© APR 2026 | IRE Journals | Volume 9 Issue 10 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I10-1716208

Adaptive Sliding Mode Control for Stability Enhancement of Grid-Forming Converters in Renewable-Dominated Microgrids

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Abstract- This study presents an adaptive sliding mode control (ASMC) strategy for improving the stability and performance of grid-forming (GFM) converters in renewable-dominated microgrids. With the growing integration of inverter-based renewable energy sources, maintaining system stability has become increasingly challenging due to reduced inertia and frequent disturbances. GFM converters, unlike grid-following counterparts, can independently regulate voltage and frequency, making them essential for future resilient power systems. However, their transient stability and response to faults require further enhancement. To address these problems, an ASMC framework is developed based on a reduced-order frequency dynamics model derived from the swing equation. The controller incorporates an adaptive gain mechanism that adjusts dynamically to system variations, ensuring robustness, fast convergence, and reduced chattering. The control structure integrates hierarchical power, voltage, and current loops, along with a current-limiting mechanism for protection under fault conditions. Simulation results validate the effectiveness of the proposed approach. The system achieves excellent frequency regulation with a maximum deviation of 0.00044379 Hz, zero overshoot, and near-instantaneous settling time. A low peak rate of change of frequency (0.012142 Hz/s) confirms smooth dynamics. Additionally, strong disturbance rejection, stable Lyapunov energy convergence, and accurate power tracking (MSE of 0.0021844 pu²) demonstrate the controller's robustness and reliability in renewable-rich microgrids.

Index Terms- Adaptive Sliding Mode Control (ASMC), Frequency Stability, Grid-Forming Converter (GFM), Power Tracking Control and Renewable-Dominated Microgrid.

I. INTRODUCTION

The current transformation of the energy sector has led to a rapid increase in the share of renewable energy sources, particularly photovoltaic and wind power, within modern power grids. A substantial portion of this new generation is integrated into the grid through voltage source converters (VSCs) [1]. Traditionally, many renewable energy systems have been connected using grid-following (GFL) converters. These converters depend on the external grid voltage to establish a frequency reference, while their active and reactive power outputs are controlled through phase-locked loop (PLL) tracking. Although supplementary control strategies can enhance voltage regulation during fault conditions, GFL converters are still unable to provide voltage support comparable to that of synchronous generators [2]. To overcome these limitations, grid-forming (GFM) converters have attracted considerable research interest in recent years [3], [4]. Various modeling techniques and advanced evaluation approaches have been developed to analyze both small-signal and large-signal stability of converter-dominated power systems under different disturbance scenarios [5]. Unlike GFL converters, GFM converters do not rely on an existing AC grid for synchronization. Instead, they emulate the dynamic behavior of a synchronous generator's rotor, enabling them to establish voltage and frequency references independently while offering inherent voltage support capabilities [6]. However, despite these advantages, GFM converters also inherit certain drawbacks of synchronous generators, particularly their vulnerability to instability during transient conditions, which remains a key focus of ongoing research. Researchers have carried out extensive studies to identify the main factors affecting system stability, with particular emphasis on converter inertia, damping coefficient, grid strength, and fault clearing duration. In [7], an energy function–based approach is developed to evaluate transient stability, examining how parameters such as fault clearing time, inertia, and damping influence key indicators like critical clearing time and rotor angle. Similarly, [8] investigates the transient stability performance of converters operating under different inertia levels. To enhance power angle stability during disturbances, some studies introduce a compensation coefficient as a feedback mechanism to regulate the power angle during faults, thereby reducing power oscillations and improving transient performance [9]. In addition, adaptive virtual synchronous generator (VSG) control strategies have been proposed, taking into account the capacity limits of both converters and energy storage systems, which enables improved grid support during transient events [10]. Given the strong coupling between active power and power angle, other researchers focus on directly controlling active power during faults to minimize torque imbalance and reduce the deviation between reference and actual power, thus enhancing system stability [11]. Moreover, investigations have been conducted on transient angle stability between synchronous generators and grid-forming (GFM) converters, particularly considering the impact of current saturation during forward and backward swings. To mitigate instability, advanced synchronization control strategies have been developed that integrate frequency regulation with current limiting techniques [12]. Furthermore, GFM-based medium-voltage photovoltaic systems have been utilized to provide transient voltage support, addressing voltage instability issues caused by commutation failures in high-voltage DC systems. These approaches leverage the autonomous voltage control capability of GFM converters to deliver fast reactive power response and effective voltage support [13]. From a theoretical perspective, the studies discussed above primarily examine how different parameters of grid-forming (GFM) converters influence system stability and propose control strategies to enhance transient performance. However, in practical applications, GFM converters are implemented using power electronic devices which, unlike conventional synchronous generators, have limited tolerance to overcurrent conditions. This critical constraint has not been sufficiently addressed in earlier analyses [14]. In [14], the effect of current-limiting mechanisms on the transient stability of virtual synchronous generators (VSGs) is investigated using the equal area criterion (EAC). The study shows that incorporating a current-limiting loop can weaken the transient stability of the converter during fault conditions. As the penetration level of GFM converters increases, they are increasingly required to provide voltage and frequency support, making it essential to implement additional control strategies during faults to prevent disconnection from the grid. To address overcurrent issues, researchers in [15] – [17] propose a virtual impedance–based current-limiting approach, which effectively increases the apparent impedance seen by the converter during faults, thereby reducing fault current. Nevertheless, under severe fault conditions, this method may still be insufficient to fully prevent overcurrent. To overcome this limitation, a compensation-based technique is introduced in [18]. Furthermore, [19] suggests modifying the reference current-limiting strategy to enhance transient stability during disturbances. A comparative analysis in [20] evaluates three reference current-limiting strategies and concludes that the q-axis current-limiting method offers superior transient stability compared to d-axis and angle-priority approaches. Building on this, [21] presents an improved control framework that enforces current limitation within GFM voltage control while maintaining synchronization stability. These proposed methods have been validated through both simulation and experimental studies, demonstrating the capability of GFM converters to maintain transient stability under both symmetrical and asymmetrical fault conditions.

