

Article

Transient Stability Enhancement Control for VSGs Based on Active-Power Deviation and Angle-Feedback Compensation

Zheng Lan ¹, Xin Guo ¹, Zihao Peng ², Fan Xiao ², Jiawei Luo ^{1,*} and Yuncheng Lei ¹

¹ School of Traffic and Electrical Engineering, Hunan University of Technology, Zhuzhou 412007, China; lan@hut.edu.cn (Z.L.); m24085800079@stu.hut.edu.cn (X.G.); leiyuncheng3@163.com (Y.L.)

² College of Electrical and Information Engineering, Hunan University, Changsha 410000, China; zhpeng@hnu.edu.cn (Z.P.); woliao321@hnu.edu.cn (F.X.)

* Correspondence: hhyliw011226@163.com

Abstract

Deep grid-voltage depressions may simultaneously induce transient power-angle instability and excessive fault current in VSGs, thereby compromising the operational security of grid-connected converters. To address this coupled challenge, an active-power deviation and angle-feedback compensation (APDAFC) strategy is developed. A fault-on power-angle model incorporating virtual damping and reactive-power-loop dynamics is first established to characterize the transient behavior of the VSG. The respective effects of grid-voltage-sag severity and power-angle variation on fault-current amplitude are subsequently identified. APDAFC introduces a compensation signal derived from the active-power deviation and power angle into the active-power-frequency loop, enabling online regulation of the equivalent active-power command. This regulation reverses the continued increase in the power angle and establishes a stable fault-period operating point whose power angle is lower than the prefault value. The resulting reduction in power-angle deviation decreases the magnitude of the voltage-phasor difference between the VSG and the grid. Consequently, transient synchronization stability and steady-state fault-current suppression are achieved simultaneously, while voltage-source operation is retained without imposing explicit current saturation. Simulations under different grid-voltage-sag severities corroborate the theoretical findings and demonstrate the effectiveness of the proposed strategy.

Keywords: virtual synchronous generator; low-voltage ride-through; transient stability; fault-current limiting; active-power deviation and power-angle-feedback compensation



Academic Editor: Alessandro Niccolai

Received: 21 September 2026

Revised: 11 October 2026

Accepted: 16 October 2026

Published: 20 October 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The increasing deployment of photovoltaic and wind generation is driving a structural transition in power systems, characterized by a shift from synchronous-generator dominance toward a growing penetration of converter-interfaced generation [1–5]. As the share of conventional synchronous generation declines, both system inertia and damping decrease. Consequently, modern power systems increasingly exhibit low-inertia and weak-damping characteristics. These characteristics impair disturbance rejection and post-disturbance recovery, posing significant challenges to secure and reliable system operation [6,7].

Virtual synchronous generator (VSG) control is based on emulating the dynamic characteristics of conventional synchronous generators. It can actively provide voltage support

and frequency regulation and has become an important solution for enhancing the stability of converter-dominated power systems [8,9]. During a grid-voltage sag, the reduction in transferable active power disrupts the VSG's input-output power balance. The resulting mismatch drives the power angle away from equilibrium and may ultimately lead to transient loss of synchronism [10–12]. As the VSG operates as a controlled voltage source, its output current depends on the phasor difference between the converter and grid voltages. Voltage depression and the associated angular displacement can enlarge this difference, causing overcurrent that compromises converter safety and stable operation [13–15]. Accordingly, fault ride-through strategies for grid-forming converters must coordinate transient synchronization stability with fault-current limitation.

Research on VSG transient stability has concentrated on active-power-reference regulation, adaptation of virtual inertia and damping, voltage-reference adjustment, and reconfiguration of synchronization mechanisms. Since grid-voltage sags disrupt the active-power balance, the methods reported in [16–18] mitigate the resulting power mismatch by regulating the reference according to sag severity. Reference [19] employs q-axis current feedback compensation to enlarge the deceleration area and enhance transient power-angle stability. Studies [20–22] analyze the influence of virtual inertia and damping on transient angle dynamics and extend the critical clearing time through dynamic parameter adjustment. Under severe voltage sags, however, inertia and damping regulation alone may be insufficient to preserve transient synchronism. Reference [23] examines the coupling between reactive-power regulation and power-angle dynamics, using output-voltage adjustment to improve the fault-period synchronization response. References [24,25] establish current-vector-based synchronization models and enhance transient synchronization by exploiting the mapping between active power and dq -axis current components. Nevertheless, a stable power-angle trajectory does not necessarily ensure compliance with fault-current constraints. Coordinating synchronization stability with current limitation is therefore essential to the design of fault ride-through control.

Since fault current exceeding limits is one of the key issues affecting the safe and stable operation of VSGs during faults, studies [26–28] employ a hard-limiting strategy; however, this strategy modifies the VSG's transient terminal characteristics, shifting operation from voltage-source control to current-source control and substantially restricting its active-power-transfer capability. References [29,30] further reveal that during a voltage sag, the power-angle trajectory may cross the current-limiting boundary; the transient active-power imbalance caused by power-transfer limitations may trigger a sustained deviation in the power angle, leading to transient instability. After fault clearance, if the VSG has difficulty smoothly exiting current-source mode, secondary current overshoot and power oscillations may occur, severely compromising the VSG's transient safety. Table 1 provides a comprehensive comparison of the operating principles and performance characteristics of the aforementioned control strategies. Existing studies primarily focus on a single objective, such as improving transient stability or suppressing fault currents. Methods that achieve coordinated improvement in transient synchronization stability and fault-current suppression remain limited.

An active-power deviation and angle-feedback compensation (APDAFC) strategy is developed to coordinate transient synchronization stability and steady-state fault-current suppression in VSGs subjected to grid-voltage sags. The active-power deviation and power-angle state are incorporated into the active-power–frequency loop to reconfigure the fault-period power-angle dynamics. This reconfiguration prevents sustained power-angle divergence while restraining the steady-state fault-current magnitude. The principal contributions are summarized below:

- (1) A transient power-angle model incorporating virtual damping and reactive-power-loop dynamics is established to elucidate the mechanism of transient loss of synchronism in VSGs. Based on this model, the respective effects of power-angle displacement and voltage-sag depth on fault-current amplitude are characterized, providing a theoretical foundation for coordinating transient synchronization enhancement and fault-current suppression through power-angle regulation.
- (2) An active-power deviation and angle-feedback compensation (APDAFC) strategy is developed. Joint feedback of the active-power deviation and power angle dynamically regulates the equivalent active-power reference and effective damping, thereby reshaping the fault-period acceleration and deceleration dynamics and reversing the power-angle trajectory from sustained positive deviation to active return. This mechanism coordinates transient synchronization stability with steady-state fault-current suppression while preserving voltage-source operation and avoiding explicit current saturation.
- (3) The control performance of APDAFC is evaluated through simulations and hardware-in-the-loop experiments covering a range of grid-voltage-sag severities, with the conventional VSG and an active-power-reference regulation method serving as benchmarks. The results show that, under severe voltage sags in weak and very weak grids, APDAFC prevents power-angle instability and restrains steady-state fault-current growth, thereby coordinating transient synchronization stability with fault-current suppression. Following fault clearance, the system returns smoothly to its normal operating condition. These results demonstrate the effectiveness and adaptability of APDAFC across different grid-voltage-sag conditions.

Table 1. Comparison of different transient control methods for VSGs.

Method	Transient Power-Angle Stability	Fault Current Suppression	Hard Current Limiting	Robustness
Power-Reference Adjustment [16–18]	✓	Additional current control is required.	×	✓
Dynamic Adjustment of Virtual Inertia and Damping [20–22]	✓		×	×
Voltage-Reference Adjustment [23]	✓		×	✓
Current Synchronization Control [24,25]	✓		×	✓
Hard Current Limiting Control [26–28]	×	✓	✓	×
Proposed APDAFC	✓	✓	×	✓

2. Analysis of the Basic Principles and Transient Characteristics of VSG

2.1. Main Circuit Model of the VSG

Figure 1 depicts the circuit topology and control architecture of the grid-connected GFM inverter. The dc link supplies the converter at voltage U_{dc} , whereas the ac interface incorporates a filter inductor L_a and a filter capacitor C_a . I_{VSG} is the current delivered by the converter; U_{VSG} denotes the PCC voltage, and U_g denotes the grid-side voltage. The grid connection is represented by the line inductance L_g and resistance R_g . PWM denotes pulse-width modulation. To highlight the relationship between the ac-side power imbalance and power-angle dynamics during grid-voltage sags, the dc side is modeled as

an ideal constant-voltage source. The dynamics of the dc source and dc-link capacitor are therefore neglected.

