

Article

Improved Adaptive Control Method of Virtual Synchronous Generator for Enhancing Transient Rotor Angle Stability of New Power Systems

Yuan-Da Hao ¹, Li-Zi Zhang ¹, Yin Wang ¹, Ze-Kai Li ¹, Yu-Tao Hao ¹, An-Jia Mao ^{1,*}, Zhong-Kuan Han ², Zhi Chen ² and Xu-Dong Zhang ³

¹ School of Electrical and Electronic Engineering, North China Electric Power University, Beijing 102206, China; hyd7729@163.com (Y.-D.H.)

² State Grid Fujian Electric Power Company, Fuzhou 350000, China

³ State Grid Corporation of China, Beijing 100000, China

* Correspondence: angel_maoyang@163.com

Abstract

With the increasing integration of large-scale renewable energy sources (RESs), modern power grids are evolving into low-inertia and weak-damping networks, creating challenges for transient power-angle stability. Conventional grid-following (GFL) control strategies present a lagging synchronization response under weak grid conditions due to their reliance on phase-locked loops (PLLs). Although grid-forming (GFM) control via virtual synchronous generators (VSGs) provides standalone voltage source properties, conventional fixed-parameter VSGs exhibit an inherent design trade-off between first-swing angular suppression and post-fault oscillation damping during severe short-circuit disturbances. To resolve these vulnerabilities, this paper proposes an adaptive VSG control strategy designed to improve the transient power-angle response of the investigated system. By establishing a parametric judgment framework based on real-time frequency deviations and acceleration rates, the virtual inertia $J(t)$ and damping coefficient $D(t)$ are adaptively adjusted within predefined limits. Furthermore, a current-limiting mechanism is incorporated into the parameter adaptation loops to prevent converter overcurrent tripping. To evaluate the proposed method, an aggregated grid-connected benchmark system comprising a 5 MVA PMSG-based wind farm, a conventional synchronous generator, and an external grid is implemented in MATLAB/Simulink. The simulation results under continuous ambient operational fluctuations and severe three-phase short-circuit faults demonstrate that the proposed strategy reduces the first-swing power-angle peak by approximately 31% compared with the conventional fixed-parameter VSG, and the response settles within approximately 0.4 s in the investigated fault case. These results indicate the simulation-based feasibility of the proposed bounded adaptive strategy. Further real-time, hardware-in-the-loop, and experimental validation is required before practical implementation.

Keywords: high-penetration renewable power systems; permanent magnet synchronous generator (PMSG); grid-forming (GFM) control; virtual synchronous generator (VSG); transient angular stability; enhanced adaptive control

Academic Editor: David Schoenwald

Received: 24 June 2026

Revised: 22 July 2026

Accepted: 25 July 2026

Published: 31 July 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

Driven by the dual carbon goals and ongoing energy transition, the installed capacity of new energy sources has grown rapidly. The power system is accelerating its evolution from a traditional model dominated by synchronous generators to a new power electronics-dominated structure centered on converter-based grid interface [1]. Over the past decade, the share of renewable energy sources such as wind and solar power has steadily increased [2]. By the end of 2025, China's total installed capacity of wind and photovoltaic power exceeded 184 million kW, accounting for 47.3% of the country's total installed capacity—surpassing thermal power for the first time [3]. Against this backdrop, the conventional power grid, historically characterized by high inertia and strong support provided by synchronous generators, is rapidly transforming into a “dual-high” new power system featuring high proportions of both renewable generation and power electronic equipment [4,5]. This transformation significantly weakens inertia and damping support, reduces voltage and frequency stability, and results in fundamentally different dynamic recovery characteristics after disturbances compared to traditional power systems [6]. In recent years, large-scale blackouts triggered by instability or disconnection of renewable units have occurred in regions such as Australia and the UK, highlighting that transient stability has become a critical challenge affecting the safe operation of modern power systems under conditions of high penetration of power electronics [7].

The growing penetration of converter-interfaced renewable generation has reshaped the dynamic behavior of modern power systems [8]. As conventional synchronous generators (SGs) are gradually retired, the rotational inertia and damping available in the grid decrease accordingly. This weakens the frequency-regulation capability of the system and increases its sensitivity to power imbalances and other disturbances [9,10]. Conventional SGs can resist frequency variations by releasing or absorbing stored kinetic energy. In contrast, inverter-based resources are electrically decoupled from grid frequency and therefore do not provide inherent inertial support [11]. Frequency stability has consequently become a major concern in low-inertia power systems.

Virtual synchronous generator (VSG) control has been widely studied to compensate for the shortage of physical inertia in converter-dominated power systems. By reproducing the electromechanical transient response of synchronous generators (SGs), a VSG enables a static inverter to exhibit inertia and damping characteristics. Previous investigations have covered several aspects of this control concept, including grid-synchronization performance [12], swing-equation-based controller implementation [13,14], and basic equivalent structures [15]. Researchers have also examined small-signal stability and oscillatory behavior to determine how virtual parameters influence system dynamics [16,17]. To improve frequency regulation under different operating conditions, various adaptive approaches have been developed, including inertia-switching techniques and adaptive schemes combined with energy-storage systems [18–21]. Nevertheless, most existing adaptive VSG strategies either regulate only one parameter, namely inertia or damping, or operate with fixed parameter settings. Consequently, the joint influence of virtual inertia and damping on transient power and frequency responses has not been adequately examined [22–24]. While promising progress has been made, existing adaptive VSG schemes still face critical technical limitations under severe grid disturbances. On one hand, single-parameter adaptation schemes (such as the virtual inertia tuning in [13]) cannot resolve the inherent “performance seesaw” trade-off between suppressing the initial transient power-angle peak and damping out post-fault oscillations. On the other hand, although joint adaptation methods for both inertia and damping have been investigated in [9,20,23,24], they are mostly tailored for small-signal frequency regulation or power sharing in microgrids under ambient variations. More importantly, these methods typically assume an ideal converter current margin and ignore the physical constraints of the

peak current limiter. Under severe large-signal faults, ignoring the hardware current saturation can trigger severe synchronization instability or equipment overcurrent tripping during parameter transitions. Although inertia and damping are closely related, they affect different stages of a transient oscillation in different ways. Adjusting either parameter alone may therefore improve response speed at the expense of oscillation attenuation, or vice versa. This limitation motivates a coordinated control scheme in which both parameters are adjusted together according to the operating conditions. Developing such a dual-parameter adaptive scheme involves several issues. First, the contribution of inertia and damping at each stage of a transient power oscillation must be clearly identified. Second, the two adaptation laws should be coordinated so that their actions do not interfere with each other or reduce overall system stability. In addition, an appropriate stability-analysis procedure and practical tuning rules are required to support simultaneous parameter adjustment. These issues have not yet been fully resolved in existing VSG studies.

This paper proposes a coordinated adaptive control strategy for the inertia and damping coefficient of virtual synchronous generators. When the rate of change in the rotor angular velocity is large, the inertia is increased; when the angular velocity deviation is significant, the damping coefficient is increased. By coordinating these two parameters, the strategy effectively suppresses rapid frequency fluctuations and excessive deviations, ensuring system stability. MATLAB/SimulinkR2024b simulations analyze the impact of the adjustment coefficients on system performance and validate the feasibility of the coordinated adaptive control strategy, which can effectively shorten the transient process and maintain system stability.

2. The Basic Principle of the Virtual Synchronous Generator

Figure 1 shows the schematic diagram of the virtual synchronous generator. The hardware topology of the virtual synchronous generator is the same as that of the typical grid-connected inverter. Considering the mechanical and electromagnetic equations of the synchronous generator, the grid-connected inverter can be simulated as a traditional synchronous generator through control methods.