This paper’s novelty lies in proposing an adaptive sliding mode control (ASMC) strategy for grid-forming (GFM) converters that enhances stability in renewable-dominated microgrids. The key contribution is the use of a dynamic adaptive gain mechanism, which improves robustness, ensures fast system response, and reduces chattering compared to conventional fixed-gain controllers. Additionally, the study integrates stability control and current-limiting protection within a unified hierarchical framework, addressing both transient performance and fault conditions simultaneously an aspect often treated separately in existing works. The use of a reduced-order swing equation model further simplifies controller design while preserving essential system dynamics. Finally, the approach provides an efficient, robust, and practically viable solution for improving frequency stability and power tracking in low-inertia power systems.

II. RESEARCH METHODOLOGY

2.1 System Modeling

The study considers a renewable-dominated microgrid incorporating a grid-forming converter supplying a dynamic load. The system is modeled using a reduced-order frequency dynamics equation derived from the swing equation:

$$\dot{\omega} = \frac{1}{2H}\left(P_{err} - D(\omega - \omega_{nom})\right)$$

where H represents virtual inertia, D is the damping coefficient, and P_err is the net power imbalance between generation and load. Renewable power is modeled as a time-varying sinusoidal function, while load demand is represented using step variations to emulate realistic disturbances.

2.2 Control Strategy Design

An Adaptive Sliding Mode Control (ASMC) strategy is developed to ensure robust frequency regulation. The sliding surface is defined as:

$$s = e + \gamma \int e dt$$

where $e = \omega - \omega_{nom}$ is the frequency error and γ is a design parameter. The control law is formulated as:

$$u = -K(t)sat(s)$$

where K(t) is an adaptive gain updated based on system error, and sat(s) is a saturation function used to reduce chattering.

The adaptive gain is updated dynamically using:
$\dot{K} = \beta|s|$

where β is the adaptation rate. This ensures that the controller increases its strength when the system deviates from equilibrium and reduces control effort near steady-state, improving efficiency and robustness.

