy delivery but also paves the way for cost-effective, hydrogen-enabled microgrid deployments in remote or off-grid locations.

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