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VSG-Based Active Support Strategy for Grid-Forming VSC-HVDC

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Abstract

As renewable generation and power-electronic interfaces account for a growing share of power systems, reduced system inertia and weakened voltage support place greater demands on the stable operation of weak and passive networks. This paper proposes a virtual synchronous generator (VSG)-based active support strategy for grid-forming voltage source converter-based high-voltage direct-current (VSC-HVDC) systems. First, the power-balance relationship between the converter station and the synchronous generator is analyzed to establish the basis for VSG control. For active-power-frequency regulation, a virtual zero-error frequency regulation (VZFR) strategy is proposed by introducing an additional power compensation term into the conventional VSG control, improving frequency recovery while retaining virtual inertia and damping. For voltage-reactive-power regulation, the transient voltage support mechanism is analyzed in two stages: the controlled voltage-source characteristic and virtual impedance provide initial voltage support, while the reactive-power-voltage loop subsequently regulates the internal voltage and reactive power output. PSCAD/EMTDC simulations under active load disturbances and different grid voltage sags show that the proposed strategy enhances both frequency regulation and voltage support provided by the VSC-HVDC system.

Keywords: grid-forming VSC-HVDC; virtual synchronous generator (VSG); virtual zero-error frequency regulation (VZFR); frequency support; voltage support

1. Introduction

The continuous expansion of renewable generation has significantly increased the proportion of converter-interfaced resources in modern power systems [1–3]. Compared with conventional synchronous generators, most renewable generation and energy storage systems interface with the AC network through power electronic converters, resulting in reduced system inertia and weakened dynamic voltage support capability [4,5]. Meanwhile, large-scale renewable energy bases are usually located far from major load centers, creating a growing need to transfer large amounts of power over long distances [6–8]. Owing to its flexible power regulation and capability to connect weak or passive AC networks, VSC-HVDC has therefore been increasingly employed for renewable energy delivery and asynchronous interconnection between AC systems [3,9].

Conventional grid-following converters obtain their synchronization reference from the grid through a phase-locked loop (PLL) and have limited capability to autonomously establish grid voltage and provide dynamic support under weak-grid conditions [10,11]. In contrast, grid-forming (GFM) converters can autonomously generate the voltage magnitude,



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frequency, and phase, and therefore exhibit voltage-source characteristics and enhanced grid-support capability [12]. Among various GFM methods, virtual synchronous generator (VSG) control introduces synchronous-machine dynamics into the converter control process, enabling power electronic devices to provide virtual inertia, damping, and frequency regulation [13].

Considerable research has been conducted on the active-power–frequency control of VSG-based converters. Ref. [14] incorporated synchronous-machine rotor dynamics into converter control to realize virtual inertia and damping responses. Ref. [15] investigated VSG control under weak-grid conditions and demonstrated its ability to improve frequency stability during active power disturbances. Ref. [16] further applied VSG control to VSC-HVDC systems for supplying passive networks. Adaptive inertia, damping optimization, and improved active power control have also been studied to enhance the transient frequency response of VSG-controlled converters [17,18]. However, the conventional VSG retains the steady-state characteristic of primary droop regulation. After a load change, the converter can compensate for the resulting active-power imbalance, but the final operating frequency may still differ from its nominal value. This motivates an additional regulation mechanism that improves frequency restoration without sacrificing the inherent inertia and damping responses of the VSG.

Voltage support is another important requirement for grid-forming VSC-HVDC systems. Existing studies have investigated reactive power control, voltage droop control, virtual impedance, and excitation regulation to enhance the voltage regulation capability of grid-forming converters [19–21]. Ref. [22] designed a reactive-power–voltage controller for improving the bus-voltage response, while Ref. [23] analyzed the influence of virtual impedance on voltage support and power-sharing characteristics. Fault ride-through and coordinated voltage–reactive-power control have also been studied under grid disturbances [24,25]. However, most existing studies focus mainly on reactive power injection or voltage control-loop design, while the respective contributions of the converter voltage-source characteristic and the dynamic Q – V regulation during different stages of a voltage sag remain insufficiently distinguished.

As summarized in Table 1, the above studies reveal two remaining issues. On the frequency side, the inherent droop behavior of conventional VSG control leaves a residual frequency error after active-power disturbances. On the voltage side, the instantaneous support determined by the converter internal voltage and equivalent impedance has not been clearly separated from the subsequent dynamic regulation of the Q – V loop. A coordinated treatment of these two responses is therefore needed to strengthen the overall support performance of grid-forming VSC-HVDC. Compared with existing VSG-based methods, the proposed strategy integrates VZFR-based frequency restoration and a two-stage voltage-support mechanism within the same grid-forming VSC-HVDC framework while retaining the original virtual inertia and damping characteristics.

Table 1. Comparison with representative VSG/GFM control studies.

Method Category	Virtual Inertia/Damping	Frequency Restoration	Voltage Support Mechanism	Integrated P – f / Q – V Support
Conventional VSG [14]	✓	Droop-type	Basic	--
Adaptive VSG [17,18]	✓	Improved transient	Limited	--
Voltage-support methods [22–25]	✓	Not primary objective	✓	Mainly voltage side
Proposed method	✓	VZFR	Two-stage mechanism	✓

This paper therefore develops a VSG-based control scheme for grid-forming VSC-HVDC that addresses both frequency and voltage support. The main contributions are as follows:

(1) A VZFR method is incorporated into the active-power–frequency control channel. An auxiliary active-power command is generated from the accumulated frequency deviation to compensate for the power imbalance. This additional regulation improves post-disturbance frequency restoration without changing the virtual inertia and damping characteristics of the original VSG.

(2) A two-stage transient voltage-support mechanism of grid-forming VSC-HVDC is clarified. At the onset of a voltage sag, the converter internal voltage together with the equivalent impedance determines the instantaneous bus-voltage response. As the transient develops, the reactive-power–voltage loop further adjusts the internal voltage and reactive-power output, thereby promoting voltage recovery.

(3) Frequency and voltage support are evaluated within the same VSG-based control framework. Active-load changes and voltage sags of different depths are considered to examine the frequency response, voltage recovery, and performance of the proposed method under different disturbance levels.

The remainder of this paper is organized as follows. Section 2 introduces the control characteristics of grid-forming VSC-HVDC and the operating principle of VSG control. Section 3 presents the improved active-power–frequency support strategy based on VZFR. Section 4 analyzes the transient voltage–reactive-power support strategy. Section 5 presents simulation results under active load disturbances and grid voltage sag conditions. Section 6 concludes the paper.