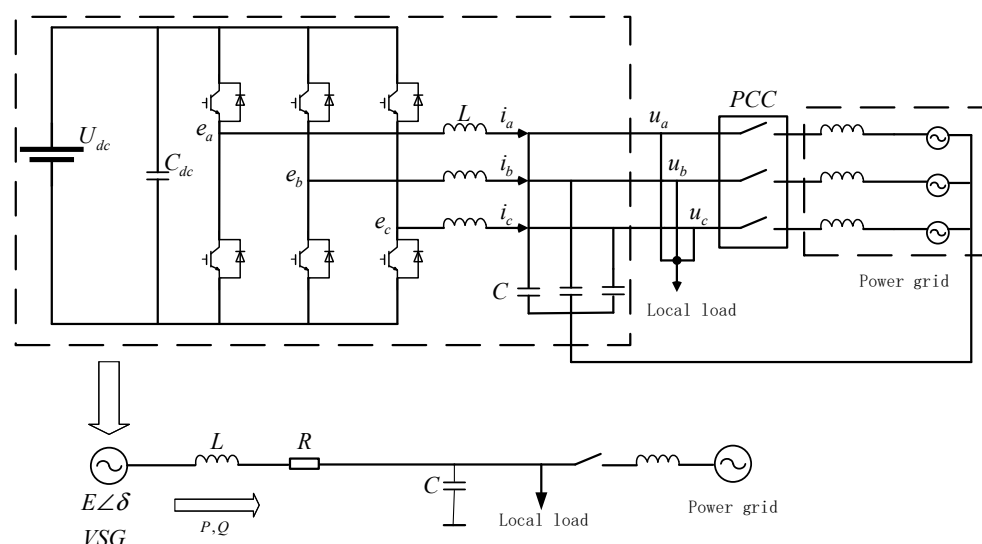


Figure 1. Structure of the Virtual Synchronous Generator.

According to the two-order model of the traditional synchronous generator, the rotor motion equation of the equivalent virtual synchronous generator is shown in Equation (1). To facilitate the analysis, it is assumed that the pole pairs of the synchronous generator

are 1. Then, the mechanical angular velocity of the synchronous generator ω and the electrical angular velocities are the same.

$$\begin{cases} J \frac{d\omega}{dt} = T_m - T_e - T_D = T_m - T_e - D(\omega - \omega_0) \\ \frac{d\delta}{dt} = \omega \end{cases} \quad (1)$$

where J is the moment of inertia of the synchronous generator, in kgm^2 ; D is the damping coefficient of the synchronous generator corresponding to the damping torque, in Nm/s/rad ; ω_0 is the grid synchronous angular velocity, which is also the rated angular velocity of the synchronous generator, in rad/s ; T_m , T_e and T_D are the mechanical torque, electromagnetic torque and damping torque of the synchronous generator respectively, in Nm ; and δ is the power angle of the synchronous generator. The relationship between the electromagnetic torque and the electromagnetic power P_e output by the virtual synchronous generator is shown in Equation (2):

$$T_e = \frac{P_e}{\omega} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \quad (2)$$

where e_{abc} and i_{abc} are the output electromotive force (EMF) and output current of the virtual synchronous generator (VSG) respectively, with units of volts (V) and amperes (A) respectively.

A synchronous generator regulates the active-power output by controlling the mechanical torque of its prime mover. On this basis, it responds to grid frequency deviations through a governor, thereby maintaining the frequency stability of the system. Drawing on this principle, in a virtual synchronous generator (VSG), the regulation of the active-power command of the VSG is achieved by adjusting the reference mechanical torque T_{ref} and the frequency deviation feedback command ΔT . Thus, the virtual mechanical torque T_m is composed of T_{ref} and ΔT :

$$T_m = T_{ref} + \Delta T \quad (3)$$

$$T_{ref} = \frac{P_{ref}}{\omega} \quad (4)$$

$$\Delta T = -K_\omega (\omega - \omega_0) \quad (5)$$

where P_{ref} is the reference active power, in watts W , and K_ω is the droop coefficient.

The frequency deviation feedback actually simulates the function of the Automatic Frequency Regulator (AFR). Taking the AFR as a proportional link, the mechanical power deviation command shown in Equation (5) is obtained. By combining Equations (1)–(5) and performing corresponding transformations, we can obtain

$$\frac{\Delta \omega}{\Delta P} = \frac{\omega_0 - \omega}{P_{ref} - P} = -\frac{1}{J\omega_0 s + D\omega_0 + K_\omega} = -\frac{K_p}{1 + \tau s} \quad (6)$$

$$\begin{cases} K_p = \frac{1}{D\omega_0 + K_\omega} \\ \tau = \frac{J\omega_0}{D\omega_0 + K_\omega} \end{cases} \quad (7)$$

where P is the active-power output by the virtual synchronous generator (VSG), in watts W ; K_p and τ are the active-power-frequency droop coefficient and the inertial time constant, respectively.

filter; and E_0 designates the nominal steady-state baseline of the virtual internal excitation voltage amplitude.

As illustrated in Figure 2b, a quasi-Proportional-Resonant (quasi-PR) controller is embedded in the inner control loop to achieve zero steady-state tracking error for the sinusoidal fundamental commands in the stationary frame. The ideal math transfer function $G_{PR}(s)$ of the quasi-PR block is expressed as follows:

$$G_{PR}(s) = K_p + \frac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (9)$$

where K_p denotes the proportional gain, K_r signifies the resonant gain, ω_c represents the cut-off bandwidth frequency used to improve system immunity against grid frequency variations, and ω_0 is the fundamental angular frequency of the grid.

The fundamental parametric contradiction of fixed VSG control during the severe large-signal disturbance can be mathematically interpreted by checking the system state trajectory across two conflicting operational intervals:

The Acceleration Interval: When the grid fault occurs, the electromagnetic power output $P_{e,vsg}$ drops instantly. To prevent the virtual synchronization frequency, and the relative rotor angle $\Delta\delta$ from accelerating too rapidly, a heavily augmented virtual inertia ($J = 8.0 \text{ pu}$) is beneficial. According to the per-unit swing equation $J(d\omega/dt) = \Delta P$, a larger J establishes a stronger inertial anchor, effectively flattening the initial transient rate of change of angular frequency and power-angle slopes.

The Post-Fault Recovery Interval: Once the transmission fault is cleared, the system must damp out the accumulated power deviation and restore synchronization. However, the virtual rotor with a high inertia ($J = 8.0 \text{ pu}$) has stored a massive amount of virtual kinetic energy ($\Delta E_k = 0.5J\Delta\omega^2$) during the acceleration phase. With a fixed damping factor $D_0 = 5.0 \text{ pu}$, this excessive energy cannot be dissipated rapidly, inevitably forcing the power-angle and active power to overshoot to a larger transient peak, while inducing prolonged low-frequency oscillations. Conversely, while a lower inertia ($J = 2.0 \text{ pu}$) recovers faster due to its lower kinetic energy storage, its transient acceleration rate during the fault is relatively steep, endangering the local frequency safety margin.

This clear physical trade-off demonstrates that any fixed-parameter combination is mathematically bound by a “performance seesaw,” where optimizing the fault-onset inertial resistance inevitably compromises the post-fault damping response. To break this static parameter bottleneck, the virtual coefficients must adaptively transform their characteristics—acting as a heavy inertia during acceleration to block frequency crashes, and transitioning into a high-damping, low-inertia coordinator during recovery to crush oscillations. This crucial operational requirement establishes the comprehensive theoretical justification for the bounded enhanced adaptive VSG control strategy formulated in Section 3.

3. Principle of Improved Adaptive Control

3.1. Influence of Moment of Inertia J and Damping Coefficient Γ on the Characteristics of Virtual Synchronous Generators (VSG)

3.1.1. Influence of Virtual Inertia and Damping on Active Power Dynamics

For a virtual synchronous generator (VSG), its output active power and reactive power can be derived using the calculation method of apparent power, as shown in Equation (10):

$$\begin{cases} P = \frac{EU \cos(\theta - \delta)}{Z} - \frac{U^2 \cos \theta}{Z} \\ Q = \frac{EU \sin(\theta - \delta)}{Z} - \frac{U^2 \sin \theta}{Z} \end{cases} \quad (10)$$

where U stands for the terminal voltage; δ refers to the power angle of the virtual synchronous generator (VSG); and Z and θ are the impedance and impedance angle of the VSG filter circuit, respectively. The expressions of Z and θ are as follows:

$$\begin{cases} Z = \sqrt{(\omega L)^2 + R^2} \\ \theta = \arctan(\omega L / R) \end{cases} \quad (11)$$

where L denotes the filter inductor and R denotes the resistance.