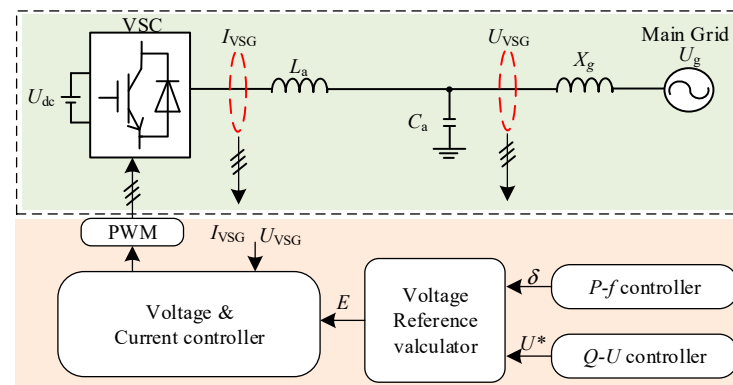


Figure 1. Main circuit and control structure of the VSG inverter.

Equation (1) defines the active-power–frequency control law of the VSG, and (2) specifies its reactive-power–voltage counterpart. Figure 2 presents a block-diagram representation of these two control loops.

$$P_{\text{ref}} - P_e - D_p \frac{d\delta}{dt} = H \frac{d^2\delta}{dt^2} \quad (1)$$

$$Q_{\text{ref}} - Q_e = -k_q (U_{\text{ref}} - U^*) \quad (2)$$

where P_{ref} and Q_{ref} specify the active- and reactive-power setpoints. The instantaneous angular speed of the virtual rotor is denoted by ω , with ω_N defining its reference value. The inverter active- and reactive-power outputs are represented by P_e and Q_e . The parameters k_q , H , and D_p characterize the droop coefficient, virtual inertia, and damping coefficient in the stated order. The symbol δ denotes the power angle. Finally, U_N is the rated voltage magnitude, and U^* is the voltage reference of the VSG.

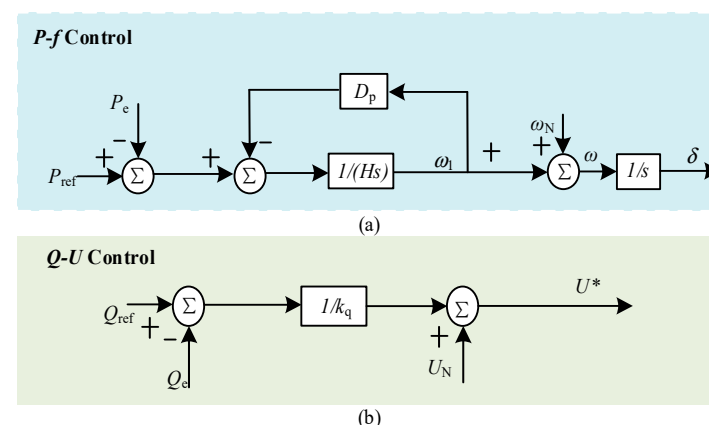


Figure 2. Block diagram of the P - f and Q - U control loops. (a) P - f and (b) Q - U .

The grid-side active- and reactive-power outputs of the VSG are formulated as follows:

$$P_e = \frac{3U_g U_{\text{VSG}}}{2X_g} \sin \delta \quad (3)$$

$$Q_e = \frac{3U_{\text{VSG}}(U_{\text{VSG}} - U_g \cos \delta)}{2X_g} \quad (4)$$

Combining Equations (2) and (4) and simplifying yields the following expression for the reactive loop output voltage U_{VSG} :

$$U_* = \frac{W(\delta) + \sqrt{W(\delta)^2 + K}}{6X_g} \quad (5)$$

$$\text{where } \begin{cases} W(\delta) = 3U_g \cos \delta - 2k_q X_g \\ K = 24X_g(k_q U_N + Q_{ref}) \end{cases}.$$

2.2. Transient Characteristic Analysis of the VSG

The conventional equal-area criterion assesses VSG transient stability by comparing the accelerating and decelerating areas. Because virtual damping and reactive-power-loop dynamics are omitted, the resulting stability margin may be underestimated. To obtain a more faithful characterization of the transient power-angle behavior, the present analysis explicitly incorporates both effects.

Under fault conditions, let the VSG's equivalent active-power reference value be $P_a = P_{ref} - D_p d\delta/dt$. Combining Equations (3) and (5) and substituting them into Equation (1) yields the VSG's active power–frequency control equation, as shown in Equation (6):

$$P_a - \frac{U_g \sin \delta}{4X_g} \left[W(\delta) + \sqrt{W(\delta)^2 + K} \right] = H \frac{d^2 \delta}{dt^2} \quad (6)$$

Equation (6) is evaluated at several voltage-sag levels to obtain the VSG power-angle characteristics and the corresponding $d\delta/dt$ - δ phase-plane trajectories presented in Figure 3. Voltage-sag severity is parameterized by the residual-voltage ratio $k = U_{gF}/U_g$, where U_{gF} is the grid-voltage amplitude during the fault and U_g is its prefault value. The characteristic angles δ_A , $\delta_{A'}$, δ_C , and δ_D identify, in the order listed, the prefault operating point, the unstable equilibrium, the intersection of the P_a and P_e curves, and the stable equilibrium established during the fault.

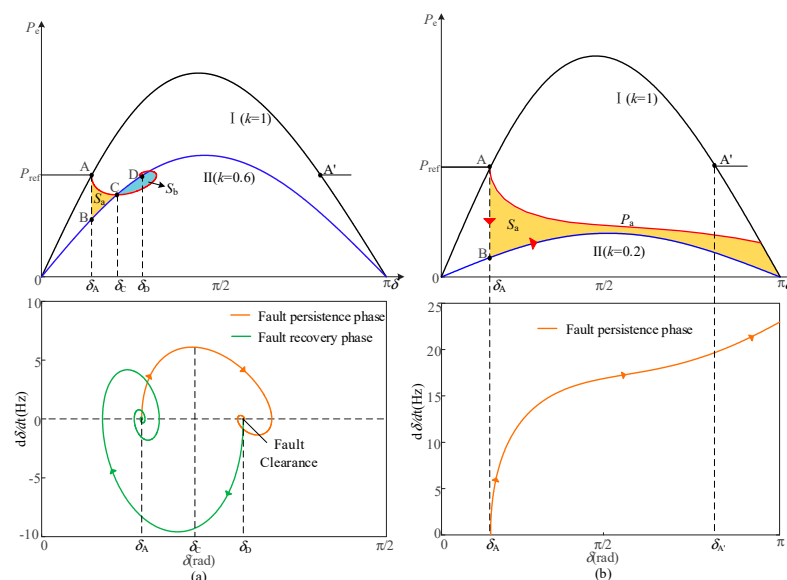


Figure 3. VSG output power-angle curve and $d\delta/dt$ - δ . (a) Stable case at 0.6 p.u.; (b) unstable case at 0.2 p.u.

Figure 3a illustrates the stable transient response when the residual grid voltage is 0.6 p.u. At fault inception, the reduction in power-transfer capability results in $P_e < P_a$, producing positive accelerating power and driving the operating point toward a larger

power angle. As δ increases, P_e rises along the fault-period power-angle curve and intersects P_a at δ_C . Beyond this point, $P_e > P_a$, and the resulting negative accelerating power forms a deceleration region that arrests further angular displacement. Consequently, the fault-on trajectory converges to the stable equilibrium δ_D . After fault clearance, the trajectory returns to the prefault equilibrium δ_A .

Figure 3b illustrates the unstable transient response when the residual grid voltage decreases to 0.2 p.u. The severe voltage depression substantially lowers the fault-period electromagnetic power curve, such that P_e remains below P_a throughout the relevant angular range. Consequently, positive accelerating power persists during the fault, and no effective deceleration region is formed to arrest the angular displacement. The power angle therefore increases continuously and eventually exceeds the unstable equilibrium $\delta_{A'}$, resulting in transient loss of synchronism.

Overall, the fault-on angular dynamics of the VSG are governed by the evolution of the accelerating-power difference. If the decelerating effect is insufficient to dissipate the kinetic energy accumulated during acceleration, the angular trajectory continues toward increasing δ and eventually crosses the stability boundary associated with the unstable equilibrium, leading to loss of synchronism. If the available decelerating area equals or exceeds the accelerating area, the trajectory remains within the attraction region of the fault-period stable equilibrium. The residual kinetic energy is then progressively dissipated by virtual damping, allowing the power angle to converge to δ_D .

