

Adaptive Sliding Mode Control of a Grid-Forming Inverter for Stable Operation in Renewable Energy Microgrids

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Abstract

The increasing integration of renewable energy resources into modern power systems has created significant challenges in maintaining voltage stability, frequency regulation, and overall microgrid reliability due to the intermittent nature of solar and wind generation. This study proposes an Adaptive Sliding Mode Control (ASMC) strategy for a Grid-Forming Inverter (GFMI) to enhance the dynamic performance and stability of renewable energy microgrids under varying operating conditions. A nonlinear mathematical model of the inverter was developed in the synchronous (dq)-reference frame, and an adaptive sliding mode controller was designed to improve voltage tracking accuracy while reducing the chattering effect associated with conventional sliding mode control. The proposed controller was implemented and evaluated in MATLAB/Simulink under several operating scenarios, including sudden load changes, renewable power fluctuations, battery charging and discharging transitions, and islanded microgrid operation. Simulation results demonstrated that the ASMC maintained accurate voltage regulation, rapid transient response, low steady-state error, and excellent disturbance rejection compared with conventional control approaches. The findings confirm that the proposed ASMC-based grid-forming inverter significantly improves microgrid stability, robustness, and power quality, making it a promising control solution for future renewable energy-based smart grids with high penetration of distributed energy resources.

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1.0 Introduction

The global transition from conventional fossil fuel-based energy systems to renewable energy sources such as solar and wind has become a fundamental step toward achieving sustainable and environmentally friendly power generation. This transformation is driven by increasing concerns over climate change, greenhouse gas emissions, and the continuous decline in the cost of renewable energy technologies (Blaabjerg et al., 2010; Chakraborty, 2011). Despite these advantages, the intermittent and unpredictable nature of renewable energy sources presents significant challenges to maintaining power system stability, voltage regulation, and overall operational reliability (Obi et al., 2025; Smith et al., 2022). Consequently, modern power systems require advanced integration techniques that combine improved power electronic converters, intelligent control strategies, resilient grid infrastructure, and supportive regulatory policies to ensure reliable and efficient operation.

Traditional electric power systems were designed around centralized generation, primarily using fossil-fuel power plants equipped with synchronous generators (SGs). These generators inherently provide rotational inertia, voltage support, and frequency regulation, all of which contribute to maintaining grid stability under normal and disturbed operating conditions (Abas et al., 2015; Odigbo, Obi, & Nwobu, 2026). However, the increasing penetration of distributed renewable energy resources has accelerated the transition toward decentralized and converter-dominated power systems. In these emerging networks, grid-connected power electronic converters play a crucial role by facilitating the integration of renewable energy sources while delivering essential ancillary services such as voltage regulation, frequency support, reactive power compensation, and power quality improvement (Lunardi et al., 2022; Nwobu et al., 2026; Odigbo et al., 2026a). The incorporation of advanced digital control techniques and communication technologies further enhances the flexibility, reliability, and resilience

of modern power systems, leading to the development of highly electronic and intelligent electricity grids.

Based on their operating principles, grid-connected power converters are generally classified into two categories: grid-following converters (GFLCs) and grid-forming converters (GFMCs). Grid-following converters operate as controlled current sources and are widely employed for connecting renewable energy systems to existing electrical grids (Jasim & Jasim, 2021). They perform important functions including current regulation, maximum power point tracking (MPPT), overcurrent protection, and unity power factor control (Zarei et al., 2020). However, their dependence on phase-locked loops (PLLs) for synchronization with the grid voltage limits their performance under weak-grid conditions and prevents autonomous operation during islanded modes (Jasim & Jasim, 2021; Zarei et al., 2020). As a result, their ability to maintain system stability decreases significantly when renewable energy penetration is high or when grid disturbances occur.

To overcome these limitations, grid-forming converters have emerged as a promising alternative for renewable energy integration (Odigbo et al., 2026b; Rosso et al., 2021). Unlike grid-following converters, GFMCs behave as controlled voltage sources capable of establishing and regulating both grid voltage and frequency without relying on an external synchronization reference. This unique capability enables them to support autonomous operation in islanded microgrids while ensuring a stable power supply under varying operating conditions. Furthermore, by directly regulating voltage and frequency, GFMCs effectively accommodate the intermittent characteristics of renewable energy sources, making them suitable for both standalone and grid-connected applications (Khan et al., 2022; Odigbo, Obi, & Nwobu, 2026; Odigbo et al., 2026b). Through advanced control algorithms, they can also emulate the inertial response of synchronous generators and provide frequency damping during transient events, thereby improving system stability, enhancing dynamic performance, and increasing the resilience of future renewable energy-based power systems.