2. Control Characteristics of Grid-Forming VSC-HVDC and Operating Principle of VSG

2.1. Control Characteristics of Grid-Forming VSC-HVDC

The VSC-HVDC controller converts the specified operating references into gating signals for the converter valves, thereby regulating active/reactive power, voltage, and current. Its control system is hierarchically divided into system, converter-station, and valve control layers. A block diagram of the hierarchical control is shown in Figure 1.

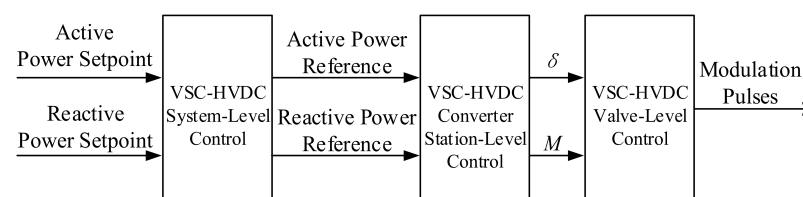


Figure 1. Schematic diagram of hierarchical control for VSC-HVDC.

As converter-interfaced resources increase, the reduction in synchronous-machine support places greater requirements on converter-based voltage establishment and dynamic regulation. Unlike grid-following (GFL) control, GFM control does not require the external grid to determine its phase and frequency reference. Instead, the converter internally generates the AC voltage magnitude and phase and therefore behaves as a controllable voltage source, as summarized in Table 2.

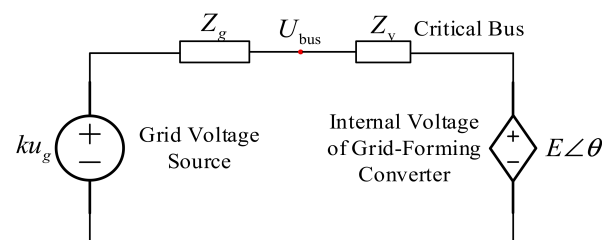
VSG-based GFM control enables grid-connected inverters to autonomously establish the AC voltage and provide synchronization support [26]. The grid-forming converter first generates a stable internal voltage reference and then delivers power to the grid through the power conversion stage, making its external characteristics more similar to those of a synchronous generator rather than a conventional controlled current source.

Table 2. Comparison of control characteristics between GFL and GFM VSG control.

Comparison Items	Grid-Following Control (GFL)	Grid-Forming VSG Control (GFM-VSG)
Equivalent Model Synchronization	Controlled Current Source PLL-dependent, tracking grid voltage	Controlled Voltage Source Self-synchronized, autonomous frequency/phase generation
Voltage Support Capability	Weak, constrained by equivalent impedance and current limits	Strong, internal voltage directly clamps the bus
Frequency Support Capability	No inherent inertia	Provides virtual inertia and damping
Fault Ride-Through Capability	Limited, PLL may degrade under severe faults	Robust, independent of external voltage reference
Islanding Operation Capability	Requires mode switching	Naturally supported
Applicable Scenarios	Strong grids, conventional grid-connected operation	Weak grids, microgrids, critical load support

For circuit-level analysis, the GFM converter is modeled by an internal controllable voltage behind a virtual impedance, as shown in Figure 2. If the upstream grid is equivalently modeled as a voltage source u_g in series with impedance Z_g , and the grid-forming energy storage system is represented as an internal electromotive force $E\angle\theta$ in series with virtual impedance Z_v , with both connected to the same critical bus (neglecting the effects of load branches), the Thevenin voltage division relationship can be derived as follows:

$$U_{\text{bus}} = \frac{Z_v}{Z_g + Z_v} u_g + \frac{Z_g}{Z_g + Z_v} \dot{E} \quad (1)$$

**Figure 2.** GFM equivalent voltage source model.

The term $Z_g \times \dot{E} / (Z_g + Z_v)$ is included in ΔU_{bus} of the GFM system, which directly participates in the voltage division. When the grid voltage drops to ku_g due to a fault, the bus voltage at the fault instant is given by Equation (1):

$$U_{\text{bus},0} = \frac{Z_v}{Z_g + Z_v} ku_g + \frac{Z_g}{Z_g + Z_v} E_0 \quad (2)$$

where E_0 is the steady-state internal voltage before the fault. Equation (2) indicates that even if the grid-side voltage drops instantaneously, as long as the converter internal voltage E_0 remains unchanged, the bus voltage can still be upheld through the voltage division relationship; the larger the voltage division ratio $Z_g / (Z_g + Z_v)$, the stronger the clamping effect. This is the fundamental reason why the GFM possesses voltage clamping capability during the initial stage of faults. This process does not depend on the dynamic response of any control loop but is determined solely by the voltage-source external characteristics of the GFM.

When the resistance is neglected and the equivalent impedance is assumed to be inductive, with the equivalent reactance denoted as X , P and Q of the grid-forming VSC-HVDC can be further expressed as follows:

$$P = \frac{EU_{\text{bus}}}{X} \sin \theta \quad (3)$$

$$Q = \frac{EU_{\text{bus}} \cos \theta - U_{\text{bus}}^2}{X} \quad (4)$$

Equations (3) and (4) reveal the classic power transfer characteristics: the power angle θ primarily affects the active power, while the internal voltage magnitude E directly influences the reactive power support and the bus voltage level. This provides the mathematical foundation for the P - f loop and the Q - V loop of the VSG, where the former adjusts θ and the latter adjusts E .

2.2. Operating Principle of VSG

The topology of the VSG is illustrated in Figure 3. The VSG regulates the inverter according to a dynamic model derived from synchronous-machine behavior, thereby introducing inertia, damping, frequency-regulation, and voltage-regulation responses into the converter. The VSG implementation contains a power circuit and its associated control system. The power stage follows the conventional inverter topology, mainly comprising the converter, filter, DC voltage source, line resistance, and inductance. The primary difference lies in the control section, where the VSG control employs the electromagnetic transient equations of the synchronous generator and introduces the rotor mechanical motion equations. From the AC terminal, the converter behaves as a controllable voltage source whose magnitude and phase are determined through the active- and reactive-power control channels. The modulation pulses for controlling the turn-on and turn-off of the IGBTs are then generated through modulation techniques.