To simplify the analytical derivation of the active-power-angle relation in (12), the equivalent output resistance R of the converter system is assumed to be zero. This approximation is physically justified because the grid-connected filter and the interface transformer are predominantly inductive. Specifically, the equivalent series resistance R is extremely small compared to the inductive reactance, yielding an X/R ratio ($\omega_0 L/R$) much larger than 10. Under such highly inductive impedance conditions, neglecting R has a negligible impact on the transient active power dynamics, which is a standard and well-accepted simplification in transient stability analysis of grid-forming converters. The transfer function of the input–output active power of the VSG can be derived as shown in Equation (12), which is a typical second-order transfer function:

$$G(s) = \frac{P(s)}{P_{\text{ref}}(s)} = \frac{\frac{1}{J\omega_0} \frac{EU}{Z}}{s^2 + \left(\frac{D}{J} + \frac{K_\omega}{J\omega_0} \right) s + \frac{1}{J\omega_0} \frac{EU}{Z}} \quad (12)$$

From Equation (12), the natural angular frequency ω_n and damping ratio ξ of the corresponding second-order model are obtained as follows:

$$\begin{cases} \omega_n = \sqrt{\frac{EU}{J\omega_0 Z}} \\ \xi = D \sqrt{\frac{\omega_0 Z}{4JEU}} + K_\omega \sqrt{\frac{Z}{4J\omega_0 EU}} \end{cases} \quad (13)$$

For $0 < \xi < 1$ and a $\pm 5\%$ tolerance band, the corresponding percent overshoot $\sigma\%$ and settling time t_s are given by

$$\begin{cases} \sigma\% = e^{-\pi\xi/\sqrt{1-\xi^2}} \times 100\% \\ t_s = \frac{3.5}{\xi\omega_n} = \frac{3.5}{\frac{D}{2J} + \frac{K_\omega}{2J\omega_0}} \end{cases} \quad (14)$$

With given active-power and reactive-power commands, the dynamic performance of the second-order system is determined by the moment of inertia J , damping coefficient D and droop coefficient K_ω . When the droop coefficient is constant and D is fixed, a larger J corresponds to a smaller ξ , larger percent overshoot $\sigma\%$ and longer settling time t_s ; when J is fixed, a larger D corresponds to a larger ξ , smaller percent overshoot $\sigma\%$ and shorter settling time t_s . The conclusions can be drawn as follows: The moment of inertia J of the virtual synchronous generator (VSG) determines the oscillation frequency in the dynamic response of output active-power, while the damping coefficient D governs the attenuation rate of oscillations in the active power response. Therefore, the moment of inertia J of the VSG cannot be excessively large; otherwise, step changes

in active power will cause fluctuations in output active power, which is harmful to system stability.

Figure 3 shows the schematic diagram of the small-signal model of the virtual synchronous generator (VSG).

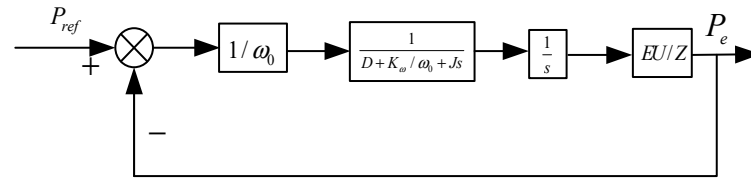


Figure 3. Small-signal model of virtual synchronous generator (VSG).

3.1.2. Effect of Virtual Parameters on Transient Frequency Response

From Equation (1), we can obtain

$$\Delta\omega = \frac{T_m - T_e - Jd\omega/dt}{D} \quad (15)$$

$$\frac{T_m - T_e - T_D}{J} = \frac{d\omega}{dt} \quad (16)$$

In Equation (15), assuming $T_m - T_e - Jd\omega/dt$ remains constant, a larger value of D leads to a smaller frequency deviation $\Delta\omega$. In Equation (16), assuming $T_m - T_e - T_D$ remains constant, a larger value of J results in a smaller rate of change of angular velocity $d\omega/dt$. It must be emphasized that the term $T_m - T_e - Jd\omega/dt$ is non-linear and highly time-varying during severe grid disturbances due to the rapid fluctuations in electromagnetic power and the dynamic tuning of the virtual parameters. Therefore, treating this combined term as a constant in the following derivation is strictly a local approximation valid only within a sufficiently small transient analytical interval. This local simplification is intended solely to provide a tractable mathematical perspective for qualitative stability boundaries; whereas, in the full system dynamics and numerical simulations, all variables are updated continuously and simulated without this localized restriction. To ensure frequency stability, the rate of change of angular velocity $d\omega/dt$ and the frequency deviation $\Delta\omega$ are suppressed by adjusting the moment of inertia J and the damping coefficient D . This mechanism is analogous to how synchronous generators maintain power grid stability through their moment of inertia and damping characteristics arising from damper windings, rotor losses and mechanical friction.

3.2. Adaptive Parameter Selection and Control Laws

The power angle curve and frequency oscillation curve of the synchronous generator are shown in Figure 4. In Figure 4a, when the set active power of the synchronous generator increases from P_1 to P_2 , the steady-state operating point of the system switches from point A to point B. Both the power variation and frequency variation during the switching process present damped oscillations, and the oscillation process of the virtual synchronous generator (VSG) is similar to this. For ease of analysis, under the condition that both the moment of inertia and damping coefficient remain constant, a typical oscillation process is divided into four intervals: ① $t_1 - t_2$, ② $t_2 - t_3$, ③ $t_3 - t_4$, ④ $t_4 - t_5$. In interval ①, the virtual rotor angular velocity of the VSG is higher than the grid angular velocity and rises gradually, and the rate of change of angular velocity $d\omega/dt$ first surges and then decreases slowly. Therefore, in interval ①, it is necessary to increase the moment of inertia J and damping coefficient D to avoid excessively large $d\omega/dt$ and $\Delta\omega$, so as to

restrain the rise in rotor angular velocity. In interval ②, the rate of change of virtual rotor angular velocity satisfies $d\omega/dt < 0$, entering the deceleration phase. ω decreases gradually from its maximum value, yet $\omega > \omega_0$, meaning the virtual rotor angular velocity is still greater than the grid angular velocity. A smaller moment of inertia should be adopted in this stage to accelerate the recovery of angular velocity to its rated value; meanwhile, the damping coefficient is increased when $|\Delta\omega|$ is relatively large to further suppress the deviation of angular velocity. In intervals ③ and ④, the selection principles of the moment of inertia and damping coefficient are analogous to those in intervals ① and ②.

The power-angle and angular-frequency oscillation curves of the synchronous generator, reproduced from Liu and Li [25], are shown in Figure 4.

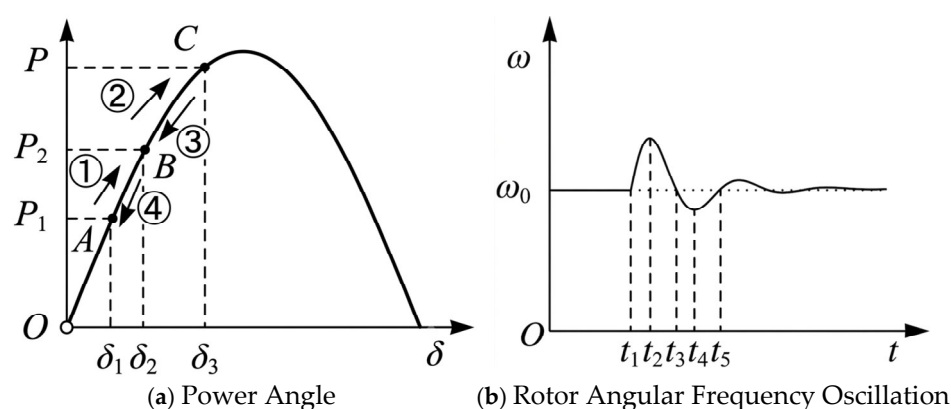


Figure 4. Power angle and frequency oscillation curves of synchronous generator.