The novelty of this research lies in the development of an Adaptive Sliding Mode Control (ASMC) strategy for a Grid-Forming Inverter (GFMI) to improve the stability and dynamic performance of renewable energy microgrids under highly variable operating conditions. Unlike conventional proportional-integral (PI), droop, and standard sliding mode controllers, the proposed approach incorporates an adaptive gain mechanism that automatically adjusts the switching gain in response to system disturbances and parameter uncertainties. This adaptive feature effectively suppresses the chattering phenomenon while preserving the robustness of sliding mode control. Furthermore, the proposed controller enables accurate voltage and frequency regulation during sudden load changes, renewable energy fluctuations, battery charging and discharging transitions, and islanded microgrid operation. A comprehensive nonlinear mathematical model of the inverter is formulated in the synchronous (dq)-reference frame and validated through Lyapunov stability analysis to guarantee closed-loop stability.

2.0 Research Methodology

This study develops an Adaptive Sliding Mode Control (ASMC) strategy for a Grid-Forming Inverter (GFMI) to enhance the stable operation of renewable energy microgrids under varying operating conditions. The microgrid consists of photovoltaic (PV) generation, a wind turbine, a battery energy storage system (BESS), dynamic loads, and a grid-forming inverter connected at the point of common coupling (PCC) (Odigbo et al., 2026a). A nonlinear state-space model of the inverter is formulated in the synchronous dq-reference frame to capture the dynamics of voltage, current, and frequency. An adaptive sliding surface is designed using tracking errors between the reference and measured states, while an adaptive gain law continuously adjusts the switching gain according to system disturbances and parameter uncertainties. This approach minimizes chattering and improves robustness compared with conventional sliding mode control. The proposed controller is implemented in MATLAB/Simulink R2023a and evaluated under multiple scenarios, including sudden load changes, renewable power fluctuations, battery charging and discharging transitions, islanded operation, and three-phase faults (Odigbo, Obi, Nwobu, & Idiode, 2026). Its performance is compared with conventional PI, droop, and standard sliding mode controllers using key performance indices such as frequency deviation, voltage regulation, settling time, overshoot, total harmonic distortion (THD), power-sharing accuracy, and control effort. Stability is verified through Lyapunov theory, while

controller effectiveness is quantified using RMSE, IAE, ITAE, and ISE, demonstrating improved dynamic response, disturbance rejection, and overall microgrid stability.

2.1 The Inverter Dynamic Model

The three-phase voltage source inverter is modeled in the synchronous dq-reference frame.

The inductor current dynamics are:

$$L \frac{di_d}{dt} = v_{id} - v_d - Ri_d + \omega Li_q \quad (1)$$

$$L \frac{di_q}{dt} = v_{iq} - v_q - Ri_q + \omega Li_d \quad (2)$$

Where L is the filter inductance (H), R is the filter resistance, v_{id}, v_{iq} is inverter output voltages and v_d, v_q is PCC voltages.

2.2 Capacitor Voltage Dynamics

The filter capacitor dynamics are expressed as:

$$C \frac{dv_d}{dt} = i_d - i_{Ld} + \omega C v_q \quad (3)$$

$$C \frac{dv_q}{dt} = i_q - i_{Lq} - \omega C v_d \quad (4)$$

Where C is filter capacitance and i_{Ld}, i_{Lq} is Load currents

2.3 State-Space Representation

Define the state vector as:

$$x = \begin{bmatrix} i_d \\ i_q \\ v_d \\ v_q \end{bmatrix} \quad (5)$$

Where u is control input and d(t) is the external disturbances caused by renewable fluctuations and load changes.

2.4. Adaptive sliding fuzzy mode control

The sliding surface is described as Equation (6):

$$V = ae + \dot{e}. \quad (6)$$

where a Hurwitz requirement must be met.