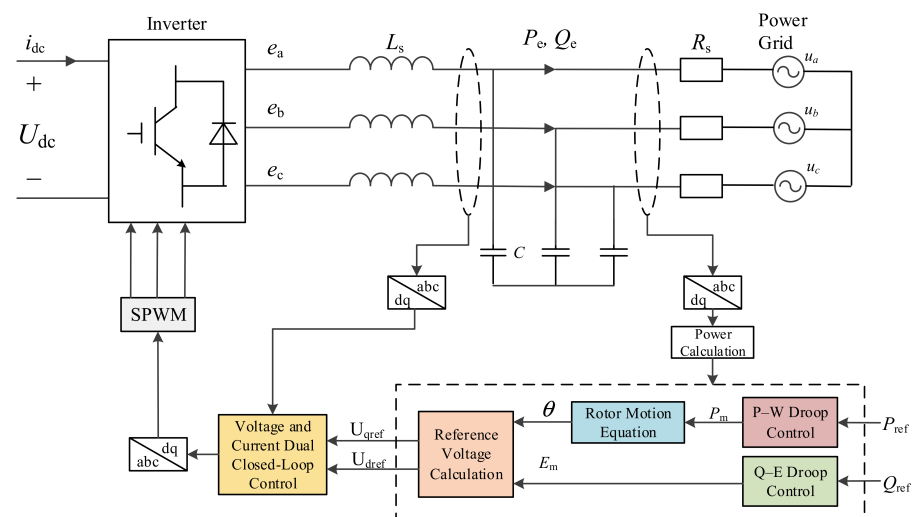


Figure 3. Schematic diagram of hierarchical control for VSC-HVDC system.

In Figure 3, $e_{\text{abc}} = [e_a, e_b, e_c]^T$, $u_{\text{abc}} = [u_a, u_b, u_c]^T$, and $i_{\text{abc}} = [i_a, i_b, i_c]^T$ denote the three-phase output voltage of the VSG, the grid voltage, and the grid-side current, respectively. R_s and L_s are the equivalent resistance and inductance of the reactor and transformer between

the converter station and the terminal grid. P_e and Q_e represent the active and reactive power output of the VSG, respectively.

$$\begin{cases} P_e = e_a i_a + e_b i_b + e_c i_c \\ Q_e = \frac{(e_a - e_b) i_c + (e_b - e_c) i_a + (e_c - e_a) i_b}{\sqrt{3}} \end{cases} \quad (5)$$

2.3. Equivalence Between Converter and VSG

Figure 4 compares the power-transfer dynamics of the converter station with those of a synchronous generator.

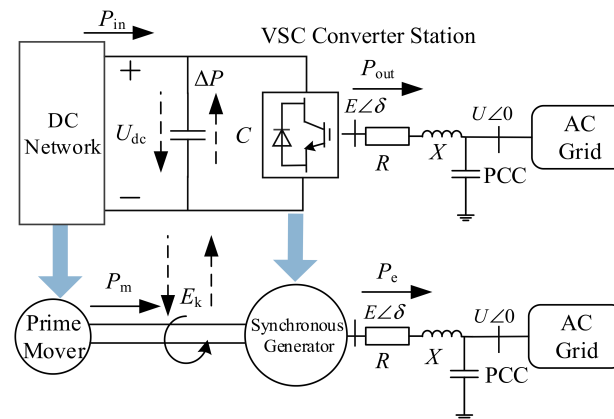


Figure 4. Comparison diagram of the converter and the synchronous generator.

In Figure 4, the point of common coupling (PCC) is the grid-connected bus. The reference voltage is set to $U\angle 0$, and the AC-side terminal voltage of the converter station and the synchronous generator terminal voltage are $E\angle \delta$. The mechanical power output of the prime mover is P_m , the rotor kinetic energy is E_k , and the electromagnetic power of the synchronous generator is P_e .

The rotor dynamics describe the instantaneous power imbalance of the synchronous generator as follows:

$$P_m - P_e = 2H \frac{d\omega}{dt} \quad (6)$$

In Equation (6), H is the generator inertia time constant.

For the converter station, the corresponding power imbalance is reflected by the energy variation of the DC-link capacitor:

$$P_{in} - P_{out} = CU_{dc} \frac{dU_{dc}}{dt} \quad (7)$$

where P_{in} denotes the input power to the VSC-HVDC system. P_{out} denotes the power delivered from the VSC-HVDC system to the AC system. C is the shunt capacitance in the converter station, and U_{dc} is the DC voltage across the capacitor. Comparison of Equations (6) and (7) shows that both systems describe an energy-buffering process driven by the mismatch between input and output power.

By reformulating Equation (6) and applying the rotor motion equation to the converter station, the VSG control strategy is adopted for the converter station. Accordingly, the converter control incorporates the virtual inertia J and damping coefficient D to represent the dynamic effects associated with frequency variation. The resulting expression is given as follows:

$$J \frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega_{ref}) \quad (8)$$

The presence of J endows the system with inertial characteristics in the power and frequency responses during dynamic transients, while the presence of D introduces damping characteristics that mitigate power oscillations in the system. For the passive network considered in this study, the receiving-end VSC cannot rely on an external grid to provide a stable voltage phase and frequency reference. Therefore, VSG control is adopted to enable the converter to behave as a controllable voltage source and to establish the AC-side voltage and frequency while providing inertial and damping support.

3. Improved VSG-Based Active Support Control Strategy for Transient Active-Power-Frequency Response

VSC-HVDC systems, owing to their self-commutation capability, are able to operate in a passive inverter mode, thereby enabling power supply to passive networks. However, the inner and outer control loops of the VSC-HVDC system cannot respond to frequency variations in the passive network and, thus, are incapable of providing frequency support. To address this issue, the virtual synchronous generator (VSG) control strategy is considered to enhance the system inertia and to achieve frequency regulation for the passive network. Nevertheless, the steady-state P - f characteristic of a conventional VSG follows a droop relation. Following a load step, a new active-power equilibrium can be established, but the corresponding steady-state frequency generally differs from the nominal value. Instead, it settles at a new steady-state point with a persistent deviation. To overcome this limitation, based on the concept of virtual zero-error frequency regulation (VZFR), an auxiliary power command derived from the accumulated angular-frequency error is added to the conventional VSG P - f loop. This enables the frequency deviation to be further reduced or even eliminated under steady-state conditions.

Due to the poor frequency stability, weak self-regulation capability, and low inertia of passive networks, higher control requirements are imposed on the converter station connected to such networks. With conventional VSC-HVDC control, it is difficult to achieve phase-locked synchronization of the voltage, and frequency regulation becomes challenging. The frequency of the passive network is highly susceptible to power or load fluctuations.

