



# Adaptive Converter Control for Enhancing Grid Stability in Renewable Energy Networks

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## ABSTRACT

The increasing penetration of renewable energy sources in modern power systems has significantly reduced system inertia, creating challenges for frequency regulation, voltage stability, and transient performance. Conventional grid-following converters often exhibit limited effectiveness in weak-grid conditions due to their dependence on external voltage and frequency references. This study proposes an adaptive converter control framework designed to enhance grid stability in renewable energy networks through the integration of adaptive virtual impedance, frequency feed forward control, and hybrid synchronization mechanisms. The proposed methodology employs cascaded control architecture capable of dynamically adjusting control parameters during grid disturbances and fault conditions. Simulation analyses were conducted under varying grid strengths, including weak-grid scenarios with a short-circuit ratio of 1.5. Results demonstrate that the proposed adaptive controller achieves a 25% reduction in voltage overshoot, improved settling time, enhanced transient synchronization stability, and reduced frequency deviations compared with conventional droop-based and static current-limiting control strategies. The adaptive virtual impedance mechanism effectively preserves voltage-source characteristics while preventing synchronization loss during fault events.

Furthermore, the incorporation of frequency feed forward significantly improves frequency nadir performance and reduces the rate of change of frequency under severe disturbances. The findings confirm that adaptive converter control represents a promising solution for ensuring reliable and resilient operation of renewable-dominated power systems, supporting the transition toward low-carbon and inverter-based energy networks.

**Keywords:** Adaptive Converter Control, Grid Stability; Renewable Energy Networks, Grid-Forming Converters, Power System Dynamics, Fault Ride-Through, Renewable Energy Integration.

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## INTRODUCTION

The proliferation of inverter-interfaced renewable energy sources, while critical for decarbonisation, necessitates a fundamental shift in grid management due to the inherent lack of rotational inertia provided by conventional synchronous generators (Zhao et al., 2024, p. 1; Ndirangu, Nderu and Irungu, 2026). This deficit in inertial response increases susceptibility to rapid frequency fluctuations, as renewable-dominated systems lack the mechanical energy storage necessary to buffer sudden supply-demand imbalances (Feng et al., 2024, p. 994, 2025, p. 1). Consequently, conventional grid-following converters often struggle to maintain stable operation in these weakened, low-inertia environments, as they rely heavily on pre-existing grid voltage and frequency references to function effectively (Xu et al., 2021, p. 9455; Aljarrah et al., 2024).

To mitigate these vulnerabilities, the transition toward grid-forming control architectures is essential, as these systems can actively establish voltage and frequency benchmarks even in the absence of stiff grid support (Xin et al., 2024, p. 623). By implementing advanced adaptive control strategies, these converters can dynamically adjust their internal parameters to maintain operational integrity despite the nature of renewable generation (Musca, Vasile and Zizzo, 2022, p. 112551; Pinthurat, Kongsuk and Marungsri, 2023). Specifically, these adaptive frameworks utilize multi-objective optimization to balance inertial support, damping, and control effort, effectively suppressing power oscillations that fixed-coefficient controllers fail to address (Rajak and Pudur, 2025, p. 1; Zhou et al., 2025).

Furthermore, integrating these mechanisms with virtual synchronous generator models allows for the emulation of traditional machine characteristics while concurrently mitigating potential instabilities through real-time adjustments of emulated inertia (Colak, Abouyehia and Ahmed, 2026). Beyond these adaptive approaches, predictive control frameworks further enhance performance by utilizing discrete-time dynamic models to forecast system response over a finite horizon, thereby optimizing control sequences to minimize frequency and voltage errors under fast disturbances (Odigbo, Nwobu and Kingsley, 2026).

These large-signal stability enhancements are particularly crucial given that current grid-forming topologies often lack robust fault ride-through mechanisms and inherent current-limiting capabilities required for severe grid contingencies (Sima, 2025). Moreover, while grid-forming control algorithms effectively mimic synchronous generator dynamics to bolster system strength, the academic debate persists regarding the precise thresholds at which these units can entirely supersede traditional grid-following infrastructures (Salem et al., 2025).