In summary, the selection of the moment of inertia is jointly determined by both the variation and the rate of change of the virtual rotor angular velocity, whereas the selection of the damping coefficient is determined solely by the variation in the virtual rotor angular velocity. Under different operating conditions, the selection principles for the moment of inertia and the damping coefficient are presented in Table 1.

Table 1. Selection Principles of Moment of Inertia J and Damping Coefficient D under Different Conditions.

Interval	$\Delta\omega$	$d\omega/dt$	$\Delta\omega(d\omega/dt)$	Variation of J	Variation of D
①	Greater than 0	Greater than 0	Greater than 0	Increase	Moderate increase
②	Greater than 0	Less than 0	Less than 0	Return to J_0	Moderate increase
③	Less than 0	Less than 0	Greater than 0	Increase	Moderate increase
④	Less than 0	Greater than 0	Less than 0	Return to J_0	Moderate increase

Based on the selection principles in Table 1, as well as the correlation between the moment of inertia J and the rate of change of rotor angular velocity $d\omega/dt$, and the correlation between the damping coefficient D and the rotor angular velocity deviation $\Delta\omega$, an adaptive control strategy is proposed as follows:

$$J = \begin{cases} J_0 & \Delta\omega(d\omega/dt) \leq 0 \\ J_0 & |d\omega/dt| \leq T_j \\ J_0 + K_j |d\omega/dt| & \Delta\omega(d\omega/dt) > 0 \cap |d\omega/dt| > T_j \end{cases} \quad (17)$$

$$D = \begin{cases} D_0 & |\Delta\omega| \leq T_d \\ D_0 + K_d |\Delta\omega| & |\Delta\omega| > T_d \end{cases} \quad (18)$$

where J_0 and D_0 are the moment of inertia and damping coefficient of the virtual synchronous generator under steady-state operation, respectively; K_j and K_d are the adjustment coefficients of the moment of inertia and damping coefficient, respectively; and T_j and T_d are the variation thresholds.

In the implementation, $\Delta\omega(k) = \omega(k) - \omega_0$ is calculated from the internal angular-frequency state of the VSG. The rate of change of angular frequency is obtained by numerical differentiation of the same signal, $d\omega/dt = [\omega(k) - \omega(k-1)]/T_s$, where T_s is the controller sampling period. No additional derivative filter or hysteresis band is employed in the present model. Consequently, switching may occur if $\Delta\omega$ or $d\omega/dt$ fluctuates near T_d or T_j , respectively.

It is worth noting that Table 1 and Equations (17) and (18) describe the adaptive-control process at different levels. Table 1 provides qualitative parameter-selection guidelines for the four dynamic intervals, whereas Equations (17) and (18) give the corresponding quantitative control laws. According to Equation (17), the virtual inertia is increased only when $\Delta\omega(d\omega/dt) > 0$ and $|d\omega/dt| > T_j$. These conditions indicate that the angular-frequency deviation is moving away from the synchronous operating point. When $\Delta\omega(d\omega/dt) \leq 0$ or $|d\omega/dt| \leq T_j$, J is restored to J_0 . Accordingly, the entries for intervals II and IV in Table 1 are described as “Return to J_0 ”; J is not reduced below J_0 . At $|d\omega/dt| = T_j$, the nominal branch $J = J_0$ is selected.

For the damping coefficient, Table 1 indicates that additional damping is desirable in all four dynamic intervals when a sufficiently large transient deviation occurs. Equation (18) implements this principle quantitatively using $|\Delta\omega|$ as the activation signal. When $|\Delta\omega| \leq T_d$, the damping coefficient remains at D_0 ; when $|\Delta\omega| > T_d$, the adaptive damping branch is activated and $D = D_0 + K_d |\Delta\omega|$. Thus, a nonzero frequency deviation does not necessarily activate damping adaptation; the deviation must exceed the deadband threshold T_d . At $|\Delta\omega| = T_d$, the nominal branch $D = D_0$ is selected. As the system approaches a new steady state and $|\Delta\omega|$ falls below T_d , the damping coefficient returns to D_0 , thereby avoiding continuous parameter accumulation.

The deadband thresholds in Equations (17) and (18) are introduced to prevent unnecessary parameter adaptation caused by small steady-state fluctuations. In the present implementation, the nominal branches are selected when the corresponding signals are exactly equal to the thresholds. Since no additional hysteresis mechanism is employed, repeated switching may theoretically occur if measurement noise causes $|d\omega/dt|$ or $|\Delta\omega|$ to fluctuate repeatedly around its activation threshold. The selected values of T_j and T_d reduce the sensitivity of the controller to small fluctuations, but they cannot mathematically eliminate chattering under severe measurement noise. The introduction of hysteresis bands or continuous transition functions will be considered in future work.

To explicitly coordinate the adaptive inertia controller with the converter current limiter, the magnitude of the unconstrained current command is first calculated using Equation (19). The current-limiting factor is then determined using Equation (20).

$$I_c^* = \sqrt{((i_d^*)^2 + (i_q^*)^2)} \quad (19)$$

$$\lambda_l = \begin{cases} 1, & I_c^* \leq I_{\max} \\ I_{\max} / I_c^*, & I_c^* > I_{\max} \end{cases} \quad (20)$$

When the unconstrained current magnitude is less than or equal to the current threshold, including the exact threshold value, the current-limiting factor is equal to one. Therefore, the current commands and the adaptive inertia command are not modified. When the unconstrained current magnitude exceeds the threshold, the current-limiting factor becomes less than one, and the d-axis and q-axis current commands are proportionally scaled according to Equation (21):

$$i_{(d,ref)} = \lambda_l i_d^*, \quad i_{(q,ref)} = \lambda_l i_q^* \quad (21)$$

The current-limiting factor is applied only to the adaptive inertia increment $J_{\text{adp}} - J_0$. Therefore, when the current limiter is activated, the inertia command is reduced toward J_0 but is never reduced below J_0 . The resulting inertia command remains subject to the bounds and rate limit specified in Table 2. The damping command remains governed by Equation (18).

Table 2. Key Parameters of the High-Voltage Grid-Connected System.

Parameter Category	Physical Quantity	Symbol	Value	Unit
System Base	Base power/Base voltage	S_B / U_B	5.0/10.0	MVA/kV
	Rated frequency	f_0	50	Hz
VSG Control	Rated virtual inertia	J_0	4.5	p.u.
	Angular-frequency-rate activation threshold	T_j	6	rad/s ²
	Rated virtual damping coefficient	D_0	80.0	p.u.
	Frequency-deviation activation threshold	T_d	0.5	rad/s
	Maximum inertia update rate	k_1	1.2	p.u./s
	Maximum damping update rate	k_2	4.0	p.u./s
	Base adaptive inertia gain	K_j	0.18	p.u.s ² /rad
	Base adaptive damping gain	K_d	2.5	p.u.s/rad
	Minimum virtual inertia	$J_{\min}$	1.5	p.u.
	Maximum virtual inertia	$J_{\max}$	10.0	p.u.
	Minimum virtual damping	$D_{\min}$	20.0	p.u.
	Maximum virtual damping	$D_{\max}$	150	p.u.
Grid/Generator Unit	Synchronous generator inertia constant	H_{sg}	4.0	S
Operating Condition	Rated active/reactive-power reference	P_{ref} / Q_{ref}	0.15/0.05	p.u.