According to Equation (8), when the passive network reaches a steady state, the following relationship holds:

$$\frac{d\omega}{dt} = 0 \rightarrow P_{VSG} - P_L = D\omega_{ref}(\omega - \omega_{ref}) \quad (9)$$

Equation (9) indicates that there exists a droop characteristic between the active power and frequency in the VSG control. Figure 5 illustrates the frequency regulation characteristic curve of the VSG for the passive network, where P_{VSG} represents the power output curve of the converter station. When the load of the passive network changes by ΔP_L , the VSG control performs primary frequency regulation from point A to point B, corresponding to a frequency deviation $\Delta f_1 = f_{ref} - f_1$. Subsequently, owing to the inherent regulation characteristics of the load itself, the operating point shifts from point B to point B', with the resulting frequency deviation $\Delta f = f_{ref} - f_2$. The frequency settles at f_2 and cannot return to the rated frequency f_{ref} . This indicates that the VSG control essentially emulates the primary frequency regulation of a conventional system, which is inherently a droop-based (or nonzero-error) regulation.

Figure 6 illustrates how the additional VZFR action modifies the conventional primary frequency response. By modifying the output power characteristic of the converter station, the VZFR control adjusts the P_{VZFR} curve to P'_{VZFR} , shifting the operating point from B to C. Consequently, the system can achieve zero-error frequency control.

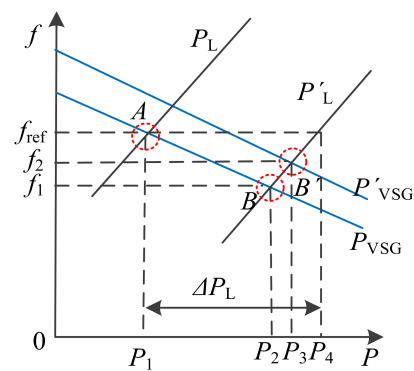


Figure 5. VSG primary frequency regulation in a passive network.

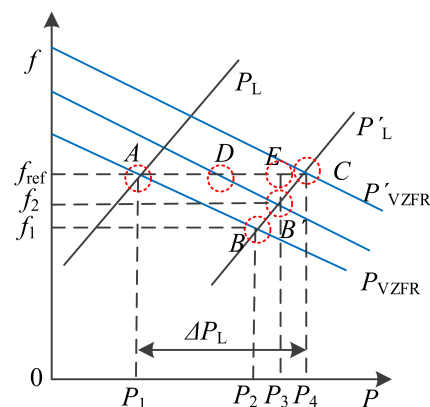


Figure 6. Primary and secondary frequency regulation of the VZFR control.

As shown in Figure 6, the increase in system load ΔP_L consists of the following three components:

$$\Delta P_L = \Delta P_{VZFR} - K_{VZFR} \Delta f - K_L \Delta f \quad (10)$$

where ΔP_{VZFR} is the power increment contributed by the VZFR control (corresponding to line segment AD in the figure), $-K_{VZFR} \Delta f$ is the power increment contributed by the primary frequency regulation of the VSG control (corresponding to line segment DE), and $-K_L \Delta f$ is the power increment resulting from the inherent frequency regulation of the load itself (corresponding to line segment EC).

Equation (10) represents the power balance equation for zero-error frequency regulation, which can be rewritten as follows:

$$\Delta P_L - \Delta P_{VZFR} = -(K_{VZFR} + K_L) \Delta f = -K \Delta f \quad (11)$$

where K is the frequency regulation coefficient of the passive network system.

The deviation expression for the converter station participating in the frequency regulation of the passive network is given by the following:

$$\Delta f = -\frac{\Delta P_L - \Delta P_{VZFR}}{K} \quad (12)$$

According to Equation (12), nominal-frequency restoration requires the VZFR power increment to compensate for the load-power variation, i.e., $\Delta P_L = \Delta P_{VZFR}$. The variation in angular frequency is integrated to obtain the change in power angle, which is then processed through an adaptive proportional link to generate the additional power required

to compensate for the power imbalance caused by load fluctuations. The expression for ΔP_{VZFR} is given as follows:

$$\Delta P_{VZFR} = K_\theta \frac{1}{s} (\omega - \omega_{\text{ref}}) \quad (13)$$

where K_θ is the power-angle synchronization coefficient.

Equation (13) links the accumulated frequency variation to the auxiliary active-power command, allowing the converter to follow changes in passive-network demand. Substituting Equation (13) into Equation (8), the second-order mathematical model of the virtual synchronous generator with additional frequency control is obtained as follows:

$$J \frac{d\omega}{dt} = \left[\frac{P_{VSG} - P_L - \Delta P_{VZFR}}{\omega_{\text{ref}}} \right] - D(\omega - \omega_{\text{ref}}) \quad (14)$$

Substituting Equation (13) into Equation (14) yields the following:

$$J \frac{d\omega}{dt} = \frac{P_{VSG} - P_L - \frac{K_\theta}{s} (\omega - \omega_{\text{ref}})}{\omega_{\text{ref}}} - D(\omega - \omega_{\text{ref}}) \quad (15)$$

From Equation (15), it can be seen that the variation in angular frequency, after being integrated and regulated by the power-angle synchronization coefficient, yields the adjusted active power. This adjusts the power deviation of the passive network system, thereby compensating for the input–output power mismatch. The VZFR control is thus derived from the active-power–frequency control of the VSG control. The additional regulation does not alter the original inertia and damping terms of the VSG and therefore preserves its transient support characteristics. The corresponding control block diagram is shown in Figure 7.

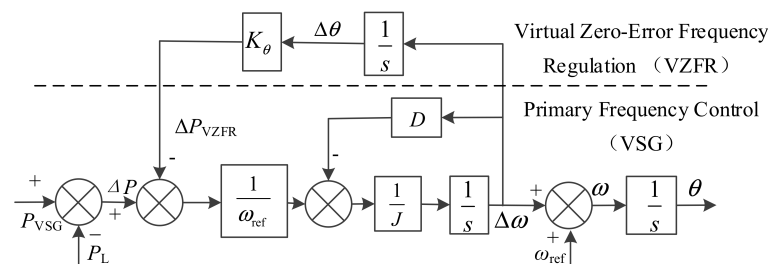


Figure 7. Control block diagram of the VZFR strategy.

To further analyze the stability of the proposed VZFR control, a small-signal model is established around the steady-state operating point. Since the equivalent impedance between the converter and the receiving-end grid is mainly inductive, the active-power relationship can be linearized under a small disturbance as:

$$P_{VZFR} = \frac{3EU_g}{X_s} \theta \quad (16)$$

where E denotes the magnitude of the inverter internal voltage, U_g denotes the receiving-end grid-voltage magnitude, and X_s denotes the equivalent reactance between the inverter and the receiving-end grid.