2.3. Analysis of Fault Current Characteristics

Grid-voltage depressions may substantially increase the output-current magnitude of a VSG. Under deep voltage sags, the resulting current can violate the converter current rating. The aggregate current magnitude alone, however, cannot distinguish the contributions of individual electrical state variables and system parameters to fault-current amplification. A more detailed characterization is therefore required to identify the dominant factors and determine how each factor governs fault-current evolution.

For a fault-on grid-voltage magnitude of U_{gF} , the corresponding VSG output voltage and current are denoted by U_{VSGF} and I_{VSGF} , respectively. The output-current magnitude can then be expressed as:

$$I_{VSGF} = \frac{\sqrt{U_{gF}^2 + U_{VSGF}^2 - 2U_{gF}U_{VSGF}\cos\delta}}{X_g} \quad (7)$$

Further analysis of Equation (7) shows that the fault current is primarily determined by the grid-voltage magnitude, VSG output-voltage magnitude, power angle, and line impedance.

Figure 4 shows the VSG fault current vector diagram before and after the power grid-voltage sag. Here, δ and δ_1 represent the power angles at different VSG output voltages, respectively; the blue and orange dashed circles represent the current loops corresponding to the rated current and the upper limit of the allowable current, respectively.

Figure 4 illustrates the evolution of the VSG output current following a grid-voltage sag. The resulting active-power imbalance drives the power angle away from its prefault operating value, rotating the VSG voltage phasor from U_{F1} toward U_{F2} . A continued positive excursion of the power angle enlarges the angular separation between the converter and grid voltage phasors and consequently increases the magnitude of the voltage difference across the grid impedance. The VSG output current therefore rises progressively. Once the endpoint of the VSG voltage phasor moves beyond the locus defined by the 1.5 p.u. current threshold, the corresponding current lies outside the permissible operating region.

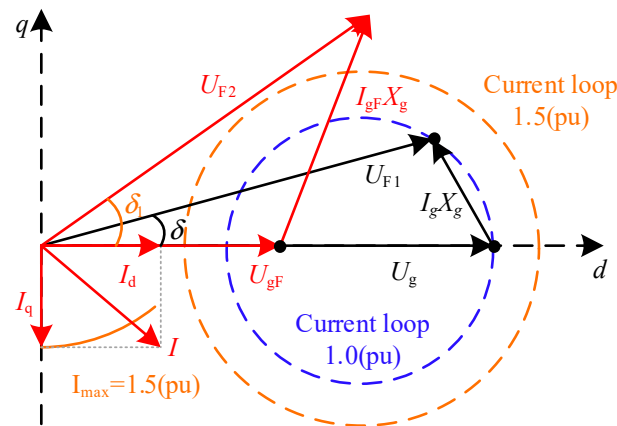


Figure 4. Fault current vector diagram.

Joint evaluation of (5) and (7) yields the three-dimensional current characteristic presented in Figure 5, which maps I_{VSGF} as a function of voltage-sag depth and power angle. The red plane identifies the allowable-current ceiling of 1.5 p.u. The current magnitude rises monotonically with the power angle. Moreover, a deeper voltage sag shifts the intersection with the current ceiling toward a smaller power angle, thereby narrowing the admissible power-angle range before overcurrent occurs. These characteristics indicate that fault-current growth can be restrained through appropriate regulation of the VSG power angle.

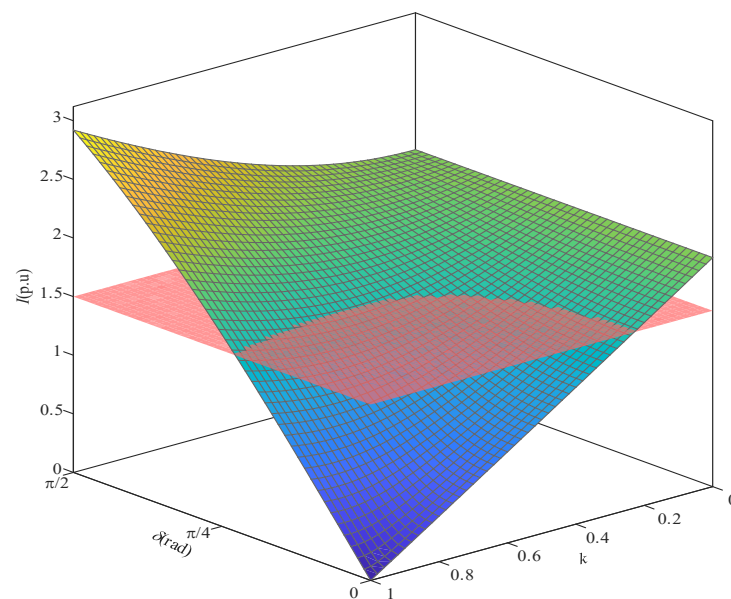


Figure 5. The effect of different fault drop levels and power angles on the output current of VSG.

Overall, the VSG fault-current magnitude is governed by the voltage-phasor difference across the grid impedance. For a fixed line impedance, a reduction in grid-voltage magnitude increases the voltage-magnitude mismatch. If the power angle simultaneously undergoes a sustained positive excursion, the growing angular separation further enlarges the phasor difference and may drive the current beyond its admissible boundary. Overcurrent can therefore be avoided by maintaining the power angle below the critical value associated with the prescribed current ceiling, thereby restricting the voltage-phasor difference to an allowable range.

3. A Control Strategy for Improving the Transient Stability of VSG Based on Active-Power Deviation and Angle-Feedback Compensation

Building on the preceding analysis, an active-power deviation and angle-feedback compensation scheme is formulated to enhance VSG transient stability under severe grid-voltage sags, where conventional VSG control may suffer transient power-angle instability and fault-current limit violations. Its control architecture is depicted in Figure 6. The considered fault condition involves a reduction in grid-voltage magnitude, while the grid frequency remains at its nominal value and no abrupt change occurs in the grid-voltage phase angle. Taking the prefault phase of the grid fundamental voltage as the angular reference, the VSG power angle δ is calculated from its prefault value by integrating the difference between the VSG internal angular frequency and the nominal angular frequency. Consequently, real-time estimation of the grid phase is not required during the fault. In Figure 6, K_w denotes an enabling signal derived from the PCC-voltage magnitude. APDAFC is activated by setting $K_w = 1$ when the voltage falls below 0.80 p.u. Following fault clearance, K_w returns to zero once the voltage recovers above 0.80 p.u., thereby deactivating the compensation and restoring the original VSG control. Reference [31] focuses on the detection, classification, and localization of microgrid faults, whereas the present work addresses VSG transient control after fault identification. Fault detection is therefore assumed to be available, and K_w serves exclusively as the enabling signal for APDAFC. It can be generated using a PCC-voltage criterion without altering the essential APDAFC control architecture.

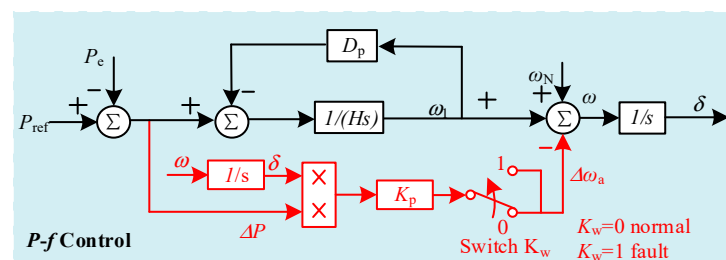


Figure 6. Block diagram of a VSG control strategy based on power deviation and angle-feedback compensation.

The proposed control strategy serves the following primary functions:

- (1) **Transient Power-Angle Stabilization:** Joint feedback of the active-power deviation and power-angle state generates a frequency-compensation signal that dynamically modifies the magnitude and sign of the equivalent accelerating power during the fault. The resulting reconfiguration of the acceleration and deceleration dynamics reverses the sustained positive excursion of the power angle and drives its trajectory toward a stable fault-period equilibrium below the prefault operating angle, thereby maintaining VSG transient synchronism.
- (2) **Steady-State Fault-Current Constraint:** By actively driving the power angle back during the fault, APDAFC narrows the angular separation between the VSG and grid voltage phasors, thereby reducing the steady-state fault-current magnitude and maintaining it within the prescribed safety boundary. This mechanism coordinates transient power-angle stabilization with safe regulation of the steady-state fault current, without relying on explicit current clamping.