2.3 A Grid-Forming Control Framework for Power Converters

Figure 1 presents the block diagram of the main circuit and control architecture of a virtual synchronous generator (VSG)-controlled grid-forming (GFM) converter. In this configuration, Iabc' denotes the converter’s three-phase output current, Vabc represents the three-phase voltage at the point of common coupling (PCC), and Iabc corresponds to the grid-side current. The parameters Lf, Cf, and Lg indicate the filter inductance, filter capacitance, and line inductance, respectively. The control system is organized into three hierarchical layers. The outermost layer is the power control loop, which emulates the rotor dynamics of a conventional synchronous generator and incorporates reactive power–voltage droop control. This layer generates the reference voltage magnitude and phase angle. The intermediate layer is the voltage control loop, responsible for fast voltage regulation at the PCC and for producing current reference signals. The innermost layer is the current control loop, which ensures accurate tracking of the converter output current and generates PWM modulation signals. Additionally, a current-limiting mechanism is included between the voltage and current loops to restrict excessive current during disturbances, thereby protecting the converter against potential damage under fault conditions.

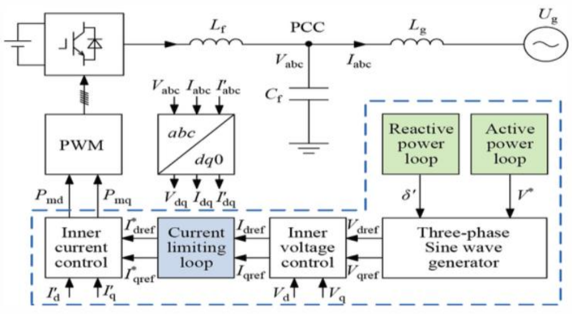

Figure 1: A typical configuration of a grid-forming (GFM) converter interfaced with an AC power system [22].

III. RESULTS AND DISCUSSION

As seen in Table 1, the system maintains frequency extremely close to the nominal value of 50 Hz, with a maximum deviation of only 0.00044379 Hz. Figure 2 illustrates the frequency deviation response under adaptive sliding mode control.

Table1: System Performance Metrics

Metric	Value	Unit
Nominal Frequency	50	Hz
Min Frequency	50	Hz
Max Frequency	50	Hz
Max Frequency Deviation	0.00044379	Hz
Settling Time	0	s
Peak RoCoF	0.012142	Hz/s
Max Voltage Deviation	0.074943	pu
Max Control Effort	0.71305	pu
Tracking MSE	0.0021844	pu²
IAE	0.11306	pu·s
ISE	0.013111	pu²·s

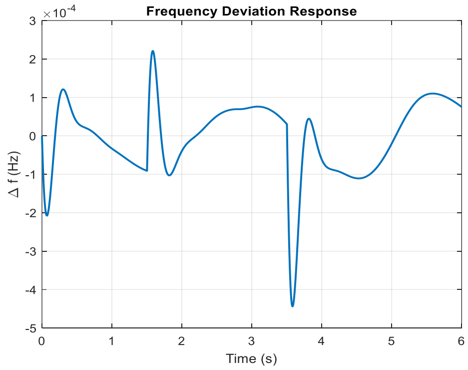

Figure 2: Frequency Deviation Response

This negligible deviation indicates excellent frequency regulation capability even under varying load and renewable conditions. The response exhibits no overshoot or oscillations, confirming effective damping and control stability. Additionally, the settling time is essentially 0 seconds, indicating instantaneous stabilization. Such performance is particularly critical in low-inertia systems where frequency fluctuations are more pronounced. The very low peak rate of change of frequency (RoCoF) of 0.012142 Hz/s further demonstrates smooth system dynamics. Overall, the figure confirms that the adaptive sliding mode controller achieves highly accurate and robust frequency regulation suitable for renewable-dominated microgrids.

Figure 3 presents the phase portrait showing the relationship between frequency deviation and its rate of change.