Combining this relationship with the VZFR dynamics derived above, the closed-loop transfer function from the load-power disturbance ΔP_L to the VZFR power response ΔP_{VZFR} can be obtained as follows:

$$\frac{\Delta P_{VZFR}(s)}{\Delta P_L(s)} = \frac{3EU_g}{(Js^2 + Ds + K_\theta)\omega_{\text{ref}}X_s + 3EU_g} \quad (17)$$

Based on the derived small-signal model, the root-locus method is employed to investigate the influence of the power-angle synchronization coefficient K_θ . With $J = 0.0236/\text{kg}\cdot\text{m}^2$ and $D = 0.03 \text{ N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$, K_θ is varied from 0 to 80. As shown in Figure 8, the conjugate characteristic roots λ_1 and λ_2 remain in the left-half complex plane throughout the investigated range and do not cross the imaginary axis. Therefore, the VZFR control loop maintains local small-signal stability for $0 \leq K_\theta \leq 80$. Moreover, since the VZFR control does not modify the original virtual inertia and damping terms, the inherent inertia and damping characteristics of the VSG are retained, while the additional power-compensation loop improves frequency restoration.

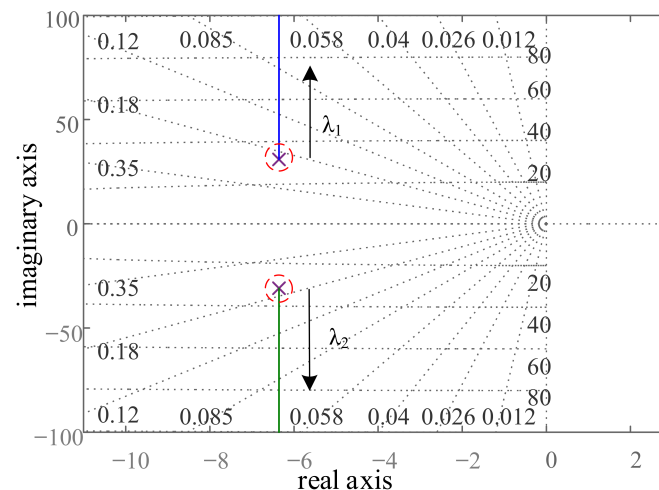


Figure 8. Root loci of the VZFR control system with K_θ varying from 0 to 80.

In a passive network system, only the load frequency regulation characteristic is available. When the VSG control strategy is adopted, primary frequency regulation can be realized. However, the frequency of the passive network remains affected by load variations and cannot be restored to its nominal value. In contrast, when the proposed VZFR control strategy is applied, the input and output powers of the passive network system are maintained in balance, and the system frequency is independent of load fluctuations, remaining at the nominal value. Moreover, the advantages of inertia support and damping characteristics inherent in the VSG are preserved, thereby enhancing the stability of the passive network.

4. VSG-Based Transient Active Support Control Strategy for Voltage–Reactive-Power Response

Voltage regulation of the VSG is mainly implemented through its reactive-power-voltage channel. This channel updates the virtual internal voltage E using the deviations in bus voltage and reactive power, thereby adjusting the converter output voltage reference. Because the GFM-VSG establishes its own voltage reference rather than deriving synchronization from the external grid, its voltage magnitude is governed by the Q – V loop, whereas the P – f loop determines the voltage phase. Therefore, during grid voltage sags or sudden increases in reactive power demand, this control loop can enhance the voltage support capability at the critical bus by boosting the virtual internal voltage.

The reactive-power-voltage control structure adopted in this paper is shown in Figure 9. This control loop takes the rated bus voltage U_n , the actual bus voltage U_s , the reactive power reference Q_{ref} , and the actual output reactive power Q_e as inputs. The virtual internal voltage magnitude E is regulated by a PI excitation regulator, which is driven by the voltage deviation and the reactive power deviation.

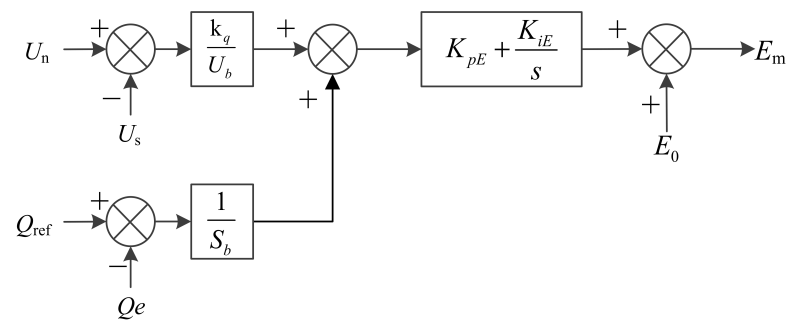


Figure 9. Block diagram of reactive-power-voltage control.

Based on Figure 9, the combined deviation signal of the reactive-power-voltage control loop can be expressed as follows:

$$\Delta_{uq} = k_q \frac{U_n - U_s}{U_b} + \frac{Q_{ref} - Q_e}{S_b} \quad (18)$$

where Δ_{uq} is the voltage-reactive-power combined deviation signal, U_b is the voltage base value, S_b is the apparent power base value, and k_q is the reactive-power-voltage regulation coefficient, which characterizes the influence of the bus voltage deviation on the regulation of the virtual internal voltage.

The virtual internal voltage adjustment output by the PI excitation regulator is given by the following:

$$\Delta E = \left(K_{pE} + \frac{K_{iE}}{s} \right) \Delta_{uq} \quad (19)$$

K_{pE} and K_{iE} are the proportional gain and integral gain of the PI regulator in the reactive-power-voltage loop, respectively. The proportional component accelerates the transient response, whereas the integral component removes the remaining steady-state deviation, enabling the internal voltage to be continuously adjusted according to the bus voltage and reactive power deviations.

Consequently, the virtual internal voltage magnitude can be expressed as follows:

$$E_m = E_0 + \Delta E \quad (20)$$

where E_0 is the base value of the virtual internal voltage, which can be obtained from the rated voltage magnitude through conversion with the base voltage.

As indicated by the control relationship described above, the variation of the virtual internal voltage is jointly driven by both the voltage deviation and the reactive power deviation. Under normal operating conditions, the critical bus voltage is close to the rated value, and the actual output reactive power is approximately equal to the reference value. In this case, the combined deviation signal Δ_{uq} remains small, and the virtual internal voltage E_m is maintained around its base value. Following a grid-voltage sag, the decrease in U_s enlarges the voltage-error component of Δ_{uq} . This deviation is processed by the PI regulator, which raises the virtual internal voltage, which raises the VSG voltage reference and provides additional support to the critical bus.

Simultaneously, when the reactive power demand of the system increases, if the actual output reactive power Q_e falls below the reactive power reference Q_{ref} , the reactive power deviation term increases, which also drives the virtual internal voltage to rise, enabling the converter to deliver more reactive power. The integral action of the PI regulator reduces the steady-state error caused by deviations in reactive power and bus voltage, thereby improving the steady-state regulation performance of the reactive-power-voltage loop.