3.1. Strategies for Improving Transient Power-Angle Stability in VSG Systems

Based on Figure 6, the equations for the improved VSG control strategy are as follows:

$$\begin{cases} \omega = \omega_1 - \Delta\omega_a + \omega_N \\ \omega_1 = \frac{P_{\text{ref}} - P_e}{Js + D} \\ \Delta\omega_a = K_p(P_{\text{ref}} - P_e)\omega/s \end{cases} \quad (8)$$

where ω_a is the frequency feedback value based on active-power deviation compensation control; K_p is defined as the active-power deviation feedback compensation coefficient; and s is the Laplace operator.

Simplifying and rearranging (8) yields the active-power loop equation incorporating active-power deviation compensation as follows:

$$P_{\text{ref}} - K_p D_p \delta \Delta P - P_e = H \frac{d^2 \delta}{dt^2} + \left[D_p + K_p H \Delta P - K_p H \delta \frac{dP_e}{d\delta} \right] \frac{d\delta}{dt} \quad (9)$$

where ΔP represents the imbalance between the active power input and output during a transient process.

Differentiating P_e in (3) with respect to δ yields:

$$P(\delta) = \frac{dP_e}{d\delta} = \frac{3U_g}{2X_g} \frac{dU}{d\delta} \sin \delta + \frac{3UU_g}{2X_g} \cos \delta \quad (10)$$

Differentiating U in (5) with respect to δ yields:

$$\frac{dU}{d\delta} = -\frac{1}{2} \left[U_g \sin \delta + \frac{W(\delta)U_g \sin \delta}{\sqrt{W^2(\delta) + K}} \right] \quad (11)$$

Further combining and simplifying (9), (10), and (11) yields:

$$P_{\text{ref}} - K_p D_p \delta \Delta P - P_e = H \frac{d^2 \delta}{dt^2} + [D_p + K_p H \Delta P - K_p H \delta P(\delta)] \frac{d\delta}{dt} \quad (12)$$

$$\text{Specifically: } P(\delta) = -\frac{3U_g}{4X_g} \left[U_g \sin \delta + \frac{W(\delta)U_g \sin \delta}{\sqrt{W^2(\delta) + K}} \right] \sin \delta + \frac{3UU_g}{2X_g} \cos \delta$$

Comparison of the corresponding terms in (1) and (12) yields the equivalent damping coefficient D_F and equivalent active-power reference P_{ref_F} of APDAFC as follows:

$$D_F = D_p + K_p H \Delta P - K_p H \delta P(\delta) \quad (13)$$

$$P_{\text{ref}_F} = P_{\text{ref}} - K_p D_p \delta \Delta P - [D_p + K_p H \Delta P - K_p H \delta P(\delta)] \frac{d\delta}{dt} \quad (14)$$

Analysis of (14) and (15) indicates that the proposed control introduces a dynamic compensation term into the active-power loop, jointly determined by the VSG power angle and active-power imbalance. As the VSG transient process evolves, this compensation equivalently adjusts the damping coefficient and active-power reference. These equivalent adjustments limit the fault-induced rate of power-angle variation and thereby improve the transient stability of the VSG.

Figure 7 presents the VSG power-angle characteristics obtained from (12), with the effects of virtual damping and reactive-power-loop dynamics included. Curve I denotes the characteristic under normal operation, whereas Curve II corresponds to the fault condition at $k = 0.2$. The angle δ_A specifies the operating point at fault inception, δ_C identifies the intersection between P_{ref_F} and P_e , and δ_D denotes the stable equilibrium established during the fault. According to the corresponding area definitions, S_a is the accelerating area, while

S_{a1} and S_{b1} denote the reverse-acceleration and reverse-deceleration areas, respectively. The transient power-angle process of the proposed control strategy is summarized in Table 2.

$$\begin{cases} S_a = \int_{\delta_A}^{\delta} (P_{\text{ref_F}} - P_{eF}) d\delta > 0 \\ S_{a1} = \int_{\delta_A}^{\delta_C} (P_{\text{ref_F}} - P_{eF}) d\delta > 0 \\ S_{b1} = \int_{\delta_C}^{\delta_D} (P_{\text{ref_F}} - P_{eF}) d\delta < 0 \end{cases} \quad (15)$$

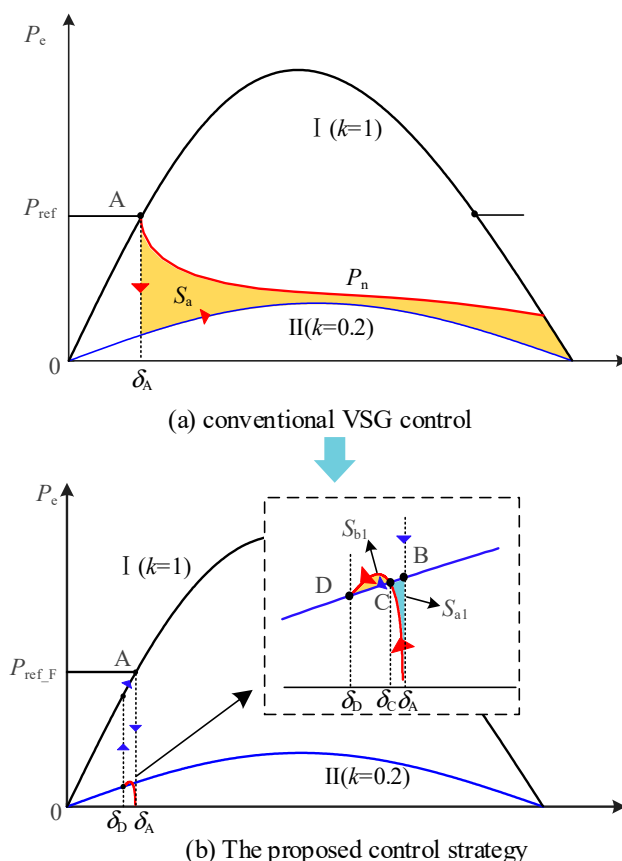


Figure 7. Transient power-angle curves.

Table 2. Transient power-angle process of the roposed control strategy.

Transient Processes	$\Delta\omega$	δ
B $\rightarrow$ C	<0	Reverse acceleration decreases
C $\rightarrow$ D	<0	Reverse acceleration decreases

Figure 7 indicates that a severe grid-voltage sag markedly reduces the electromagnetic active power of the conventional VSG while its active-power reference remains fixed. The resulting positive accelerating power drives a sustained forward excursion of the power angle. With APDAFC, the equivalent active-power reference becomes state-dependent, modifying both the magnitude and sign of the fault-on active-power mismatch. This modification reverses the power-angle trajectory and establishes a stable fault equilibrium at δ_D .

The enlarged view in Figure 7b clarifies the two-stage power-angle return process. During stage B–C, $P_{\text{ref_F}} < P_e$, yielding negative equivalent accelerating power. The operating point therefore moves toward a smaller power angle with an increasing negative angular velocity, and the accumulated area constitutes the reverse-acceleration area S_{a1} . After point C is crossed, the active-power mismatch changes sign. The resulting equivalent

accelerating power then opposes the ongoing negative power-angle motion, giving rise to the reverse-deceleration area S_{b1} . Although the power angle continues to decrease, the magnitude of its rate of change progressively diminishes. As S_{b1} counterbalances S_{a1} , the frequency deviation approaches zero, and the trajectory ultimately settles at point D, which represents the stable fault equilibrium.

Figure 8 compares the VSG phase-plane trajectories under different control strategies for a fault duration of 1 s. Under conventional control, the trajectory remains in the positive-acceleration region throughout the fault. Both the power angle and its rate of change increase continuously, eventually resulting in transient power-angle instability. In contrast, APDAFC dynamically modifies the equivalent active-power reference, causing the rate of change in the power angle to become negative and redirecting the trajectory toward a smaller power angle. The power angle therefore changes from a sustained positive excursion to an active return. As this return continues, the active-power mismatch reverses its sign, and the resulting accelerating effect opposes the ongoing motion toward a lower power angle. Consequently, the power angle continues to decrease, while the magnitude of its rate of change gradually diminishes. The trajectory ultimately converges to the corresponding stable equilibrium.