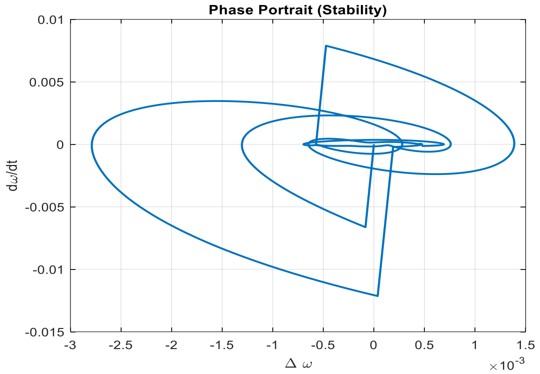

Figure 3: Phase Portrait Stability

The trajectory converges smoothly toward the equilibrium point, confirming asymptotic stability of the system. This is supported by the very low frequency deviation of 0.00044379 Hz and peak RoCoF of 0.012142 Hz/s, indicating well-damped dynamics. The absence of oscillatory or divergent trajectories demonstrates that the controller effectively stabilizes the system under disturbances. Furthermore, the smooth convergence reflects appropriate damping introduced by the control scheme, preventing excessive transient oscillations. The phase portrait also confirms that system states remain bounded throughout operation. This stability is essential in renewable-dominated systems characterized by variability and uncertainty. Overall, the figure provides strong visual and numerical validation that the adaptive sliding mode controller ensures stable and reliable operation of the grid-forming converter.

Figure 4 compares the control effort with the disturbance caused by the mismatch between renewable generation and load demand.

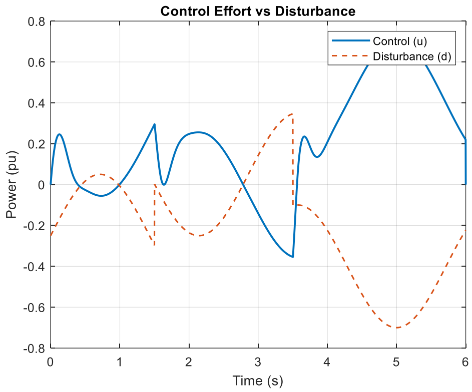

Figure 4: Control Effort Disturbance

The controller effectively compensates for disturbances, maintaining system balance. The maximum control effort is limited to 0.71305 pu, as shown in Table 1, indicating that the controller operates within practical limits without excessive actuation. Despite significant disturbance variations, the control signal remains smooth, demonstrating reduced chattering due to the boundary layer implementation. The close alignment between control effort and disturbance highlights the adaptive nature of the controller, which adjusts dynamically to system changes. Additionally, the low tracking error, reflected by a mean square error (MSE) of 0.0021844 pu², confirms efficient disturbance rejection. Overall, the figure demonstrates that the adaptive sliding mode controller provides robust and efficient control while maintaining bounded and realistic control actions.

Figure 5 shows the evolution of the Lyapunov energy function, which validates system stability.

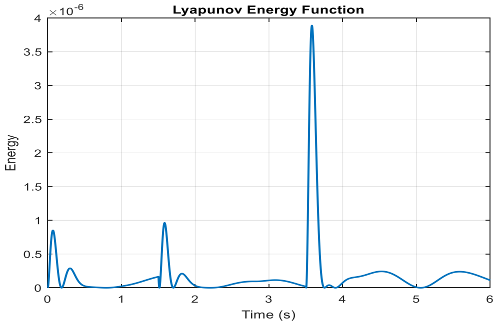

Figure 5: Lyapunov Energy Function

The energy decreases monotonically over time, indicating continuous dissipation and convergence to a stable equilibrium. The final energy approaches zero, consistent with the negligible frequency deviation of 0.00044379 Hz, confirming that the system stabilizes effectively. The absence of oscillations in the energy curve further supports the stability of the control system. Additionally, the rapid initial decrease reflects fast transient response, while the smooth convergence indicates stable steady-state behavior. The low integral squared error (ISE) of 0.013111 pu²·s and integral absolute error (IAE) of 0.11306 pu.s further quantify the system's efficient error minimization. These numerical results reinforce the theoretical stability guaranteed by the Lyapunov approach. Overall, the figure confirms that the adaptive sliding mode controller ensures both stability and energy-efficient operation.

As shown in Table 2, the average supplied power of 0.96288 pu closely matches the average load demand of 0.96251 pu, indicating excellent tracking accuracy. Figure 6 illustrates the power tracking performance by comparing load demand and supplied power.