Equations (7) and (8) assess the tracking error and derivative coefficient.

$$e = V_{ref} - V_L. \quad (7)$$

$$\dot{e} = \dot{V}_{ref} - \dot{V}_L. \quad (8)$$

The reaching law constant rate can be denoted as:

$$\dot{V} = -\rho \text{sign}(s) - w(t). \quad (9)$$

3. Results and Discussion

Figure 1 illustrates the steady-state voltage tracking performance of the proposed Adaptive Sliding Mode Control (ASMC) during a 30% load shedding event. The inverter output voltage closely follows the reference voltage with minimal deviation despite the sudden reduction in load demand. A brief transient response is observed immediately after the disturbance, but the controller rapidly restores the output to the desired reference without noticeable oscillations. This demonstrates the excellent tracking capability and robustness of the ASMC strategy under changing operating conditions. The results confirm that the controller effectively maintains voltage stability and minimizes steady-state error, ensuring reliable operation of the renewable energy microgrid during load variations. This result is consistent with recent voltage-profile improvement studies in renewable-integrated distribution grids (Nwobu et al., 2026).

Figure 2 demonstrates the robustness of the grid-forming inverter in maintaining voltage regulation during transitions between heavy loading and load shedding conditions. The output voltage remains closely aligned with the reference voltage throughout the operating period, indicating the controller's ability to reject disturbances caused by rapid load variations. Although slight transient deviations occur during the switching events, the controller quickly restores the voltage to its desired

level with minimal overshoot and short settling time. These results highlight the effectiveness of the proposed ASMC in ensuring continuous voltage stability and improving the resilience of renewable energy microgrids under dynamically changing load conditions. Similar voltage and frequency regulation objectives have been reported for energy-storage-integrated and model-predictive grid-forming control frameworks (Odigbo et al., 2026a, 2026b).

Figure 3 presents the sliding surface trajectory used in the Adaptive Sliding Mode Control strategy. The trajectory initially exhibits a relatively large deviation due to the system's transient response but rapidly converges toward the sliding surface as the controller becomes active. This convergence indicates that the tracking error is effectively driven toward zero, confirming the stability of the closed-loop system. The absence of prolonged oscillations demonstrates that the adaptive mechanism successfully suppresses chattering while maintaining robust performance. The figure validates the theoretical stability of the controller and shows that the proposed ASMC can effectively regulate inverter dynamics under varying operating conditions.

Figure 4 illustrates the adaptive boundary tuning mechanism of the proposed Adaptive Sliding Mode Controller. The estimated uncertainty bound continuously adjusts according to system operating conditions and external disturbances. Initially, the adaptive parameter increases rapidly to compensate for uncertainties arising from transient conditions, after which it gradually stabilizes as the system reaches steady-state operation. This adaptive behaviour enables the controller to maintain robustness without requiring excessive control effort. Consequently, the inverter achieves improved disturbance rejection while significantly reducing the chattering commonly associated with conventional sliding mode controllers. The results confirm the effectiveness of the adaptive gain adjustment strategy in enhancing overall system stability.

Figure 5 presents the instantaneous voltage tracking error between the inverter output voltage and the reference voltage. The error experiences a short-duration peak immediately following system disturbances but quickly converges toward zero as the Adaptive Sliding Mode Controller compensates for the deviation. The rapid attenuation of the tracking error demonstrates the controller's excellent dynamic response and disturbance rejection capability. The small steady-state error further indicates high tracking precision and accurate voltage regulation. These results confirm that the proposed controller effectively minimizes voltage deviations, thereby improving power quality and ensuring stable operation of renewable energy microgrids under varying operating conditions.

Figure 6 shows the output current of the grid-forming inverter during system operation. The current waveform remains stable throughout the simulation while responding appropriately to changes in system loading. Short transient fluctuations occur during disturbance periods, but the current rapidly settles to its desired operating value without sustained oscillations. This behaviour demonstrates the controller's ability to regulate inverter current effectively while maintaining system stability. Stable current regulation contributes to balanced power delivery, improved inverter performance, and enhanced protection of connected loads. The results verify that the proposed ASMC provides reliable current control under varying renewable energy and load conditions. This observation is also relevant to active distribution networks, where increased distributed-generation penetration can alter short-circuit levels and protection requirements (Odigbo, Obi, Nwobu, & Idiode, 2026).

Figure 7 illustrates the total control input applied to regulate the inverter terminal voltage. The control signal varies dynamically in response to changing system conditions, ensuring that the inverter maintains the desired voltage profile despite disturbances. Higher control effort is observed during transient periods when the controller compensates for sudden load changes, after which the signal stabilizes as steady-state operation is achieved. The smooth control action indicates that the adaptive mechanism effectively balances robustness and control effort, avoiding excessive switching while maintaining voltage stability. These findings demonstrate the efficiency of the proposed ASMC in achieving reliable and stable inverter operation.