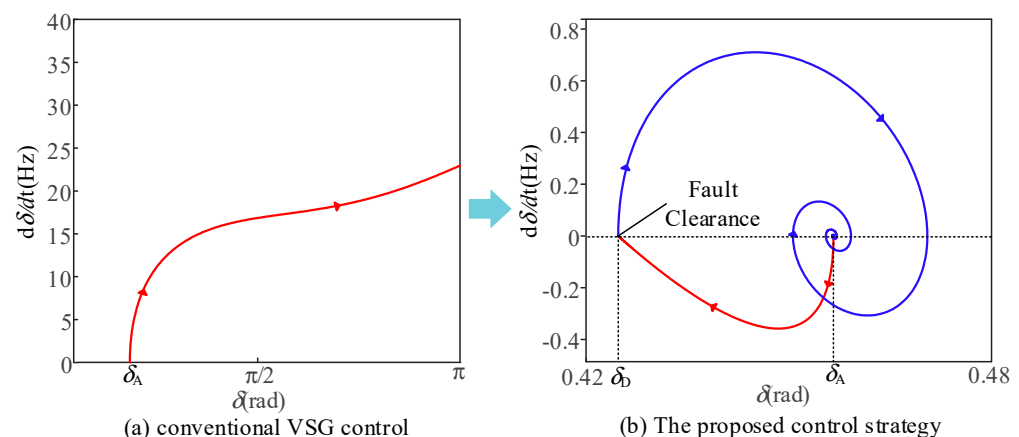


Figure 8. Phase portraits of VSG under different control strategies.

3.2. Fault-Current Limiting

As demonstrated in the previous section, the proposed strategy dynamically regulates the equivalent active-power reference, thereby changing the magnitude and direction of the transient power imbalance during a fault. This drives the VSG power angle back instead of allowing it to continuously advance, and the power angle eventually settles below its initial value. According to the current–power-angle relationship established in Section 2.3, this power-angle return further affects the voltage–vector difference between the VSG and the grid, as well as the fault-current magnitude.

Figure 9 shows the voltage–current vector relationship before and after the proposed control action. In the figure, the black vector represents normal operating conditions, the red vector represents fault conditions, and the blue and orange dashed circles correspond to current amplitudes of 1.0 p.u. and 1.5 p.u., respectively.

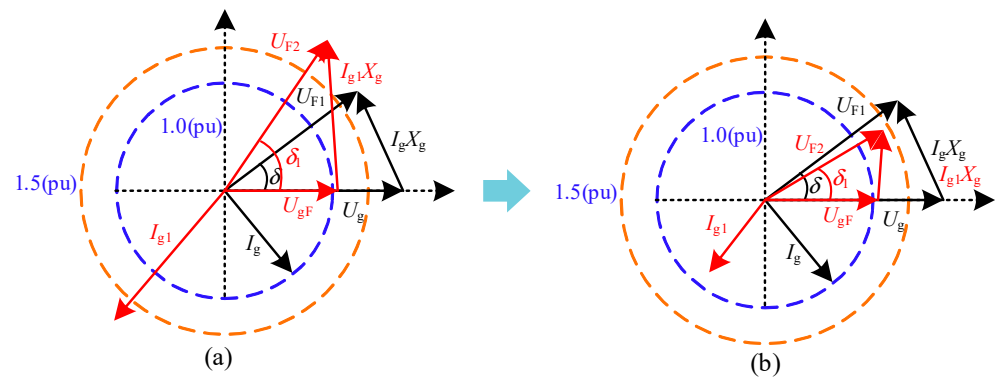


Figure 9. Vector diagrams of fault currents: (a) before applying the proposed control; (b) after applying the proposed control.

Figure 9 illustrates the voltage–current phasor relationships before and after applying APDAFC. Under conventional control, the fault-on VSG voltage phasor rotates toward a larger power angle, causing the endpoint of the current phasor to move beyond the 1.5 p.u. allowable-current boundary. With the fault-on grid voltage held constant, APDAFC drives the VSG voltage phasor back toward a smaller power angle, which ultimately settles below its initial value. According to the reactive-power droop relationship and (7), this power-angle return reduces the separation between the converter and grid voltage phasors and, consequently, the voltage drop across the grid impedance. The fault-current magnitude therefore decreases, and the current-phasor endpoint moves from outside to inside the allowable-current boundary. Accordingly, APDAFC suppresses the fault current primarily by reshaping the voltage-phasor relationship through power-angle regulation, rather than by directly lowering the VSG output-voltage magnitude.

In summary, during the fault period, as the power angle stabilizes at a smaller feedback value, the current increase caused by the continuous power-angle deviation is suppressed, and the output current consequently stabilizes at a lower level. When the fault steady-state current meets the permissible limit, the VSG can maintain a fault operating state that balances power-angle stability and current safety.

4. Simulation Verification

A grid-connected VSG simulation model corresponding to Figure 1 was implemented in MATLAB2024b/Simulink to assess the analytical findings and the effectiveness of the proposed control strategy. The model parameters are listed in Table 3. The proposed strategy is primarily developed to address transient power-angle instability and fault-current violations of VSGs during grid-voltage sags under weak and very weak grid conditions.

Table 3. Simulation parameters.

Symbol	$\Delta\omega$	δ
U_{dc}	DC-Side Voltage	800 V
U_g	Power Grid Voltage	380 V
P_{ref}	Rated Active Power	50 kW
C_f	Filter Capacitor	50 μ F
L_f	Filter Inductor	3 mH
L_g	Line Inductance	4 mH
H	Moment of Inertia	94.2 kg/m ²
D_p	Damping Coefficient	1570 (N·m·s)/rad
k_q	Reactive-Power Droop Coefficient	2000 Var/V
K_p	Proportional Compensation Coefficient	0.0015 W/s

Figure 10 compares the system responses when the grid voltage is reduced to 0.5 p.u. for 1 s. Under conventional VSG control, the power angle drifts continuously during the fault, accompanied by sustained oscillations in power and current, indicating loss of synchronism. With the combined active-power-reference adjustment and fault-current-limiting method, the system reaches a fault-period equilibrium at approximately 0.495 rad, which remains above the prefault value of 0.455 rad. The current peaks at fault inception, during the fault steady state, and at fault clearance are approximately 1.68, 1.18, and 1.60 p.u., respectively. In contrast, APDAFC reduces the stable fault-period power angle to approximately 0.42 rad, representing a decrease of 0.035 rad from its prefault value. The steady-state current peak during the fault is further reduced to approximately 1.15 p.u. The transient current peaks at fault inception and clearance are approximately 1.68 and 2.30 p.u., respectively. Following fault clearance, all state variables progressively return to their normal operating values within approximately 0.5 s. Therefore, under this operating condition, both control methods preserve transient synchronism and maintain the steady-state fault current within the prescribed limit.

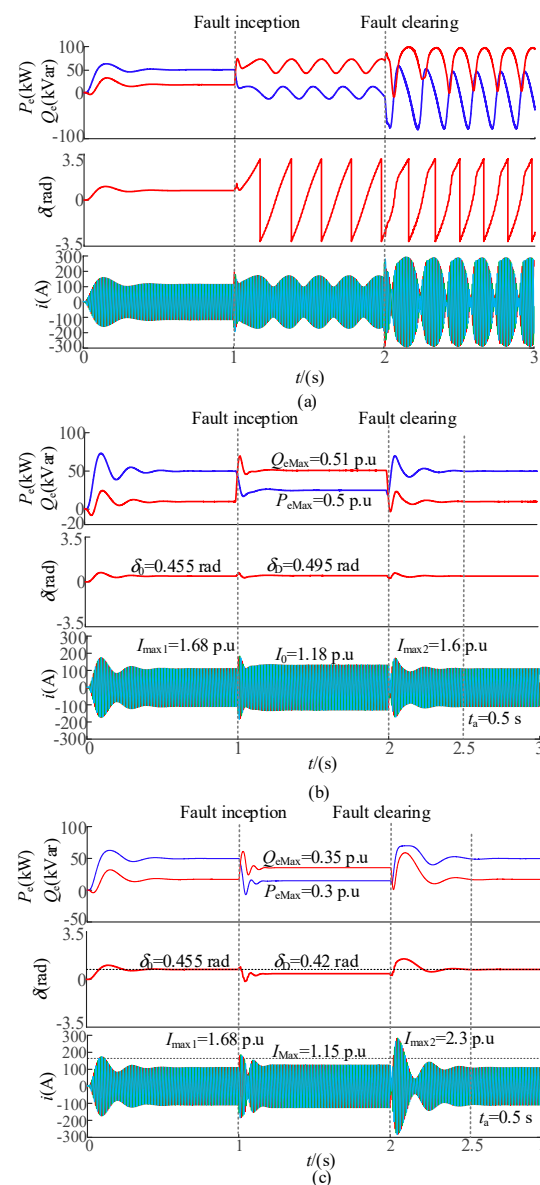


Figure 10. Simulation results under $U_g = 0.5$ p.u. (a) Traditional VSG. (b) Active-power-reference adjustment based on [18]. (c) The proposed strategy.