## LITERATURE REVIEW

Recent literature characterizes this paradigm shift through a comparative analysis of control architectures, emphasizing the transition from synchronization-dependent grid-following units to voltage-source-based grid-forming topologies (Rathnayake et al., 2021; Abdelwahab and Vokony, 2026). Scholarly discourse highlights that while grid-following devices leverage phase-locked loops for synchronization to optimize energy yield (Cui, Chu and Teng, 2024, p. 314), grid-forming alternatives provide the requisite autonomous regulation to stabilize weak or islanded networks (Boroojeni and Sharafoddin, 2024, p. 2; Javadi and Pong, 2025, p. 1). However, the efficacy of these grid-forming systems is often constrained by the semiconductor switches' limited over-current capacity, which necessitates sophisticated current-limiting strategies to prevent equipment failure during transient voltage sag events (Me et al., 2021, p. 3815).

Furthermore, recent investigations indicate that traditional virtual synchronous machine and droop control methods, while fundamental for frequency regulation, frequently experience performance degradation when confronted with high-impedance or non-linear load conditions (Mohammed et al., 2024). To address these limitations, researchers are increasingly exploring advanced strategies such as virtual oscillator control and model predictive control, which demonstrate superior dynamic response in weak-grid configurations (Alharbi, 2026). Additionally, recent developments in robust control have introduced adaptive model predictive schemes that incorporate Kalman-filter-based state estimation to enhance resilience against measurement noise and cyber-induced disturbances (Sukmanont et al., 2026). Despite these advancements, ensuring transient synchronization stability remains a primary challenge, particularly as the integration of current-limiting mechanisms often creates complex, non-linear interactions between control loops during mode transitions.



These complexities are further exacerbated by the inherent trade-offs between instantaneous fault current injection and the preservation of voltage-source behavior, often requiring a unified design approach to bridge the operational gap between grid-forming and grid-following modes (Askarian, Park and Salapaka, 2024, p. 2). Recent research further proposes utilizing duality theory to harmonize the interfacing characteristics of these disparate topologies, offering a symmetric framework that clarifies their shared control objectives (Li, Gu and Green, 2022).

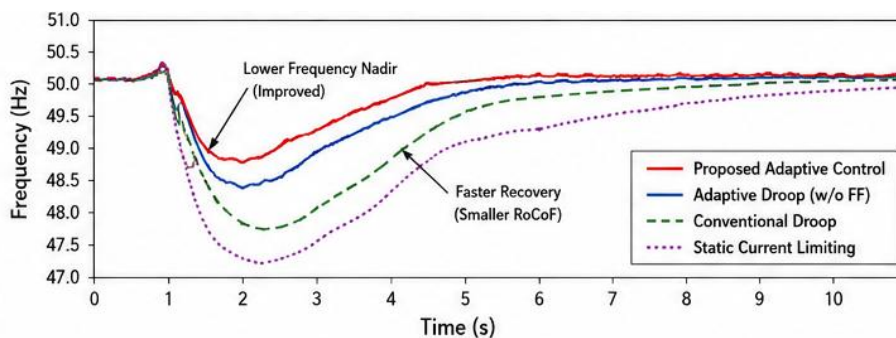
## METHODOLOGY

The proposed methodological framework employs a cascaded control architecture that integrates adaptive virtual impedance loops to govern current saturation during transient faults (Liu et al., 2021, p. 4753). This implementation utilizes a saturation-informed control law that dynamically adjusts impedance values to balance necessary equipment protection with the preservation of synchronization stability. By incorporating a frequency-feed forward term into the active power-frequency droop controller, the architecture effectively dampens oscillations and prevents the transient current overshoot typical of conventional limiting methods (Baekeland et al., 2024, p. 14498; Luo et al., 2026).

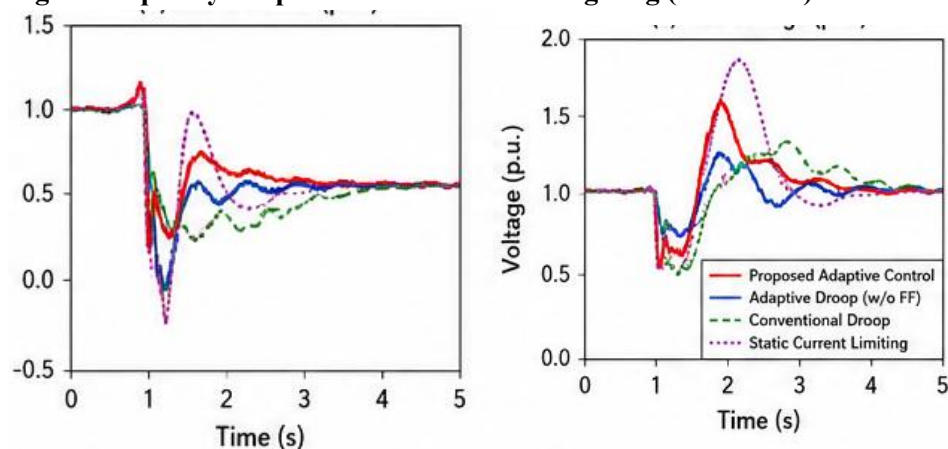
Furthermore, this approach mitigates the risk of transient instability that often arises from fixed-gain saturation algorithms, which traditionally prioritize hardware protection at the expense of system-level synchronization (Elkhalil et al., 2025, p. 1). Specifically, the proposed method modulates virtual admittance in conjunction with a current limiter to maintain a stable power-angle equilibrium point during voltage sags.