In Equation (22), J_{adp} is the adaptive inertia obtained from Equation (17), J_{cmd} is the coordinated inertia command, and $I_{\max} = 1.2$ p.u. is the converter-current limit listed in Table 3.

$$J_{\text{cmd}} = \text{sat}_{[J_0, J_{\max}]} \left\{ J_0 + \lambda_l [J_{\text{adp}} - J_0] \right\} \quad (22)$$

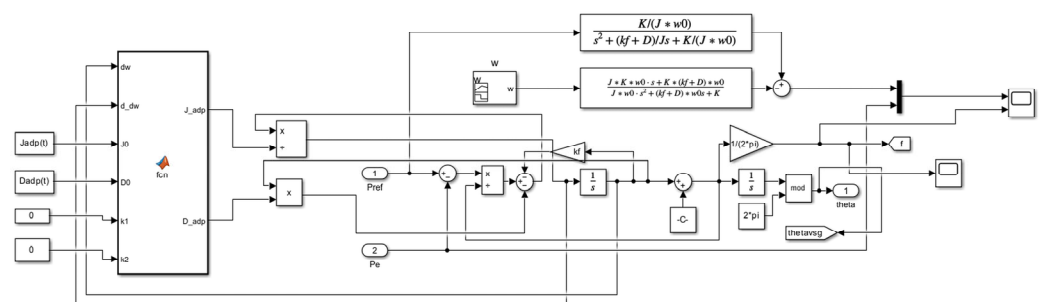
Table 3. Main Parameters of the Aggregated Wind-Farm and Grid-Equivalent System.

Parameter Category	Physical Quantity	Symbol	Value	Unit
Wind Farm	Number of PMSG units	N_{WT}	5	—
	Rated capacity per unit/aggregated capacity	S_{WT} / S_{WF}	1.0/5.0	MVA
Converter/Filter	Filter resistance/reactance	R_f / X_f	0.01/0.15	p.u.
	Converter current limit	$I_{\max}$	1.2	p.u.
Transformer	Voltage ratio/rated capacity	$U_L / U_H / S_T$	0.69/10/5.0	kV/kV/MVA
	Leakage reactance	X_T	0.06	p.u.
Grid Equivalent	Thevenin resistance/reactance	R_g / X_g	0.02/0.20	p.u.
	X/R ratio	X_g / R_g	10	—
	Short-circuit capacity/short-circuit ratio	S_{sc} / SCR	25/5	MVA/—
Fault Condition	Fault location	—	Midpoint of the main transmission line	—
	Fault interval	t_f	4.0–4.1	s

3.3. Control Structure and Implementation Analysis

To integrate the proposed enhanced adaptive control strategy into the conventional VSG control framework, this section provides a detailed analysis of the interaction logic between the adaptive parameters and the VSG power feedback loop.

The core control scheme of the proposed strategy is illustrated in Figure 5. In conventional VSG control, the active-power regulation loop emulates inertia and damping characteristics through the rotor motion equation. In the architecture proposed in this paper, the original fixed moment of inertia J_0 and damping coefficient D_0 are substituted with $J_{\text{adp}}(t)$ and $D_{\text{adp}}(t)$, which are dynamically updated in real time.

**Figure 5.** Implementation block diagram of the enhanced adaptive control strategy.

Crucially, the “Fcn” block serves as the mathematical processing core of the adaptive mechanism. This block explicitly encapsulates the non-linear algebraic formulations derived in Equations (17) and (18). The frequency deviation $\Delta\omega$ and its rate of change $d\omega/dt$ serve as the input signals of the adaptive decision unit. The adaptive correction values are fed back in real time to the integral and proportional terms of the power loop, thus realizing online adjustment of the moment of inertia and damping coefficient without altering the basic control architecture of the system.

To ensure the stability of the control strategy under extreme fault operating conditions, a two-stage limiting mechanism is designed in the control block diagram.

Saturation constraint: A limiter is introduced after the adaptive calculation output to ensure that J_{adp} always operates within the safe interval $[J_{\text{min}}, J_{\text{max}}]$, preventing abrupt parameter changes from triggering instability in the inner loop of the converter. **Current-limiting coordination:** The proposed strategy achieves coordination with the current-limiting link of the converter. When the system detects that the current reaches the protection threshold, the adaptive regulator will prioritize reducing J_{adp} to mitigate current deviation, giving priority to reducing the converter overcurrent risk of the converter.

The proposed scheme converts the complex nonlinear optimization problem into online parameter adjustment based on algebraic logic. While preserving the voltage source characteristics of the VSG, it endows the converter with the capability of automatic parameter tuning. This approach not only significantly reduces the computational overhead of the algorithm, but also effectively counteracts the transient power angle deviation of the system during fault periods through the nonlinear dynamic response generated by parameter adaptation.

A concise sufficient stability condition is provided for the time-varying adaptive parameters. Let $\Delta\omega = \omega - \omega_0$ and let δ_s denote the stable equilibrium power angle. Considering the Lyapunov energy function $V = 0.5J(t)(\Delta\omega)^2 + \int_{\delta_s}^{\delta} [P_c(\sigma) - P_m] d\sigma$, its derivative along the VSG trajectory is given by $dV/dt = -[D(t) - 0.5dJ(t)/dt](\Delta\omega)^2$. Therefore, the adaptive system is locally stable within the synchronizing region if $J(t)$ and $D(t)$ remain positive and bounded, the synchronizing coefficient is positive, and $|dJ(t)/dt| < 2D_{\text{min}}$. In the proposed controller, the saturation constraints maintain $J(t)$ within [1.5, 10.0] p.u. and $D(t)$ within [20.0, 150.0] p.u. In addition, the parameter update rates are limited by $|dJ/dt| \leq k_1 = 1.2$ p.u./s and $|dD/dt| \leq k_2 = 4.0$ p.u./s. Thus, $k_1 < 2D_{\text{min}} = 40.0$ p.u./s and $D_{\text{min}} - 0.5k_1 = 19.4 > 0$, satisfying the above sufficient local stability condition.

4. Simulation Verification and Analysis

4.1. Simulation Parameter Configuration

To verify the effectiveness of the proposed enhanced adaptive virtual synchronous generator (VSG) control strategy, this chapter establishes a multi-machine grid-connected simulation model comprising a 5 MVA permanent magnet direct-drive wind farm and a conventional synchronous generator in the MATLAB/Simulink environment. The model is configured with a base line voltage of 10 kV and a rated frequency of 50 Hz. By simulating a three-phase symmetrical short-circuit fault occurring on the main transmission line at $t = 4.0$ s (with a duration of 0.1 s), the transient power angle stability characteristics of the system under extreme operating conditions are investigated.

The 5 MVA wind farm consists of five identical 1 MVA direct-drive PMSG units and is represented by one aggregated wind-farm model at the point of common coupling. The aggregated model preserves the total rated capacity of the wind farm and employs a standard dq-axis PMSG electrical model together with a single-mass mechanical model. The machine-side converter regulates the generator torque and speed. The grid-side converter operates with conventional PLL-based GFL control in the baseline case, fixed-parameter VSG control in the second case, and the proposed adaptive VSG control in the third case.

The main parameters of the aggregated wind farm, converter filter, step-up transformer, and external-grid equivalent are summarized in Table 3. The external grid is

represented by a Thevenin equivalent, and the three-phase fault is applied at the midpoint of the main transmission line at $t = 4.0$ s and cleared at $t = 4.1$ s.

For a fair comparison, all three control cases use the same converter power stage, rated capacity, filter, transformer, network parameters, current limit, active- and reactive-power references, initial voltage and frequency, fault location, and fault-clearing time. The controller-specific loops are tuned to provide comparable pre-fault dynamic responses. The principal differences among the three cases are the grid-side synchronization method and the outer inertia and damping control algorithms.

The key physical parameters and control parameters of the system adopted in this study are presented in Table 2. The values of virtual moment of inertia J_0 and virtual damping coefficient D_0 are converted to per-unit values based on a base capacity of 5 MVA. The adaptive gains were selected through offline parameter-sensitivity analysis to obtain a satisfactory response under the investigated operating conditions.

4.2. Transient Response and Performance Analysis

To comprehensively evaluate the performance of the proposed enhanced adaptive VSG control strategy, this section subjects the system to a three-phase symmetrical short-circuit fault condition and compares three typical operation modes: conventional GFL (grid-following) control, fixed-parameter VSG control, and the enhanced adaptive VSG control proposed in this paper. The simplified schematic of the operating condition (VSG-synchronous generator-infinite bus system) is shown in Figure 6, and the simulation results are presented in Figures 7–11.