Figure 11 presents the comparative responses when the grid voltage is reduced to 0.2 p.u. As shown in Figure 11a, the conventional VSG loses synchronism and exhibits sustained oscillations in power and current. In Figure 11b, the transient-stability method combining active-power-reference adjustment with fault-current limiting establishes a stable fault-period power angle of approximately 0.56 rad and restricts the steady-state fault current to 1.50 p.u. Nevertheless, the transient current peaks at fault inception and clearance still reach approximately 2.05 and 1.90 p.u., respectively. Moreover, activation of the current-limiting function alters the inherent voltage-source terminal characteristics of the converter. By contrast, APDAFC in Figure 11c reduces the stable fault-period power angle to approximately 0.43 rad without introducing fault-current limiting, while the steady-state fault-current peak remains at approximately 1.50 p.u. The transient current peaks at fault inception and clearance are approximately 2.10 and 2.65 p.u., respectively. Following fault clearance, the power angle, power, and output current under APDAFC return smoothly to their normal operating values, without sustained oscillations or secondary loss of synchronism. These results demonstrate that APDAFC effectively coordinates transient power-angle stabilization and steady-state fault-current limitation under severe voltage sags.

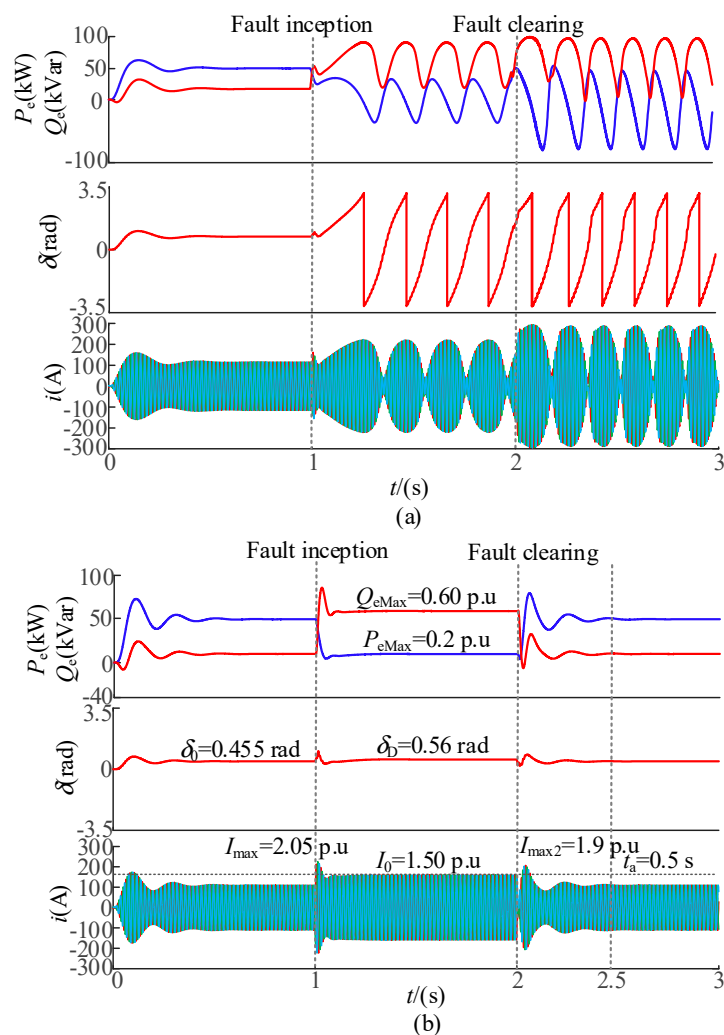


Figure 11. Cont.

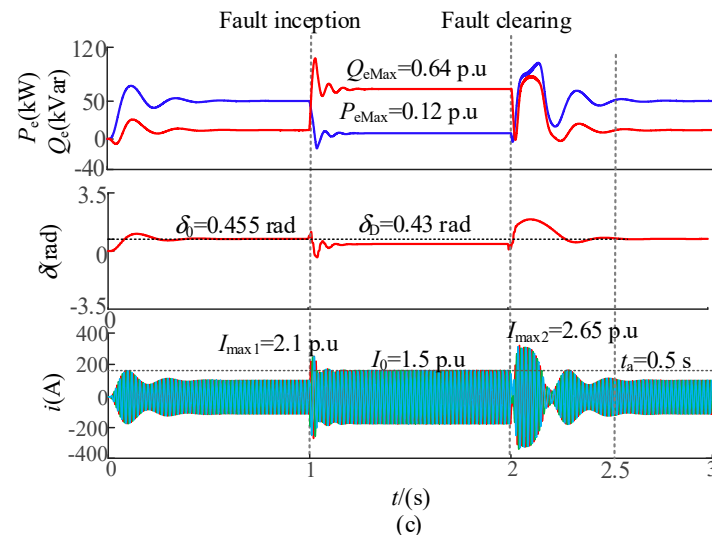


Figure 11. Simulation results under $U_g = 0.2$ p.u. (a) Traditional VSG. (b) Active-power-reference adjustment based on [18]. (c) The proposed strategy.

5. Hardware-in-the-Loop Validation

The implementation feasibility of APDAFC was evaluated using the hardware-in-the-loop platform shown in Figure 12. The grid-connected VSG power circuit and grid model depicted in Figure 1 were executed in real time on an OPAL-RT OP5607 simulator, whereas the APDAFC algorithm was implemented on a TMS320F28335 DSP control board. The sampled voltage and current signals were transmitted from the real-time simulator to the DSP through analog interfaces. The PWM signals generated by the DSP were then returned to the real-time model through digital interfaces, thereby forming a closed-loop system. Both the DSP sampling frequency and PWM switching frequency were set to 5 kHz, corresponding to a control period of 200 μ s. The system parameters and operating settings used for the hardware-in-the-loop tests were consistent with those adopted in the simulations.

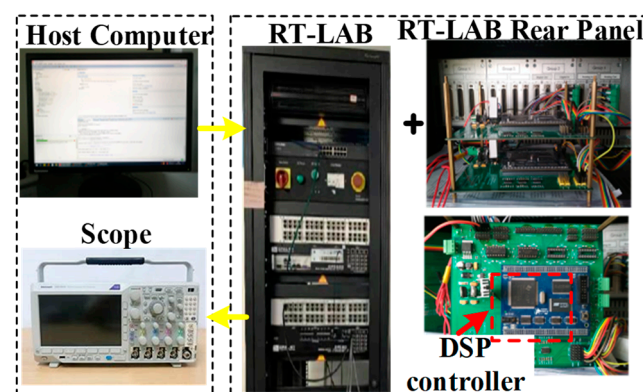


Figure 12. Hardware-in-the-loop simulation experimental platform.

Figure 13 presents the hardware-in-the-loop comparison results for a grid-voltage sag to 0.5 p.u. During the fault, the conventional VSG loses power-angle synchronism and exhibits sustained power and current oscillations. With the combined active-power-reference adjustment and fault-current-limiting method in [18], the power angle settles at approximately 0.495 rad, and the steady-state fault-current magnitude is approximately 131 A. In contrast, APDAFC drives the power angle back and stabilizes it at approximately 0.42 rad without hard fault-current limiting. The steady-state fault-current magnitude is

further reduced to approximately 127 A. After fault clearance, the system smoothly returns to normal operation.