In summary, the modulation-wave phase is determined by θ generated from the active-power loop, whereas its amplitude is specified by E_m obtained from the reactive-power loop. Finally, the pulse-width modulation (PWM) signals are generated, and the three-phase modulation waveforms are given by:

$$\begin{cases} e_{am} = E_m \sin \theta \\ e_{bm} = E_m \sin(\theta - \frac{2\pi}{3}) \\ e_{cm} = E_m \sin(\theta + \frac{2\pi}{3}) \end{cases} \quad (21)$$

where e_{am} , e_{bm} , and e_{cm} are the three-phase modulation signals.

Based on the VZFR control, the active support strategy for the VSC-HVDC converter station is illustrated in Figure 10.

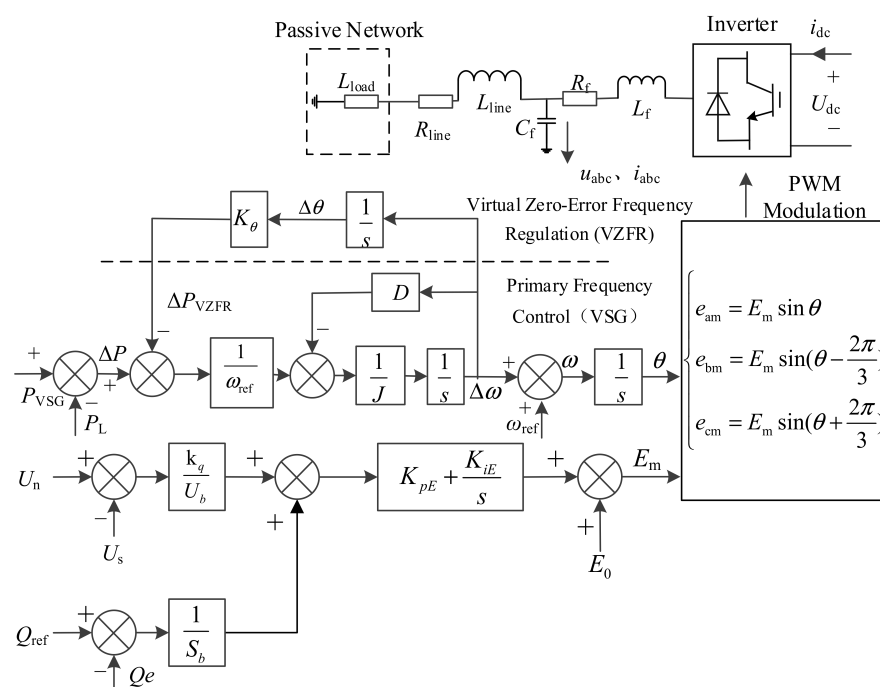


Figure 10. Block diagram of VSG-based active support strategy for VSC-HVDC.

5. Simulation Verification

The proposed control is evaluated using the PSCAD/EMTDC model shown in Figure 11. Table 3 gives the main parameters of the two-terminal VSC-HVDC model. The AC grid connected to the rectifier station VSC1 adopts the conventional inner-outer loop control strategy of VSC-HVDC, while the inverter station VSC2, which is connected to a passive network, employs VSG control.

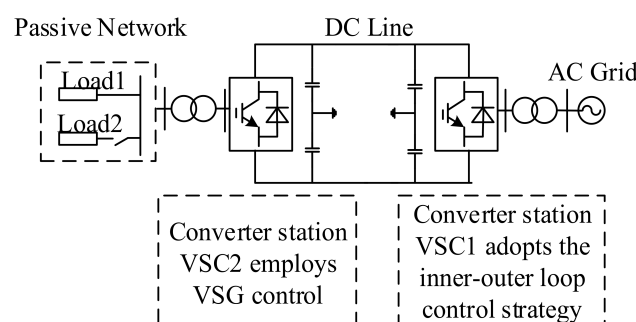


Figure 11. Structural diagram of the VSC-HVDC system for supplying power to a passive network.

Table 3. Main parameters of the VSC-HVDC system.

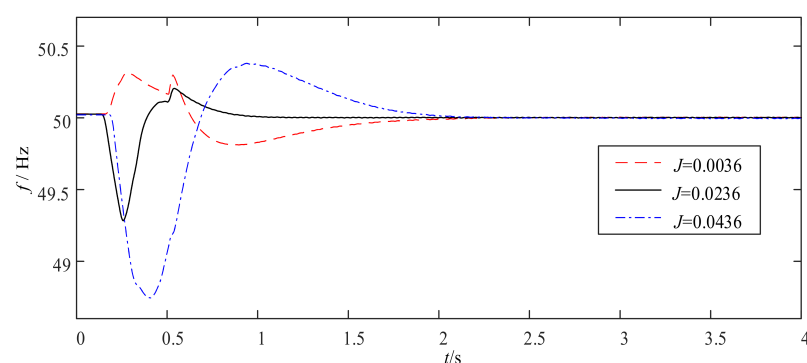
Parameter	Value
DC voltage U_{dc}/kV	400
DC capacitance/ μF	2000
Passive network voltage U/kV	110
Rated capacity of VSC2/MW	400
Rated capacity of VSC1/MW	400
Filter capacitance/ μF	5
Filter resistance/ Ω	0.1
Filter inductance/H	0.1
Fixed load/MVA	$300 + j100$
Damping coefficient/ $\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$	0.03
Moment of inertia/ $\text{kg}\cdot\text{m}^2$	0.0236
Initial value of synchronization coefficient (K_0)	400

5.1. Validation of the Improved VSG-Based Active Support Strategy for Active-Power–Frequency Response

To validate the effectiveness of the proposed control strategy in providing necessary frequency support for the passive network system and enhancing its dynamic stability performance, a comparative study is conducted based on the simulation model shown in Figure 11. Both the conventional VSG and the improved VSG are implemented in converter station VSC2 for comparison. The system frequency and active power responses under various disturbance conditions are analyzed through simulations.

5.1.1. Parameter Impact Analysis

With the damping coefficient $D = 0.03 \text{ N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$, simulations are carried out for three different values of the inertia coefficient J , namely $0.0036 \text{ kg}\cdot\text{m}^2$, $0.0236 \text{ kg}\cdot\text{m}^2$, and $0.0436 \text{ kg}\cdot\text{m}^2$. The frequency responses during the system startup process are illustrated in Figure 12. From the simulation waveforms, it can be observed that an excessively large inertia coefficient results in a larger frequency overshoot and a slower response speed, leading to a longer settling time. Conversely, if the inertia coefficient is too small, the system responds too rapidly, which is detrimental to frequency regulation. Therefore, the appropriate selection of the inertia coefficient is crucial to the system performance. Considering all factors, $J = 0.0236/\text{kg}\cdot\text{m}^2$ is adopted in this paper.