Figure 6 presents the simplified grid-side equivalent topology for the VSG-based control cases. The converter labeled “VSG control” represents the grid-side converter of the aggregated 5 MVA PMSG-based wind farm after its conventional PLL-based grid-following control is replaced by the VSG-based grid-forming control investigated in this study. The detailed PMSG and machine-side converter subsystems are omitted from Figure 6 for clarity. For the conventional GFL comparison, the same converter power stage, filter, transformer, network parameters, current limit, and operating point are retained, while the grid-side converter operates with conventional PLL-based grid-following control. Therefore, Figure 6 illustrates the VSG-based configuration of the same benchmark system rather than a separate physical test system.

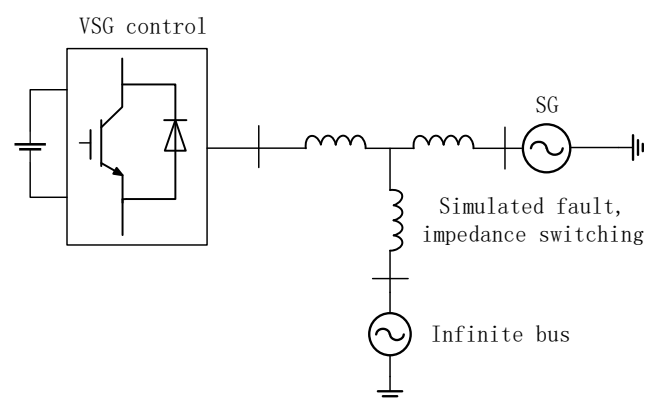


Figure 6. VSG-Synchronous Generator-Infinite Bus System.

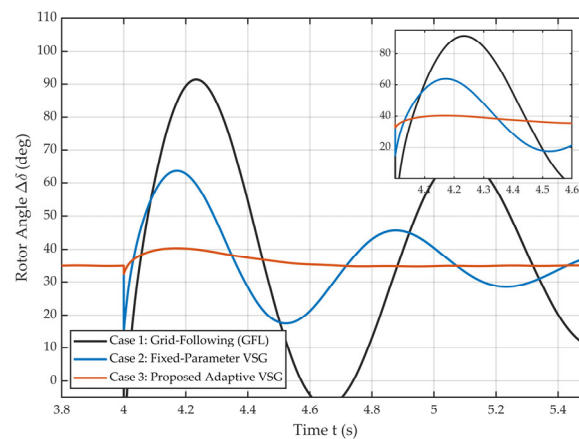


Figure 7. Comparison of Power Angle.

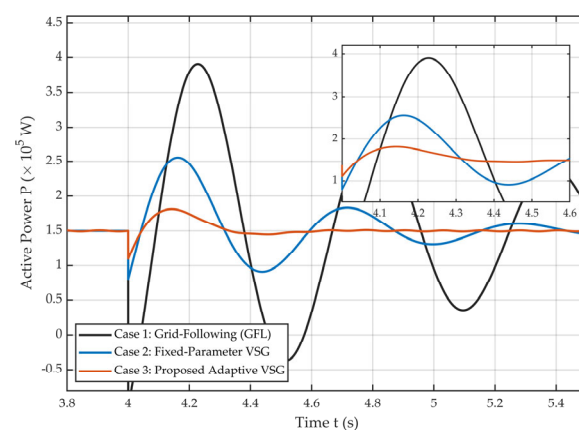


Figure 8. Comparison of Active Power.

Figure 7 shows the variation in the system power angle during the fault and after fault clearance. At the fault inception time of $t = 4.0$ s, the power angle changes markedly. Under conventional grid-following (GFL) control, the peak power angle reaches approximately 92 degrees, and the response does not settle within the displayed simulation interval. With fixed-parameter VSG control, the peak power angle is reduced to approximately 65 degrees, although noticeable low-frequency oscillations remain after fault clearance. With the proposed adaptive VSG control, the peak power angle is approximately 45 degrees, and the response settles within approximately 0.4 s in the investigated case. This response is associated with the increase in virtual inertia during the initial transient stage and the subsequent increase in damping during the recovery stage.

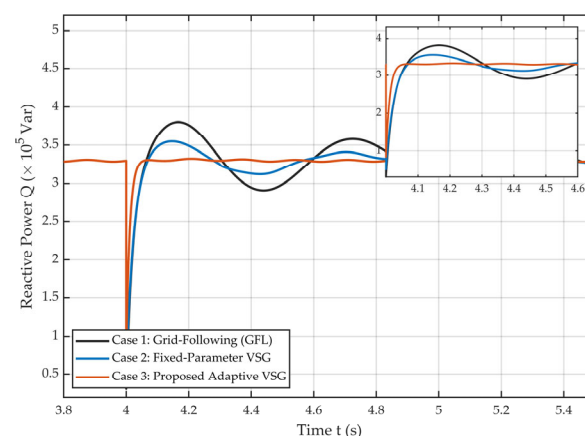


Figure 9. Comparison of Reactive Power.

Figures 8 and 9 show the transient active- and reactive-power responses, respectively. Under the investigated fault condition, the proposed adaptive VSG produces smaller post-fault active-power oscillations than the fixed-parameter VSG, and the active power returns toward its pre-fault operating value after fault clearance.

The reactive-power response also returns toward its steady-state value with smaller post-fault fluctuations. This behavior results from the coordinated adjustment of J and D together with the current-limiting action defined in Equation (19). The proposed method adjusts only the virtual inertia and damping coefficient; no adaptive virtual-impedance adjustment is employed.

To further examine the behavior of the proposed adaptive law beyond the baseline 0.10-s three-phase fault, supplementary reduced-order time-domain simulations were conducted using the VSG swing equation together with Equations (17) and (18). The same adaptive parameters, thresholds, rate limits, and saturation bounds listed in Table 2 were retained. The additional cases include three-phase-fault clearing times of 0.08, 0.10, and 0.15 s, an equivalent positive-sequence voltage-depression case corresponding to a single-line-to-ground disturbance, and combined disturbances under $SCR = 5$ and $SCR = 3$. The combined disturbance includes an active-power-reference increment, bounded renewable-power fluctuations, small measurement noise, and a 1-ms control delay.

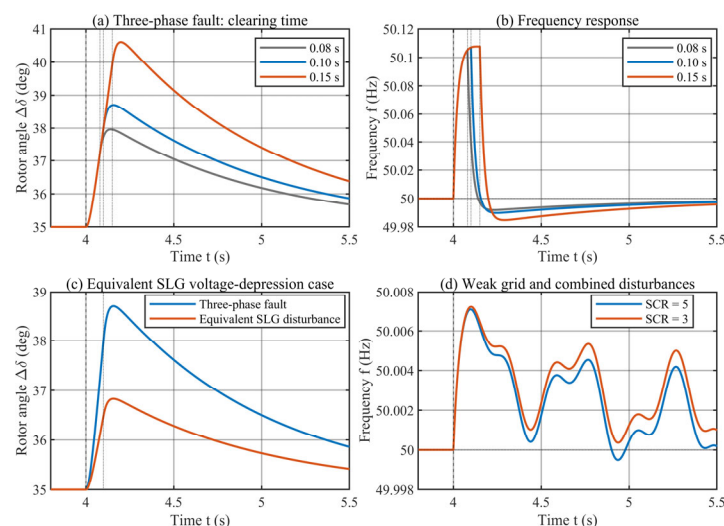


Figure 10. Supplementary reduced-order responses under different fault-clearing times, an equivalent SLG voltage-depression disturbance, and different grid strengths.

As shown in Figure 10, increasing the three-phase-fault clearing time from 0.08 to 0.15 s increases the peak rotor angle from approximately 37.96° to 40.61° , while the responses remain bounded and gradually return toward the operating point. The equivalent SLG voltage-depression disturbance produces a lower rotor-angle peak of approximately 36.83° than the three-phase fault. Under the combined disturbance, reducing the grid strength from $SCR = 5$ to $SCR = 3$ slightly increases the frequency fluctuation, but no sustained oscillation or divergence is observed during the investigated interval.