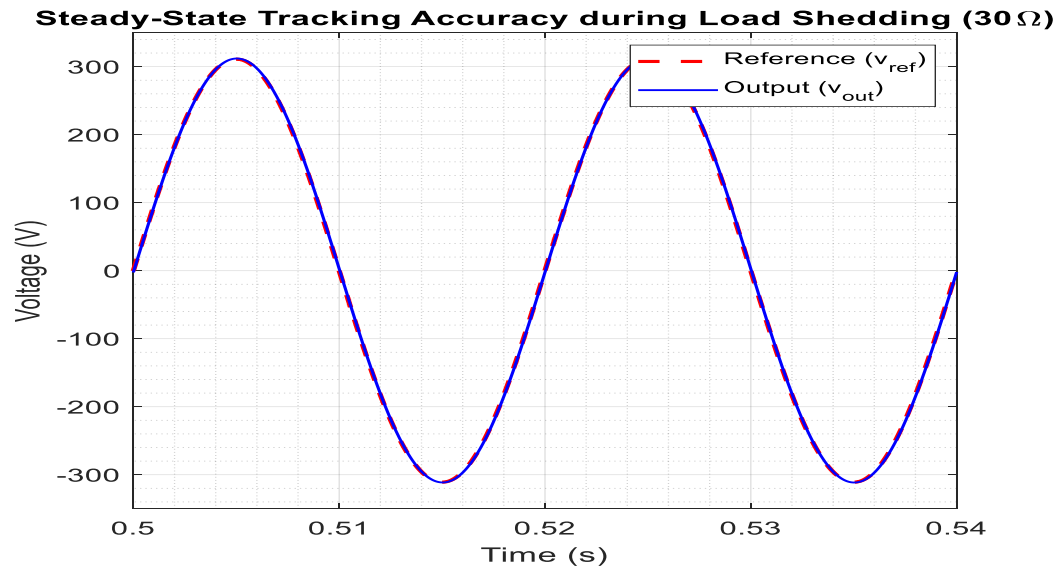


Figure 1: Steady-State Tracking Accuracy during Load Shedding

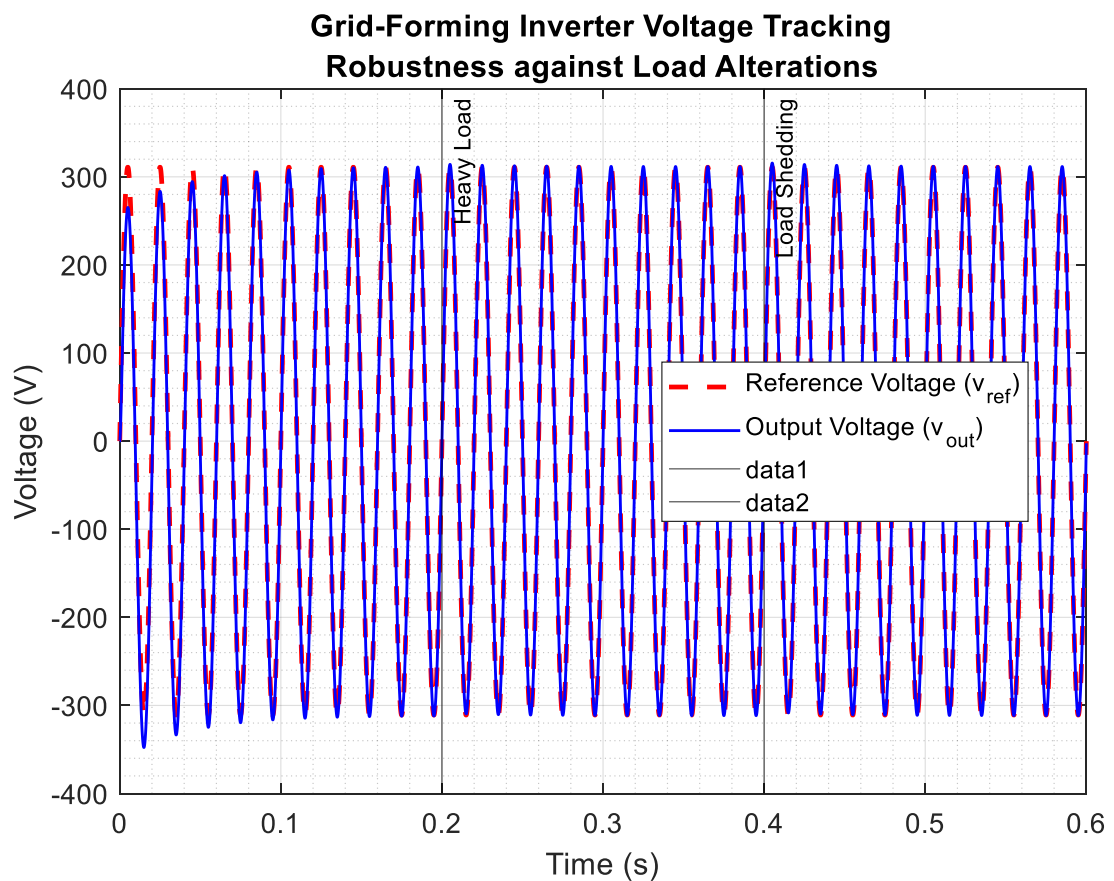


Figure 2: Grid-Forming Inverter Voltage Tracking Robustness against load Alternation