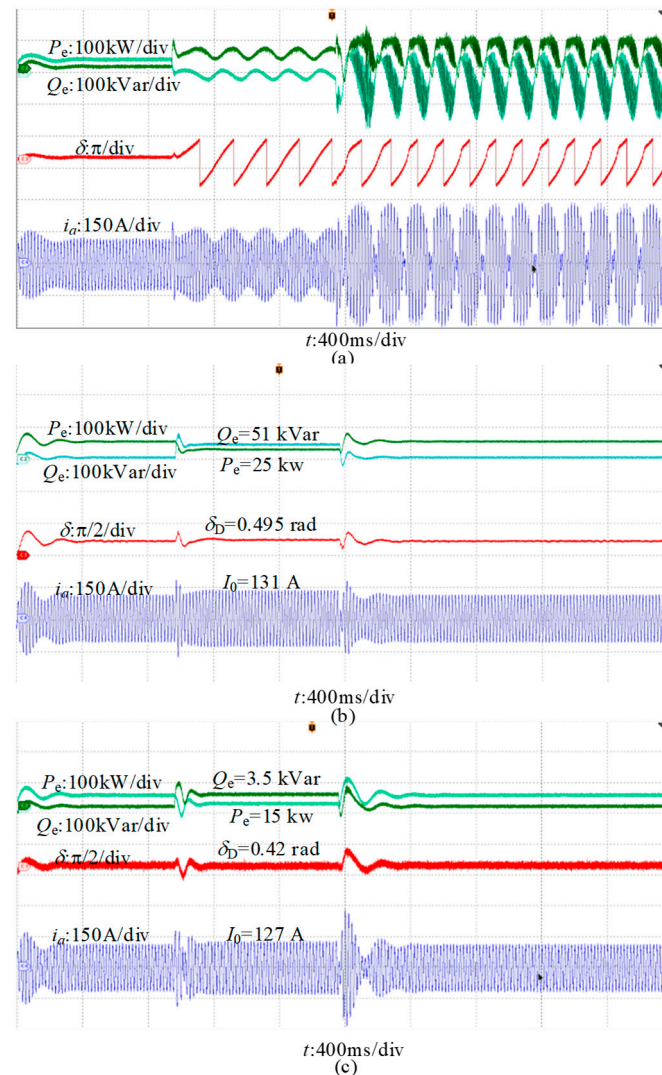


Figure 13. Experimental waveform for $U_g = 0.5$ p.u. (a) Traditional VSG. (b) Active-power-reference adjustment based on [18]. (c) The proposed strategy.

Figure 14 further presents the hardware-in-the-loop results for a grid-voltage sag to 0.2 p.u. As the voltage sag deepens, the conventional VSG exhibits more pronounced loss of power-angle synchronism and current oscillations. The method in [18], which combines active-power-reference adjustment with fault-current limiting, stabilizes the power angle at approximately 0.56 rad and limits the steady-state fault current to approximately 165 A. However, activation of the current-limiting loop changes the original voltage-source output characteristics of the converter. In contrast, APDAFC stabilizes the power angle at approximately 0.43 rad and maintains the steady-state fault current at approximately 165 A without hard fault-current limiting. After fault clearance, all state variables recover smoothly. The hardware-in-the-loop and simulation results exhibit consistent trends, confirming the coordinated control of the fault-period power angle and steady-state fault current achieved by the proposed strategy.

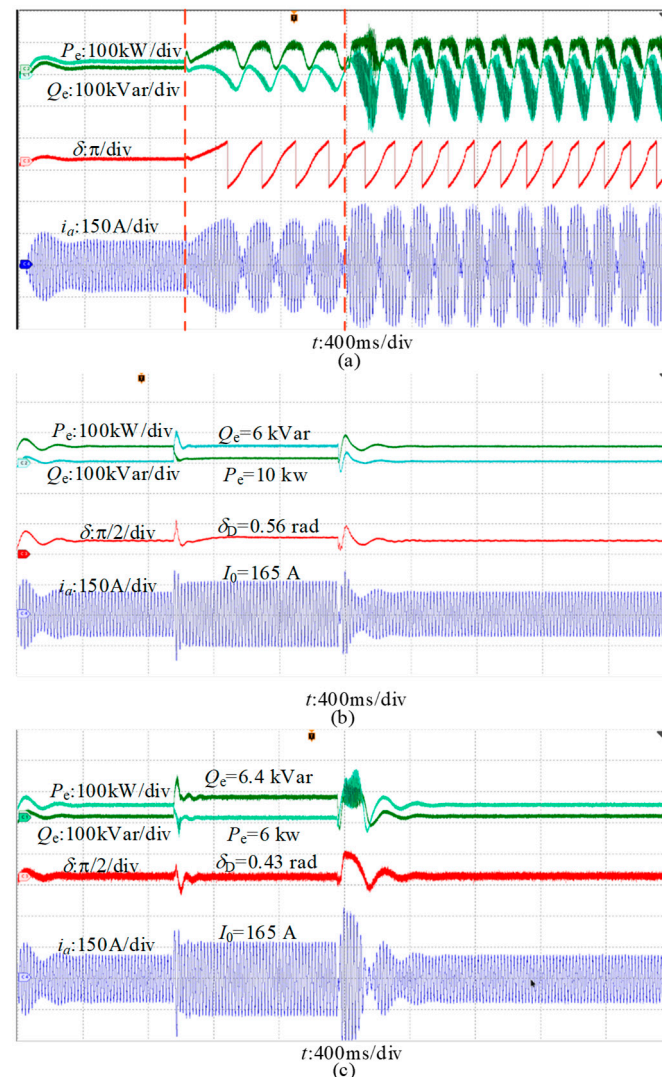


Figure 14. Experimental waveform for $U_g = 0.2$ p.u. (a) Traditional VSG. (b) Active-power-reference adjustment based on [18]. (c) The proposed strategy.

6. Conclusions

To address transient angle instability and steady-state fault overcurrent violations in virtual synchronous generators (VSGs) under severe voltage sags, this paper proposes a transient stability enhancement strategy based on active-power deviation and power-angle-feedback compensation. By dynamically adjusting the equivalent active-power reference, this strategy induces reverse acceleration and deceleration dynamics during grid faults, which drives the power angle to shift from a persistent forward deviation to a backward return and settle below its initial value. Such power-angle retreat further shrinks the vector difference between the VSG output voltage and the grid voltage. Consequently, without sacrificing the intrinsic voltage-source characteristics of the VSG, steady-state fault-current suppression is accomplished via active-power loop regulation, achieving a synergistic improvement in both transient angle stability and fault current behavior.

Author Contributions: The conceptualization and methodology were proposed by Z.L. and X.G.; the investigation was carried out by Z.L., X.G. and Z.P.; the data curation was performed by Z.P.; the formal analysis was conducted by Z.L., F.X. and J.L.; the validation was performed by F.X. and J.L.; the original draft was written by X.G. and Y.L.; the manuscript was reviewed and edited by J.L. and

Y.L.; and the supervision was provided by J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number [52577193]; the Natural Science Foundation of Hunan Province, grant number [2025JJ50232]; and the Key Scientific Research Project of the Hunan Provincial Department of Education, grant number [24A040].

Data Availability Statement: Data are contained within the article. The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The funding support for our work is greatly appreciated.

Conflicts of Interest: Authors Lan Zheng, Guo Xin, Luo Jiawei, and Lei Yuncheng were affiliated with the Hunan University of Science and Technology. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this research was funded by the National Natural Science Foundation of China, grant number [52577193]; the Natural Science Foundation of Hunan Province, grant number [2025JJ50232]; and the Key Scientific Research Project of the Hunan Provincial Department of Education, grant number [24A040]. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