**Figure 12.** System frequency response under different inertia coefficients.

After selecting $J = 0.0236/\text{kg}\cdot\text{m}^2$, simulations are carried out for three different values of the damping coefficient D , namely $0.02/\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$, $0.03/\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$, and $0.04/\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$. The frequency responses during the system startup process are illustrated in Figure 13. From the simulation waveforms, the results show that insufficient damping increases the frequency overshoot and slows the decay of oscillations. Conversely,

if the damping coefficient is too large, the settling time becomes longer. Therefore, the appropriate selection of the damping coefficient is crucial to the system performance. Considering all factors, $D = 0.03/\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$ is adopted in this paper. Therefore, J and D are selected by balancing frequency overshoot, response speed, and settling time. The parameter-sensitivity results also indicate that the system remains stable within the tested parameter ranges, although the transient performance varies with the selected values.

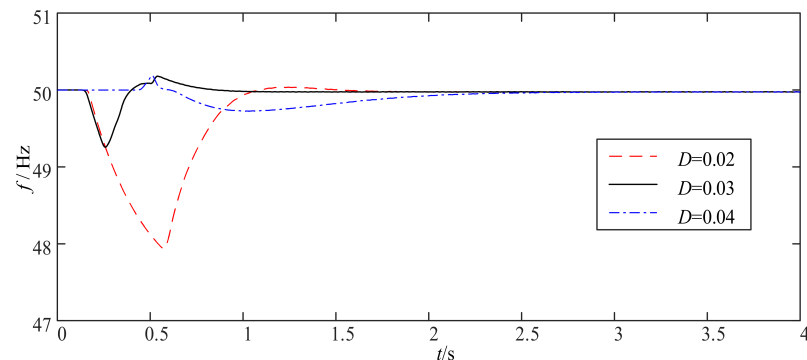


Figure 13. System frequency response under different damping coefficients.

5.1.2. Comparison of System Response Under Active Load Step Change

To compare the transient active support performance of the conventional VSG and the improved VSG under active load disturbances, an additional active load of $\Delta P_L = 30$ MW is applied at $t = 2.5$ s and removed at $t = 3.5$ s.

Figure 14 presents the system frequency response curves of the conventional VSG and the improved VSG under an active load step change. After the additional load is applied at $t = 2.5$ s, the system frequency under both control strategies gradually decreases from a higher value and converges toward 50 Hz. In the initial stage of the disturbance, the two curves overlap closely, indicating that the transient response is primarily governed by the virtual inertia and damping characteristics. This also demonstrates that the improved VSG does not compromise the inherent inertia support capability of the conventional VSG.

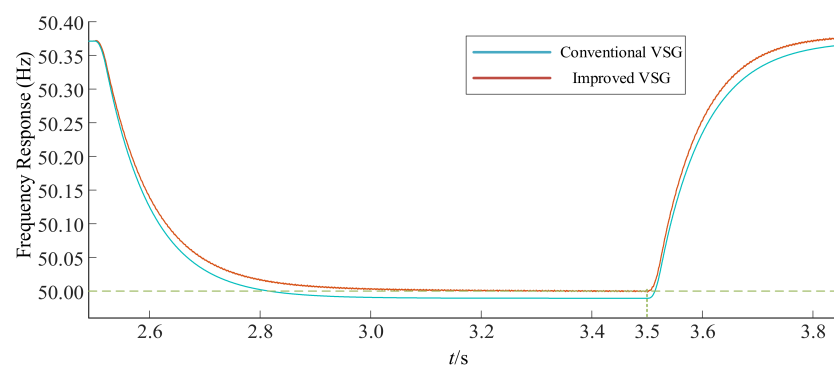


Figure 14. Comparison of system frequency responses under load step change.

As shown in Figure 15, during the regulation process after the load is applied, the frequency curve of the improved VSG is slightly higher than that of the conventional VSG, and after 0.5 s of stabilization, it becomes closer to the rated frequency. This behavior confirms that the auxiliary power loop reduces the residual frequency error and improves post-disturbance frequency restoration. When the additional load is removed at $t = 3.5$ s, the system frequency rises, and both control strategies gradually settle down, with the improved VSG exhibiting a relatively smaller frequency overshoot.

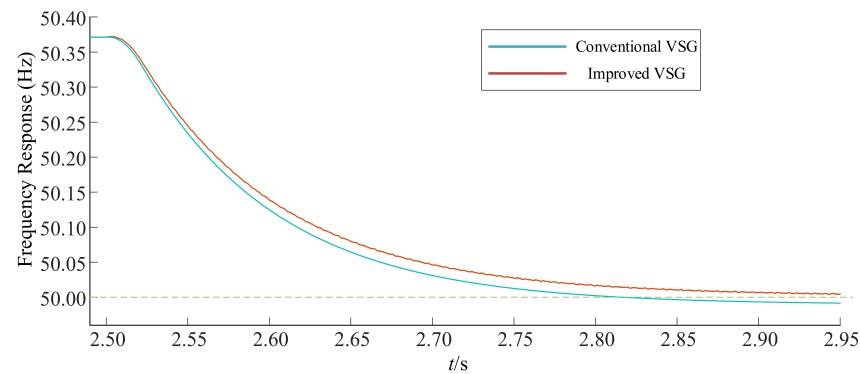


Figure 15. Local characteristics of system frequency response under load step change.

As shown in Table 4, the proposed VZFR significantly reduces the frequency deviation compared with the conventional VSG. The absolute frequency deviation is reduced by 62.5% at $t = 3.0$ s and by 96.4% at $t = 3.4$ s, while the frequency enters and remains within the ± 0.01 Hz band approximately 0.364 s after the disturbance.

Table 4. Quantitative comparison of frequency regulation under the 30 MW load disturbance.

Performance Index	Conventional VSG	Improved VSG	Improvement
Frequency at $t = 3.0$ s/Hz	49.991	50.004	--
Absolute frequency deviation at $t = 3.0$ s/Hz	0.0093	0.0035	62.5% ↓
Frequency at $t = 3.4$ s/Hz	49.9890	50.0004	--
Absolute frequency deviation at $t = 3.4$ s/Hz	0.0106	0.0004	96.4% ↓
Time to enter and remain within ± 0.01 Hz/s	Not achieved	0.364	--

In summary, while maintaining the inertia response characteristics of the conventional VSG, the improved VSG can reduce the frequency deviation caused by load variations, driving the operating frequency toward its nominal value. This demonstrates its superior active-power–frequency active support capability.