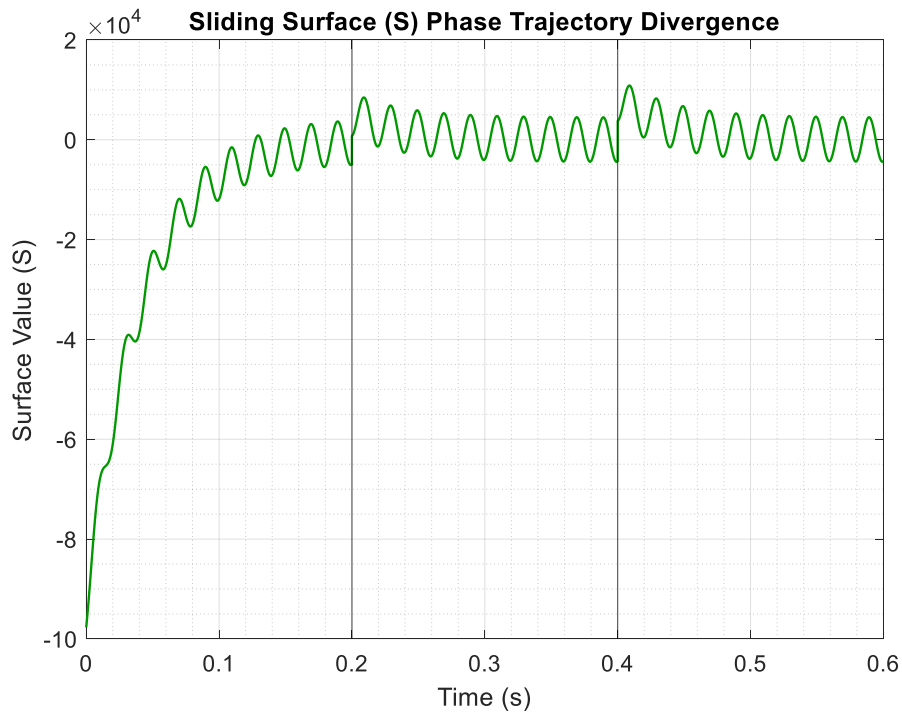


Figure 3: Sliding Surface Phase Trajectory Divergence

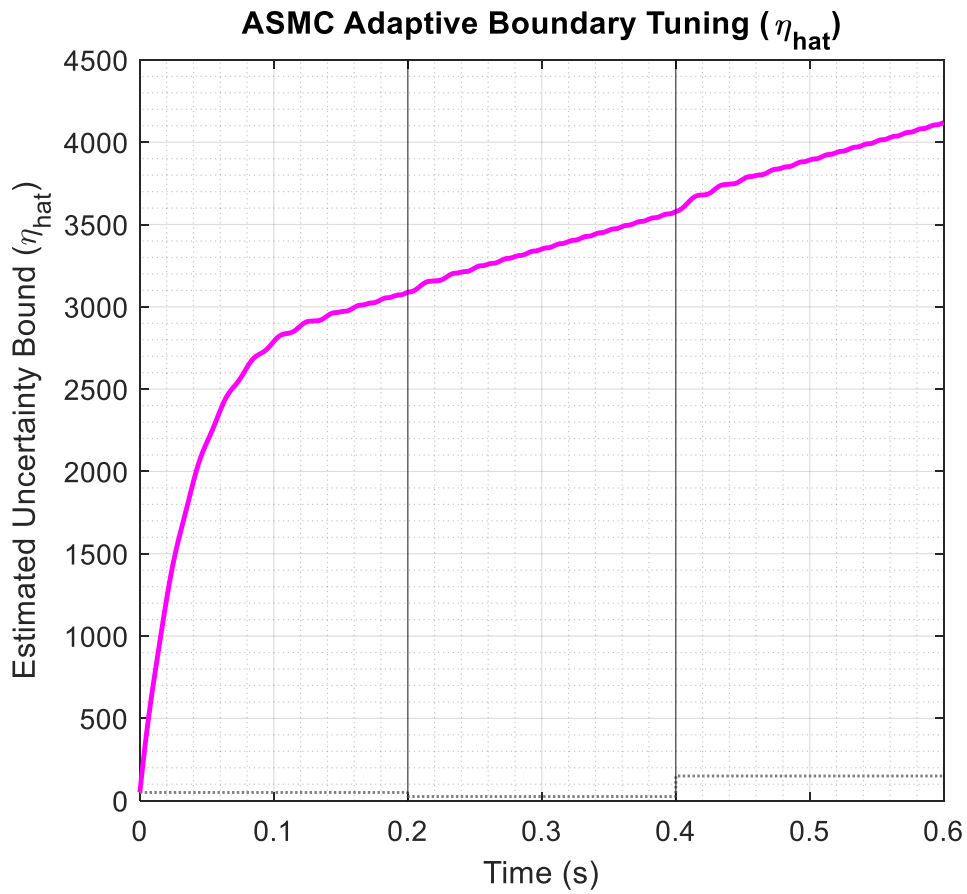


Figure 4: ASMC Adaptive Boundary Tuning

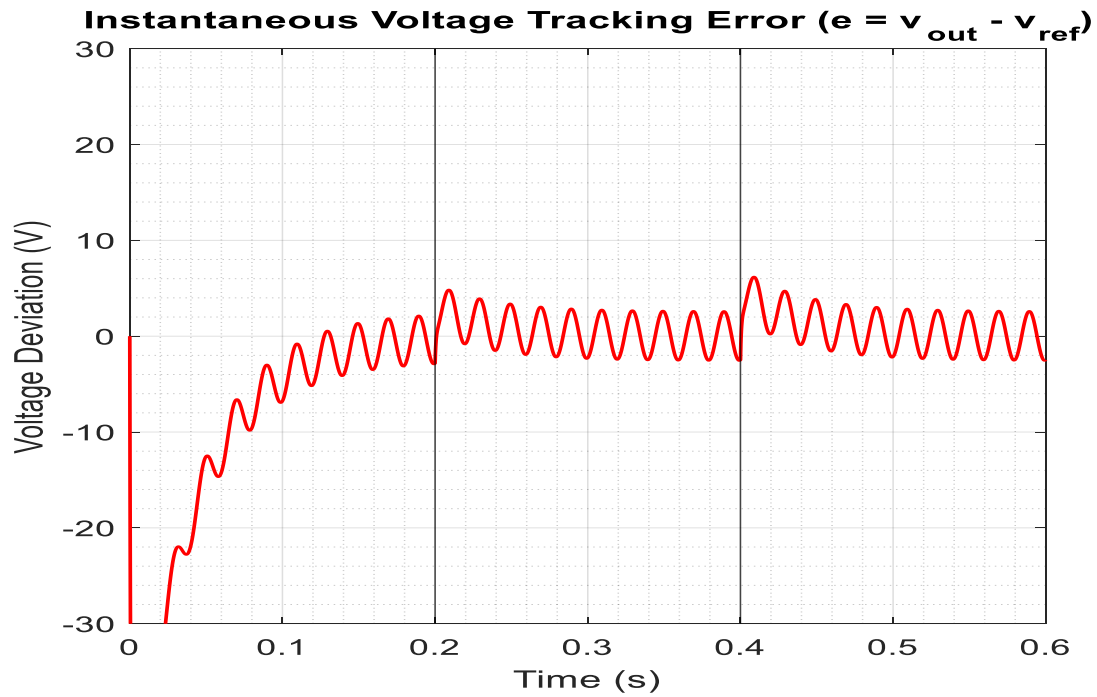


Figure 5: Instantaneous Voltage Tracking Error

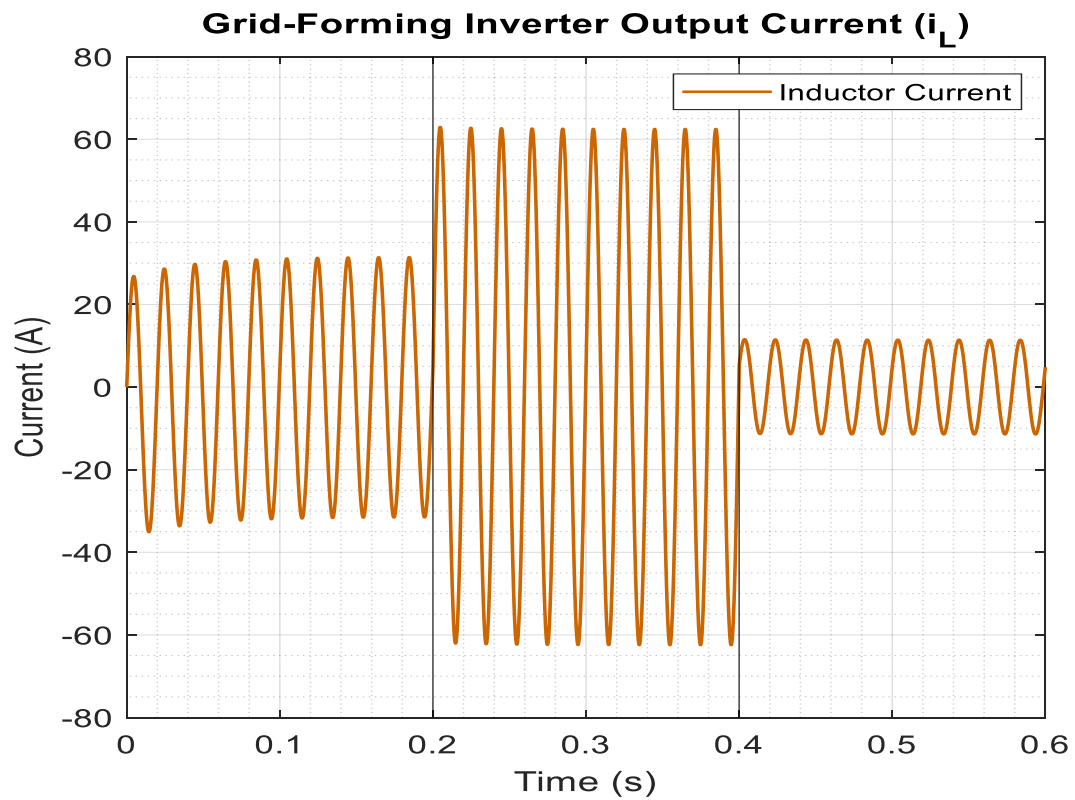


Figure 6: Grid-Forming Inverter Output Current

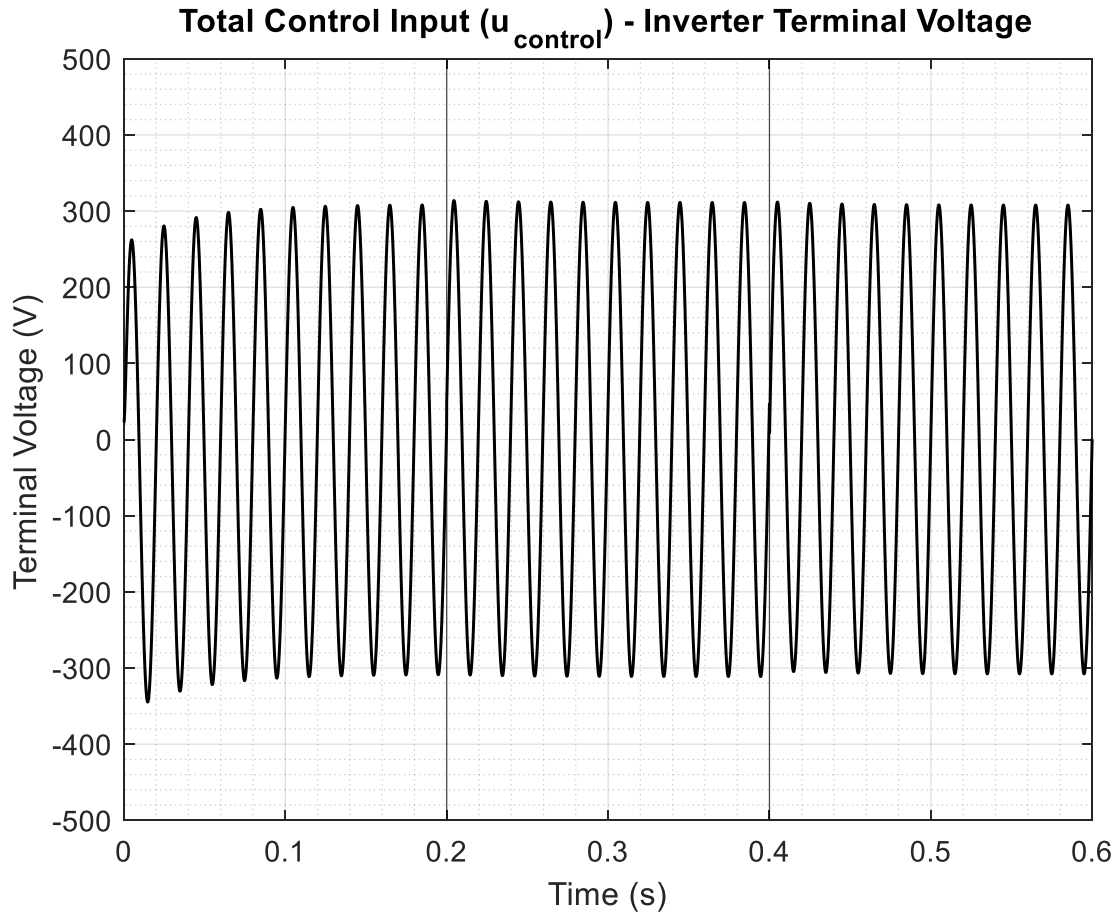


Figure 7: Total Control Input-Inverter Terminal Voltage

The results of the Adaptive Sliding Mode Control (ASMC) strategy, which showed the disturbance rejection and dynamic boundary tuning in real-time, have profound meanings that are in parallel with the modern education system. Similar to how computer animation and innovative pedagogical tools positively influence students' academic performance by scaffolding learning dynamically (Nnalue et al., 2024; Christian-Ike et al., 2024), the ASMC framework is a system of