References

1. Peng, Z.; Xiao, F.; Tu, C.; Wang, L.; Yuan, Y.; Tang, Y.; Guo, X. Optimal Control Strategy for LVRT and Quasi-Synchronous Droop-Controlled Inverter Considering Voltage Drop on the Distribution. *Prot. Control Mod. Power Syst.* **2026**, *11*, 144–158. [\[CrossRef\]](#)
2. Zarif Mansour, M.; Me, S.P.; Hadavi, S.; Badrzadeh, B.; Karimi, A.; Bahrani, B. Nonlinear Transient Stability Analysis of Phased-Locked Loop-Based Grid-Following Voltage-Source Converters Using Lyapunov's Direct Method. *IEEE J. Emerg. Sel. Top. Power Electron.* **2022**, *10*, 2699–2709. [\[CrossRef\]](#)
3. Wang, X.; Chen, X.F.; Ding, L.; Tse, C.K.; Hui, S.Y.R. Constant Output Voltage Three-Phase Capacitive-Power-Transfer Converters With Phase Expansion and Design Methods. *IEEE Trans. Power Electron.* **2026**, *41*, 12331–12343. [\[CrossRef\]](#)
4. Chen, Z.; Wang, X.; Guo, Q.; Tu, C.; Xiao, F.; Li, J. Flexible Reconfiguration Strategy for Novel Advanced Traction Power Supply Equipment Under Fault Conditions. *IEEE Trans. Transp. Electr.* **2026**, *12*, 5893–5902. [\[CrossRef\]](#)
5. Rokrok, E.; Qoria, T.; Bruyere, A.; Francois, B.; Guillaud, X. Transient Stability Assessment and Enhancement of Grid-Forming Converters Embedding Current Reference Saturation as Current Limiting Strategy. *IEEE Trans. Power Syst.* **2022**, *37*, 1519–1531. [\[CrossRef\]](#)
6. Zhang, Y.; Zhang, C.; Yang, R.; Molinas, M.; Cai, X. Current-Constrained Power-Angle Characterization Method for Transient Stability Analysis of Grid-Forming Voltage Source Converters. *IEEE Trans. Energy Convers.* **2023**, *38*, 1338–1349. [\[CrossRef\]](#)
7. Wang, G.; Fu, L.; Hu, Q.; Liu, C.; Ma, Y. Transient Synchronization Stability of Grid-Forming Converter During Grid Fault Considering Transient Switched Operation Mode. *IEEE Trans. Sustain. Energy* **2023**, *14*, 1504–1515. [\[CrossRef\]](#)
8. Chen, S.; Sun, Y.; Hou, X.; Han, H.; Fu, S.; Su, M. Quantitative Parameters Design of VSG Oriented to Transient Synchronization Stability. *IEEE Trans. Power Syst.* **2023**, *38*, 4978–4981. [\[CrossRef\]](#)
9. Ge, P.; Yang, M.; Xu, H.; Liu, N.; Mao, R. Voltage Deviation Feedforward Adaptive Design for VSG Oriented to Transient Stability Boundary Optimization. *IEEE Trans. Consum. Electron.* **2026**, *72*, 2973–2982. [\[CrossRef\]](#)
10. Liao, Q.; Huang, Z.; Chen, X.; Wen, J.; Chen, Y. Transient Stability Analysis of Parallel Grid-Following and Grid-Forming Inverters With the Current Limiting Mode. *IEEE Trans. Ind. Electron.* **2026**, *73*, 10071–10083. [\[CrossRef\]](#)
11. Ma, T.; Du, X.; Du, C. Transient stability control method for reducing power angle/frequency fluctuations in grid-forming converters during fault ride-through. *Int. J. Electr. Power Energy Syst.* **2026**, *176*, 111722. [\[CrossRef\]](#)
12. Sun, J.; Xing, X.; Zhang, R.; Zhang, C. An Enhanced Transient Angle Stability Scheme of VSG Based on the PCH Theory. *IEEE Trans. Ind. Electron.* **2025**, *72*, 3861–3871. [\[CrossRef\]](#)
13. Sun, Z.; He, Z.; Liu, N.; Zhang, R.; Wang, B.; Cai, G. Enhanced Transient Stability Strategy for Grid-Forming Converter Based on Current Limiting. *CSEE J. Power Energy Syst.* **2025**, *11*, 960–971. [\[CrossRef\]](#)
14. Sun, K.; Yao, W.; Wen, J.; Jiang, L. A Two-Stage Simultaneous Control Scheme for the Transient Angle Stability of VSG Considering Current Limitation and Voltage Support. *IEEE Trans. Power Syst.* **2022**, *37*, 2137–2150. [\[CrossRef\]](#)

15. Si, W.; Fang, J. Transient Stability Improvement of Grid-Forming Converters Through Voltage Amplitude Regulation and Reactive Power Injection. *IEEE Trans. Power Electron.* **2023**, *38*, 12116–12125. [[CrossRef](#)]
16. Koiwa, K.; Inoo, K.; Zama, T.; Liu, K.-Z. Virtual Voltage Control of VSG for Overcurrent Suppression Under Symmetrical and Asymmetrical Voltage Dips. *IEEE Trans. Ind. Electron.* **2022**, *69*, 11177–11186. [[CrossRef](#)]
17. Zhang, Y.; Zhang, C.; Molinas, M.; Cai, X. Control of Virtual Synchronous Generator With Improved Transient Angle Stability Under Symmetric and Asymmetric Short Circuit Fault. *IEEE Trans. Energy Convers.* **2024**, *39*, 2184–2201. [[CrossRef](#)]
18. Ge, P.; Xiao, F.; Tu, C.; Guo, Q.; Gao, J.; Song, Y. Comprehensive transient stability enhancement control of a VSG considering power angle stability and fault current limitation. *CSEE J. Power Energy Syst.* **2025**, *11*, 173–183. [[CrossRef](#)]
19. Long, B.; Hu, C.; Chen, Z.; Hu, J.; Rodríguez, J. Transient Stability Analysis and Virtual Power Compensation of a Virtual Synchronous Generator Under Low-Voltage Fault. *IEEE Trans. Power Electron.* **2024**, *39*, 12803–12814. [[CrossRef](#)]
20. Chen, J.; Gong, Q.; Zhang, Y.; Fawad, M.; Wang, S.; Li, C.; Liang, J. Comprehensive Assessment of Transient Stability for Grid-Forming Converters Considering Current Limitations, Inertia and Damping Effects. *CSEE J. Power Energy Syst.* **2025**, *11*, 1–12. [[CrossRef](#)]
21. Huang, S.; Yao, J.; He, W.; Yang, D.; Xie, H. Transient Stability Analysis and Control Strategy for Paralleled Grid-Forming Renewable Power Generations Under Symmetric Faults. *Prot. Control Mod. Power Syst.* **2025**, *10*, 165–180. [[CrossRef](#)]
22. Ge, P.; Tu, C.; Xiao, F.; Guo, Q.; Gao, J. Design-Oriented Analysis and Transient Stability Enhancement Control for a Virtual Synchronous Generator. *IEEE Trans. Ind. Electron.* **2023**, *70*, 2675–2684. [[CrossRef](#)]
23. Chen, M.; Zhou, D.; Blaabjerg, F. Enhanced Transient Angle Stability Control of Grid-Forming Converter Based on Virtual Synchronous Generator. *IEEE Trans. Ind. Electron.* **2022**, *69*, 9133–9144. [[CrossRef](#)]
24. Zhu, G.; Chen, M.; Jiang, F.; Wang, P.; Liang, Z.; Zhang, Y.; Hua, K.; Li, Z. D-Axis Current-Based Droop Control of Grid-Forming Converters for Improving Low-Voltage Ride-Through Performance. *IEEE Trans. Power Electron.* **2026**, *41*, 9755–9773. [[CrossRef](#)]
25. Jiang, S.; Zhu, Y.; Xu, T.; Konstantinou, G. Current-Synchronization Control of Grid-Forming Converters for Fault Current Limiting and Enhanced Synchronization Stability. *IEEE Trans. Power Electron.* **2024**, *39*, 5271–5285. [[CrossRef](#)]
26. Sun, H.; Lin, X.; Wei, J. Transient Synchronization Stability and Enhanced-LVRT Scheme for Grid-Forming Converters Considering Current Limitation and Nonlinear Damping Simultaneously. *IEEE Trans. Energy Convers.* **2025**, *40*, 2466–2484. [[CrossRef](#)]
27. Baekeland, N.; Yang, B.; Seo, G.-S. Transient Stability-Enhancing Method for Grid-Forming Inverters Under Current Limiting. *IEEE Trans. Power Electron.* **2025**, *40*, 6714–6725. [[CrossRef](#)]
28. Me, S.P.; Ravanji, M.H.; Leonardi, B.; Ramasubramanian, D.; Ma, J.; Zabihi, S.; Bahrani, B. Transient Stability Analysis of Virtual Synchronous Generator Equipped With Quadrature-Prioritized Current Limiter. *IEEE Trans. Power Electron.* **2023**, *38*, 10547–10553. [[CrossRef](#)]
29. Sun, P.; Tian, Z.; Huang, M.; Zha, X.; Li, X.; Wang, W. Additional Kinetic Energy Injection and Piecewise Damping Based Postfault Antiwindup and Transient Stability Enhanced Control for Grid-Forming Inverter. *IEEE Trans. Power Electron.* **2024**, *39*, 8007–8023. [[CrossRef](#)]
30. Fan, B.; Wang, X. Fault Recovery Analysis of Grid-Forming Inverters With Priority-Based Current Limiters. *IEEE Trans. Power Syst.* **2023**, *38*, 5102–5112. [[CrossRef](#)]
31. Arevalo, P.; Cano, A.; Fedoseienko, O. A Data-Driven Approach to Microgrid Fault Detection and Classification Using Taguchi-Optimized CNNs and Wavelet Transform. *Appl. Soft Comput.* **2025**, *170*, 112667. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.