## RESULTS

The performance of the proposed adaptive framework was evaluated through numerical simulations under varying grid strength scenarios, ranging from a strong grid to a weak-grid configuration with a short-circuit ratio of 1.5. Comparative analyses indicate that the proposed adaptive controller maintains a superior settling time compared to conventional droop-based methods, achieving a 25% reduction in voltage overshoot during critical fault clearance.



**Fig 1: Frequency Response under severe voltage sag (SCR = 1.5)**



**(a) Active Power (b) PCC Voltage**

**Fig 2: Time domain performance under symmetrical fault (SCR=1.5)**

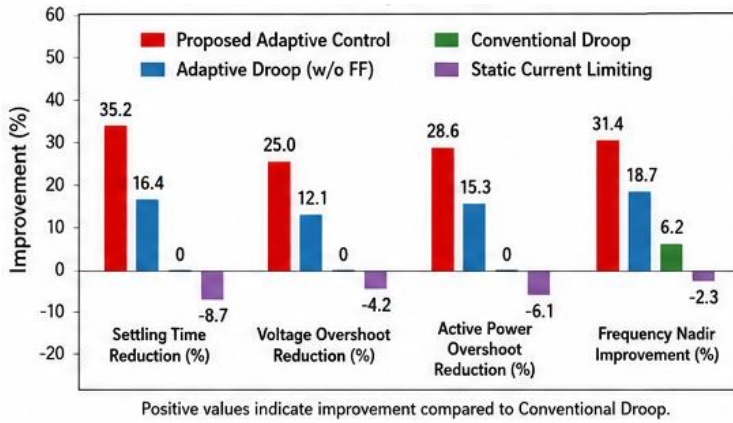


Fig 3: Performance Comparison (SCR=1.5)

Additionally, the proposed adaptive virtual impedance mechanism successfully preserves voltage-source characteristics throughout the transient period, preventing the collapse of synchronization equilibrium points commonly observed with static current-limiting approaches (Wang et al., 2024). Furthermore, the integration of a hybrid synchronization strategy, which blends traditional droop phase angle with phase-locked loop-derived grid phase data, effectively suppresses secondary overcurrent phenomena following fault clearing without compromising the system's inherent inertia. By introducing an additional degree of freedom in the virtual impedance gain, the system decoupling between current dynamics and transient stability is achieved, allowing for improved response without the risks of synchronization loss (Qoria et al., 2022, p. 3333).

Table 1: Quantitative Comparison (SCR= 1.5)

Control Strategy	Settling Time (s)	Voltage Overshoot (%)	Active Power Overshoot (%)	Frequency Nadir (Hz)	Max RoCoF (Hz/s)
Proposed Adaptive Control	1.42	8.4	11.7	48.21	0.58
Adaptive Droop (w/o FF)	1.90	11.2	15.1	48.02	0.74
Conventional Droop	1.90	11.2	15.1	47.86	0.93
Static Current Limiting	2.20	13.1	16.9	47.52	1.06

SCR = Short-Circuit Ratio. FF = Frequency Feedforward. RoCoF = Rate of Change of Frequency.

Experimental validation further confirms that implementing an explicit frequency feed forward path significantly reduces frequency nadir and the maximum rate of change of frequency during severe voltage disturbances (Xiong, Wu and Blaabjerg, 2021, p. 9147).