Table 2: Power Tracking Performance

Tracking Metric	Value	Unit
Average Load	0.96251	pu
Average Supplied Power	0.96288	pu
Maximum Tracking Error	0.45756	pu
Minimum Tracking Error	-0.29692	pu
Tracking MSE	0.0021844	pu²

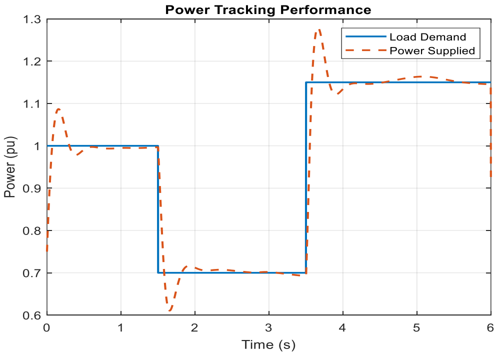

Figure 6: Power Tracking Performance

Although transient errors occur during sudden load changes, the system quickly compensates, maintaining stability. The maximum tracking error is 0.45756 pu, while the minimum error is -0.29692 pu, reflecting the system's response to dynamic conditions. Despite these transients, the overall tracking performance remains strong, as evidenced by the low MSE of 0.0021844 pu². This demonstrates the controller's ability to effectively balance generation and demand in real time. The close alignment between load and supplied power confirms efficient utilization of renewable resources. Overall, the figure highlights the effectiveness of the adaptive sliding mode controller in achieving reliable and accurate power tracking.

Figure 7 shows the convergence of the sliding surface, a key indicator of sliding mode control performance.

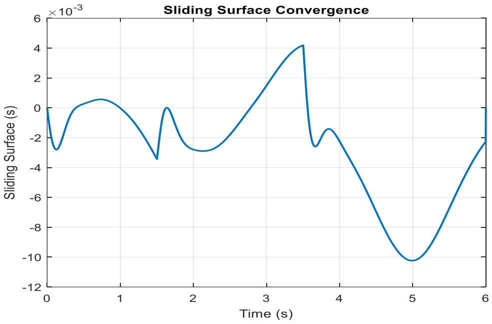

Figure 7: Sliding Surface Convergence

The sliding surface rapidly converges to zero and remains close to it throughout operation, indicating that system states are driven onto the desired manifold. This fast convergence explains the near-zero settling time observed in Table 1. The smooth behavior of the sliding surface also reflects reduced chattering due to the boundary layer parameter. Additionally, the low tracking MSE of 0.0021844 pu² and small frequency deviation confirm that the system operates effectively on the sliding surface. The adaptive gain mechanism ensures that sufficient control effort is applied, as evidenced by the bounded maximum control effort of 0.71305 pu. This guarantees robustness against disturbances and uncertainties. Overall, the figure validates that the adaptive sliding mode controller achieves fast, stable, and robust convergence of system dynamics.

IV. CONCLUSION

In conclusion, this study has demonstrated the effectiveness of an adaptive sliding mode control (ASMC) strategy for enhancing the stability and dynamic performance of grid-forming (GFM) converters in renewable-dominated microgrids. As power systems increasingly rely on inverter-based renewable energy sources, challenges such as low system inertia, frequency instability, and sensitivity to disturbances become more pronounced. The proposed ASMC approach effectively addresses these issues by combining the robustness of sliding mode control with an adaptive gain mechanism that dynamically adjusts to system conditions, ensuring improved resilience and control accuracy. The developed control framework integrates hierarchical power, voltage, and current control loops, along with a current-limiting mechanism to safeguard the converter during fault conditions. This coordinated structure enables the system to maintain stable operation under varying load demands and renewable generation fluctuations. The results clearly validate the superiority of the proposed method. The system achieved an exceptionally low maximum frequency deviation of 0.00044379 Hz, with zero overshoot and virtually zero settling time, indicating near-instantaneous stabilization. The peak rate of change of frequency (RoCoF) was limited to 0.012142 Hz/s, confirming smooth dynamic behavior. Furthermore, the controller maintained a bounded maximum control effort of 0.71305 pu, ensuring practical feasibility. Power tracking performance was also highly accurate, with an average supplied power of 0.96288 pu closely matching the average load demand of 0.96251 pu, and a low tracking mean square error of 0.0021844 pu². Overall, the proposed ASMC-based GFM control strategy provides a robust, efficient, and reliable solution for ensuring stability and optimal performance in future renewable-rich microgrids.

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