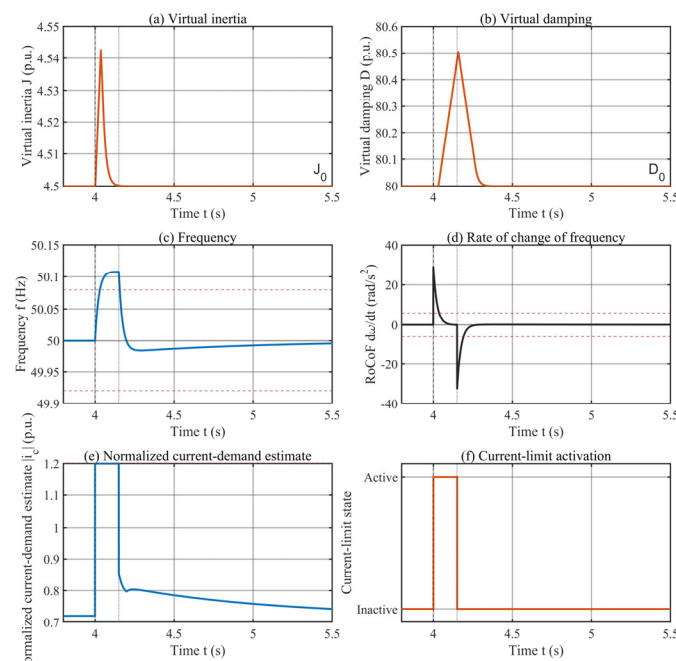


Figure 11. Time-domain trajectories of the adaptive parameters and current-limit variables during a 0.15-s three-phase fault.

Figure 11 presents the internal trajectories of the adaptive controller under the more severe 0.15-s three-phase fault. When the rate of change of angular frequency and frequency-deviation thresholds are exceeded, J and D increase from their nominal values and remain within the prescribed bounds. Their peak values are approximately 4.543 p.u. and 80.504 p.u., respectively. The relatively small parameter excursions are consistent with the imposed rate limits of $k_1 = 1.2$ p.u./s and $k_2 = 4.0$ p.u./s. The frequency remains between approximately 49.985 and 50.108 Hz, and the rate of change of angular frequency remains finite. The normalized current-demand estimate reaches the 1.2-p.u. limit, and the current-limit flag remains active from $t = 4.0$ s to $t = 4.15$ s. After fault clearance, the limiting action is released and J and D return smoothly to J_0 and D_0 .

In Figure 11d, $d\omega/dt$ denotes the rate of change of angular frequency expressed in rad/s^2 , rather than RoCoF expressed in Hz/s . As shown in Figure 11e,f, the normalized current-demand estimate is clamped at 1.2 p.u., and the current-limit flag remains active from $t = 4.0$ s to $t = 4.15$ s. During this interval, the current-limiting factor is less than one and attenuates the adaptive inertia increment. After fault clearance, the current demand falls below the threshold, the current-limiting factor returns to unity, and the normal adaptive law is restored.

To provide a concise quantitative comparison, the principal performance indices of the three control cases are summarized in Table 4. Compared with the fixed-parameter VSG, the proposed adaptive VSG reduces the peak power angle from approximately 65 deg to 45 deg, corresponding to a reduction of 30.77%, or approximately 31%. The power-angle overshoot is also reduced from approximately 30 deg to 10 deg, and the settling time is shortened to approximately 0.40 s.

Table 4. Quantitative comparison of the three control cases.

Performance Index	GFL	Fixed VSG	Proposed Adaptive VSG
Peak power angle (deg)	92	65	45
Power-angle overshoot (deg)	57	30	10
Settling time (s)	Not settled	>1.5	0.40

Maximum frequency deviation (Hz)	0.412	0.107	0.107
Maximum absolute rate of change of angular frequency (rad/s ²)	105.48	30.60	30.60
Peak normalized current demand (p.u.)	1.20	1.20	1.20
Maximum post-fault active-power deviation ($\times 10^5$ W)	2.40	1.05	0.30
Maximum post-fault reactive-power deviation ($\times 10^5$ Var)	0.50	0.24	0.05

Note: The power-angle, settling-time, active-power, and reactive-power metrics reported in Table 4 are extracted from the detailed MATLAB/Simulink benchmark model shown in Figures 7–9. The frequency, rate-of-change-of-angular-frequency, and normalized current-demand metrics are obtained from the supplementary reduced-order model shown in Figures 10 and 11. The reduced-order power-angle curves in Figure 10 are used only to illustrate parameter sensitivity and are not used for quantitative comparison with the detailed-model results.

It should be noted that the supplementary reduced-order simulations are intended to verify the threshold activation, bounded parameter adaptation, and current-limiting logic. They do not reproduce switching-level electromagnetic transients or the complete negative- and zero-sequence dynamics of the detailed PMSG converter system.

5. Conclusions

This study investigated an adaptive virtual-inertia and damping control strategy for improving the transient response of a VSG-based grid-connected system. The main findings obtained from the theoretical analysis and MATLAB/Simulink simulations are summarized as follows.

1. The analysis indicates that virtual inertia and damping have different effects on the transient response. Increasing the virtual inertia can reduce the initial rate of change of the power angle, whereas increasing the damping can reduce post-fault oscillations. This observation provides the basis for coordinating the two parameters during different transient stages.
2. A threshold-based adaptive mechanism was developed to adjust the virtual inertia J and damping coefficient D according to the frequency deviation and rate of change of angular frequency. The imposed parameter bounds and rate limits prevent continuous parameter accumulation and restrict the adaptive variables to their predefined ranges.
3. Under the investigated three-phase short-circuit fault, the proposed adaptive VSG reduces the peak power angle from approximately 65 degrees for the fixed-parameter VSG to approximately 45 degrees, corresponding to a reduction of approximately 31%. The simulated power-angle response settles within approximately 0.4 s. The supplementary reduced-order simulation also shows that the normalized current-demand estimate is limited to 1.2 p.u. during the fault interval.
4. The present results demonstrate the simulation-based feasibility of the proposed control strategy for the investigated benchmark system. The supplementary reduced-order model does not reproduce switching-level electromagnetic transients or complete negative- and zero-sequence dynamics. Moreover, experimental, real-time simulation, and hardware-in-the-loop validation have not yet been conducted. Future work will therefore investigate controller implementation, experimental validation,

and coordinated control among multiple converter-interfaced units under weak-grid conditions.

Author Contributions: Conceptualization, Y.-D.H., Z.-K.L., A.-J.M. and X.-D.Z.; methodology, Y.-D.H., Y.-T.H., Y.W., Z.-K.H. and Z.C.; formal analysis, L.-Z.Z., Z.-K.H., Z.C. and X.-D.Z.; validation, Y.-D.H., A.-J.M., Z.-K.H. and Z.C.; resources, A.-J.M.; data curation, Y.-D.H.; software, Y.-D.H., Z.-K.L. and Y.-T.H.; writing—original draft preparation, Y.-D.H.; writing—review and editing, L.-Z.Z., Y.W., A.-J.M., Z.-K.H., X.-D.Z. and Z.C.; supervision, A.-J.M., Z.-K.H., X.-D.Z. and Z.C.; project administration, A.-J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Science and Technology Project of State Grid Fujian Electric Power Company (Grant No. SGFJJY00GHJS2400136) and Headquarters Science and Technology Project of State Grid Corporation of China (Grant No. 1400-202457360A-3-1-DG).

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Yuan-Da Hao, Li-Zi Zhang, Yin Wang, Ze-Kai Li, Yu-Tao Hao and An-Jia Mao were employed by the School of Electrical and Electronic Engineering, North China Electric Power University. Authors Zhong-Kuan Han and Zhi Chen were employed by State Grid Fujian Electric Power Company. Author Xu-Dong Zhang was employed by State Grid Corporation of China. This work was funded by State Grid Fujian Electric Power Company Science and Technology Project and State Grid Corporation of China. The 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.