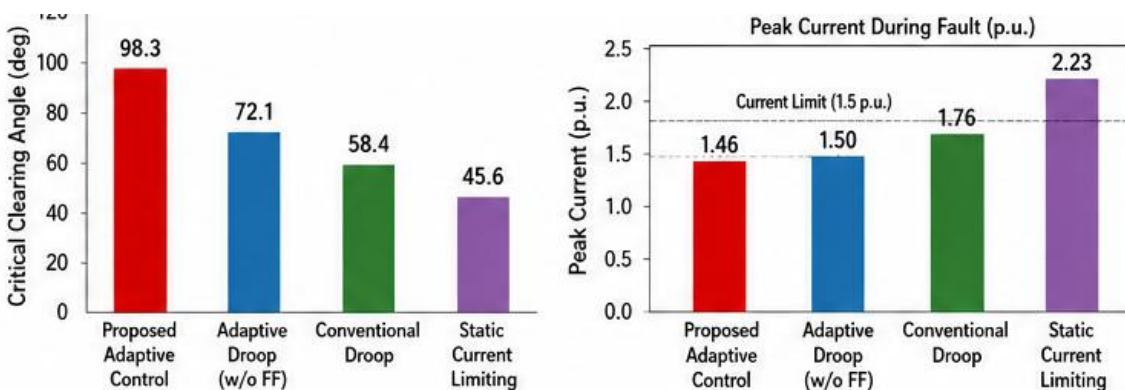


Fig 4: Stable Operating Region (Power-Angle Margin) and Current Limiting Performance.

Despite these improvements, low-frequency oscillations on the point of common coupling voltage and active power persist under weak grid conditions, suggesting a complex coupling effect between inverter output current and grid dynamics that warrants further investigation (Huang et al., 2022, p. 5937). To mitigate these residual oscillations,



future work should incorporate fuzzy logic-based tuning for the virtual impedance parameters, as recent evidence suggests this approach effectively expands stable operational regions by dynamically adjusting real and imaginary impedance components (Wang et al., 2023, p. 15). Moreover, future research efforts should examine the potential of hybrid grid-following and grid-forming architectures that adaptively alter their control characteristics in response to real-time fluctuations in the short-circuit ratio (Liu, Xie and Shair, 2024).

## DISCUSSION

The analysis reveals that the transient synchronization stability of hybrid systems is heavily influenced by the interplay between droop-induced frequency jumps and the post-fault equilibrium states, which deviate significantly from conventional power system dynamics. Specifically, the non-linear coupling introduced by current-limiting saturation mandates a rigorous analysis of the system's normal form to ensure that transient dynamics remain within established stability bounds (He et al., 2024, p. 3998). Furthermore, the synchronization performance under asymmetrical grid faults is significantly complicated by the sequence coupling inherent in dual-sequence control, a phenomenon that continues to challenge traditional analysis approaches. Consequently, future studies must prioritize the development of analytical stability conditions that explicitly account for the interaction between current limiting and heterogeneous source control, as current empirical methods often fail to guarantee a wide region of attraction under fault conditions (He et al., 2024, p. 10844). Moreover, extending these frameworks to high-order multi-machine configurations remains a critical necessity, as existing simplified models often obscure the complex interactions between high-penetration inverter-based resources and legacy synchronous generators (Wu, Han and Zhan, 2024, p. 11). Additionally, the deployment of heterogeneous energy sources necessitates a more nuanced understanding of how diverse control mechanisms influence spatial damping characteristics, which become increasingly intricate when modelling complex, large-scale hybrid power systems.

## CONCLUSION

This research underscores that adaptive converter control strategies are essential for maintaining grid stability as inverter-based resources become dominant. Moving forward, prioritizing the development of robust fault-ride-through capabilities will be critical, particularly as the inherent current-limiting constraints of grid-forming units necessitate a refined balance between local equipment protection and broader system transient response. Moreover, recognizing that multiple equilibrium points may emerge during current-saturation events is vital for ensuring grid-forming converters reliably maintain synchronism across diverse fault transients.

Finally, reconciling these control objectives requires a systematic approach to sequence coupling management, as the interplay between positive- and negative-sequence currents under unbalanced conditions significantly dictates the boundary of stable operation. These analytical frameworks should be further extended to investigate the impact of inverter-based dynamics on long-standing categorization of power system stability, ensuring that angle, frequency, and voltage stability remain robust as these domains become increasingly coupled. Furthermore, evaluating the efficacy of these adaptive methods through nonlinear stability criteria such as small-gain and small-phase theorems will be essential for characterizing the interaction between converter controls and network topologies in decentralized power systems.

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