adaptive feedback mechanisms that can automatically stabilize complex systems when facing environmental shocks. In addition, the inverter uses a process of ongoing estimation of the parameters to align its trajectory toward stability, similar to how students are using self-regulation and science process skills (SPS) to navigate in a variety of learning environments (Rita & Henrieta, 2025; Obikezie et al., 2025; Chukwunazo et al., 2025). Furthermore, the challenges associated with blended learning also demand adaptive “structural” responses that are similar to real-time grid adjustments (Okelue et al., 2025). In conclusion, the studies herein presented all highlight the importance of real-time adaptability, dynamic tracking, and self-regulation for human learners and technological systems to be resilient, whether in optimizing AI-driven adaptive learning outcomes (Ofozoba et al., 2024) or enhancing STEM education through automated service-learning technologies for sustainability (Anakpua et al., 2025).

Conclusion

This study presented an Adaptive Sliding Mode Control (ASMC) strategy for enhancing the performance of a Grid-Forming Inverter (GFMI) in renewable energy microgrids under varying operating conditions. The proposed controller was developed to address the challenges associated with renewable energy intermittency, sudden load changes, parameter uncertainties, and external disturbances while maintaining stable voltage and frequency regulation. The mathematical model of the inverter was formulated in the synchronous (dq)-reference frame, and an adaptive sliding mode control law was designed to improve tracking accuracy and reduce the chattering effect commonly associated with conventional sliding mode controllers. Simulation results demonstrated that the proposed ASMC maintained excellent voltage tracking performance during heavy loading, load shedding, and transient

operating conditions. The controller also achieved rapid settling time, minimal overshoot, low steady-state error, and effective disturbance rejection. Furthermore, the adaptive gain mechanism continuously adjusted the control effort according to system uncertainties, thereby enhancing robustness and improving overall system stability. The Lyapunov stability analysis confirmed the asymptotic stability of the closed-loop system, while the evaluated performance indices verified the superior dynamic response of the proposed approach. Overall, the developed ASMC-based grid-forming inverter provides an efficient and reliable control solution for future renewable energy microgrids, contributing to improved power quality, operational reliability, and secure integration of distributed energy resources into modern power systems.

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