References

1. Huang, L.; Xin, H.; Ju, P.; Hu, J. Synchronization Stability Analysis and Unified Synchronous Control Structure of Grid-Tied Power Electronic Equipment. *Proc. Chin. Soc. Electr. Eng.* **2020**, *40*, 10–25. <https://doi.org/10.16081/j.epae.202009042>.
2. Song, J.; Bao, Y.; Zhang, J.; Xu, T.; Ren, X.; Wang, W. Characterization and Calculation of Transient Stability Boundary for New-Type Power Systems: A Review and Prospect. *Power Syst. Autom.* **2025**. <https://link.cnki.net/urlid/32.1180.TP.20250813.1719.006>
3. China Electricity Council. China's Wind and Solar Installed Capacity Historically Surpasses Thermal Power: Remarkable Results in Green and Low-Carbon Transition of Power Industry—CEC Releases In *Analysis and Forecast Report on National Power Supply and Demand Situation in Q1 2025*; China Electrical Equipment Industry: Shanghai, China, 2025; pp. 10–13.
4. Zhang, Z.; Kang, C. Challenges and Prospects of Constructing New-Type Power Systems Under Carbon Neutrality Goal. *Proc. Chin. Soc. Electr. Eng.* **2022**, *42*, 2806–2819. <https://doi.org/10.13334/j.0258-8013.pcsee.220467>.
5. Xie, X.; He, J.; Mao, H.; Li, H. New Issues and Classification Discussion on Power System Stability Under the 'High Penetration of Renewable Energy and Power Electronic Equipment' Scenario. *Proc. Chin. Soc. Electr. Eng.* **2021**, *41*, 461–475. <https://doi.org/10.13334/j.0258-8013.pcsee.201405>.
6. Liu, J.; Tu, Z.; Zhang, Y.; Zhang, Y.; Li, J.; Li, Y. Stability Criterion of Grid-Forming Converters Based on DC Voltage Synchronization Considering Current Limiting. *Electr. Power Eng. Technol.* **2025**, *44*, 3–12.
7. Sun, P.; Mu, Z.; Zha, X.; Huang, M.; Wang, W.; Yang, D.; Liu, W. Review on Transient Synchronous Stability of Grid-Forming Converter Grid-Tied Systems Based on Power Synchronization. *Power Syst. Autom.* **2025**, *49*, 1–19.
8. Valikhany, M.; Astero, P.; Lehtonen, M.; Peltoniemi, P. A Review on the Suitability of Virtual Inertia Strategies for Next-Generation Low-Inertia Power Systems. *Adv. Electr. Electron. Eng.* **2025**, *14*, 101131. <https://doi.org/10.1016/j.prime.2025.101131>.
9. Wang, L.; Zhou, H.; Hu, X.; Hou, X.; Su, C.; Sun, K. Adaptive Inertia and Damping Coordination (AIDC) Control for Grid-Forming VSG to Improve Transient Stability. *Electronics* **2023**, *12*, 2060. <https://doi.org/10.3390/electronics12092060>.
10. Tan, B.; Zhao, J.; Netto, M.; Krishnan, V.; Terzija, V.; Zhang, Y. Power System Inertia Estimation: Review of Methods and the Impacts of Converter-Interfaced Generations. *Int. J. Electr. Power Energy Syst.* **2021**, *134*, 107362. <https://doi.org/10.1016/j.ijepes.2021.107362>.
11. Perez, F.; Damm, G.; Verrelli, C.M.; Ribeiro, P.F. Adaptive Virtual Inertia Control for Stable Microgrid Operation Including Ancillary Services Support. *IEEE Trans. Control Syst. Technol.* **2023**, *31*, 1552–1561. <https://doi.org/10.1109/TCST.2023.3234282>.

12. Wang, J.; Ramli, N.; Aziz, N.H. A Pre-Synchronization Control Strategy of Virtual Synchronous Generator (VSG) for Microgrid. *IEEE Access* **2023**, *11*, 139004–139016. <https://doi.org/10.1109/ACCESS.2023.3341102>.
13. Hou, X.; Sun, Y.; Zhang, X.; Lu, J.; Wang, P.; Guerrero, J.M. Improvement of Frequency Regulation in VSG-Based Microgrid via Adaptive Virtual Inertia. *IEEE Trans. Power Electron.* **2020**, *35*, 1589–1602. <https://doi.org/10.1109/TPEL.2019.2923734>.
14. Fu, S.; Sun, Y.; Li, L.; Liu, Z.; Han, H.; Su, M. Power Oscillation Suppression in Multi-VSG Grid by Adaptive Virtual Impedance Control. *IEEE Syst. J.* **2022**, *16*, 4744–4755. <https://doi.org/10.1109/JSYST.2022.3173666>.
15. Suvorov, A.; Askarov, A.; Ruban, N.; Rudnik, V.; Radko, P.; Achitaev, A.; Suslov, K. An Adaptive Inertia Control Strategy Based on Enhanced Virtual Synchronous Generator Model. *Mathematics* **2023**, *11*, 3938. <https://doi.org/10.3390/math11183938>.
16. Li, J.; Wen, B.; Wang, H. Adaptive Virtual Inertia Control Strategy of VSG for Micro-Grid Based on Improved Bang-Bang Control Strategy. *IEEE Access* **2019**, *7*, 39509–39514. <https://doi.org/10.1109/ACCESS.2019.2904943>.
17. Liu, A.; Liu, J.; Wu, Q. Coupling Stability Analysis of Synchronous Generator and Virtual Synchronous Generator in Parallel Under Large Disturbance. *Electr. Power Syst. Res.* **2023**, *224*, 109679. <https://doi.org/10.1016/j.epsr.2023.109679>.
18. Liu, H.; Yang, B.; Xu, S.; Du, M.; Liu, S. Universal Virtual Synchronous Generator Based on Extended Virtual Inertia to Enhance Power and Frequency Response. *Energies* **2023**, *16*, 2983. <https://doi.org/10.3390/en16072983>.
19. Sheir, A.; Sood, V.K. Enhanced Virtual Inertia Controller for Microgrid Applications. *Energies* **2023**, *16*, 7304. <https://doi.org/10.3390/en16217304>.
20. Xia, Y.; Chen, Y.; Wang, Y.; Chen, R.; Li, K.; Shi, J.; Yang, Y. A Virtual Synchronous Generator Control Strategy Based on Transient Damping Compensation and Virtual Inertia Adaptation. *Appl. Sci.* **2025**, *15*, 728. <https://doi.org/10.3390/app15020728>.
21. Sang, W.; Guo, W.; Dai, S.; Tian, C.; Yu, S.; Teng, Y. Virtual Synchronous Generator, a Comprehensive Overview. *Energies* **2022**, *15*, 6148. <https://doi.org/10.3390/en15176148>.
22. Alghamdi, B.; Cañizares, C. Frequency and Voltage Coordinated Control of a Grid of AC/DC Microgrids. *Appl. Energy* **2022**, *310*, 118427. <https://doi.org/10.1016/j.apenergy.2021.118427>.
23. Ren, B.; Li, Q.; Fan, Z.; Sun, Y. Adaptive Control of a Virtual Synchronous Generator with Multi-Parameter Coordination. *Energies* **2023**, *16*, 4789. <https://doi.org/10.3390/en16124789>.
24. Gurski, E.; Kuiava, R.; Perez, F.; Benedito, R.A.S.; Damm, G. A Novel VSG with Adaptive Virtual Inertia and Adaptive Damping Coefficient to Improve Transient Frequency Response of Microgrids. *Energies* **2024**, *17*, 4370. <https://doi.org/10.3390/en17174370>.
25. Liu, H.; Li, Z. Adaptive control strategy of inertia and damping coefficients based on virtual synchronous generator. *J. Phys.: Conf. Ser.* **2023**, *2584*, 012080. <https://doi.org/10.1088/1742-6596/2584/1/012080>.

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.