5.1.3. Validation of Support Capability Under Different Disturbance Magnitudes

To simulate the system recovery capability under disturbances of different magnitudes, four independent simulation cases are carried out. An additional active load is applied at $t = 2.5$ s and removed at $t = 3.5$ s, with the load magnitudes set to 30 MW, 40 MW, 50 MW, and 60 MW, respectively. The frequency waveforms for comparison are shown in Figure 16.

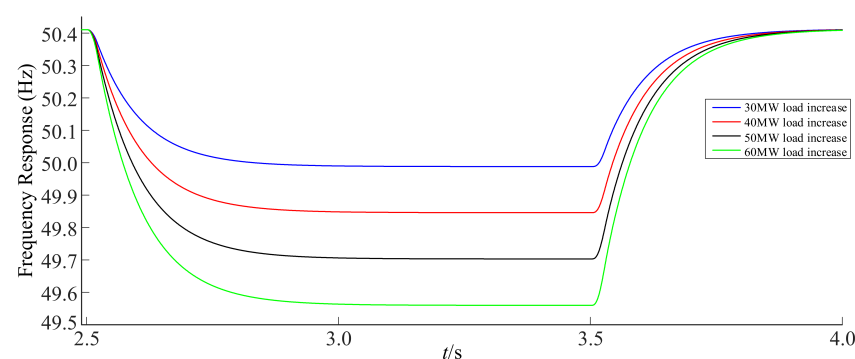


Figure 16. Comparison of frequency responses under different disturbances.

As can be observed from the frequency response waveforms, at the instant of load application at $t = 2.5$ s, the system frequency under all four operating conditions drops rapidly to its respective steady-state deviation value. The steady-state frequency deviation deepens monotonically with the disturbance magnitude, with the smallest deviation occurring in the 30 MW case and the largest in the 60 MW case. Moreover, the increment of frequency deviation is approximately proportional to the increment of disturbance magnitude. This linear relationship indicates that, within the disturbance range of 30–60 MW, the additional compensation loop does not reach its saturation limits. The frequency responses in the steady-state period are flat and oscillation-free under all conditions, suggesting that the system possesses sufficient damping margin. At $t = 3.5$ s, following the removal of the additional load, the frequency recovers toward the rated value, and the transient process is smooth without overshoot.

The active power output waveform of VSC2 reflects the capability of the VSG to undertake power disturbances. As shown in Figure 17, at the instant of load application, the active power steps up to a new steady-state value without noticeable overshoot or oscillations. Upon load removal, the power drops back rapidly, with only a brief negative spike during the transition, lasting on the order of milliseconds, which does not affect system stability. Comparing the two sets of waveforms, it can be seen that the larger the disturbance magnitude, the greater the increase in active power, which corresponds to a deeper steady-state frequency deviation, exhibiting a strict correspondence between the two. This correspondence directly reflects the physical mechanism of the improved VSG control strategy: the additional compensation loop, through the integral action on the frequency deviation, generates a compensation power command that matches the power deficit. This enables the VSG to achieve power balance under various disturbance magnitudes with a relatively small steady-state frequency deviation, without the need for secondary frequency regulation. The stable and well-damped responses under the 30–60 MW load disturbances further demonstrate that the proposed strategy maintains satisfactory transient performance within the investigated operating range.

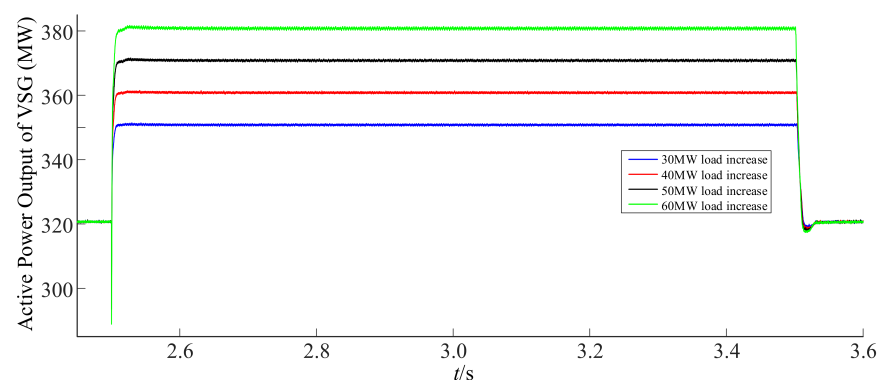


Figure 17. Comparison of VSC2 active power output under different disturbances.

5.2. Validation of the VSG-Based Transient Active Support Strategy for Voltage–Reactive-Power Response

To validate the transient active support capability of the VSG control for the critical bus under grid voltage sag conditions, a balanced three-phase voltage-sag scenario is considered. The system operates at the rated condition prior to $t = 1.0$ s. At that point, a three-phase symmetrical voltage sag occurs in the upstream grid, with the voltage magnitude dropping to $0.8 U_N$. After a sag duration of 150 ms, the voltage recovers to its rated value at $t = 1.15$ s.

Figure 18 presents the RMS voltage of the critical bus under grid voltage sag. At the instant of fault occurrence, the critical bus voltage experiences a temporary drop. However, under the VSG control, the bus voltage does not fully follow the grid voltage sag. Instead, it is supported within a short period and gradually recovers. The minimum value is approximately 0.975 p.u., and the time required to recover to 0.98 p.u. is about 40 ms.

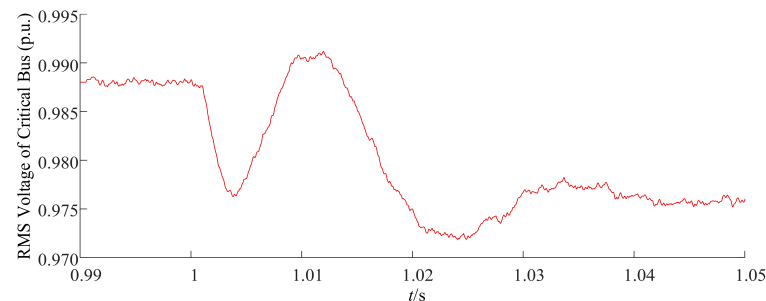


Figure 18. RMS voltage of critical bus under grid voltage sag.

This result indicates that the energy storage converter under VSG control exhibits the characteristics of a controlled voltage source. At the moment of grid voltage sag, the virtual internal voltage can still participate in the formation of the critical bus voltage through the virtual impedance and line impedance, thereby providing instantaneous voltage division clamping to the bus voltage. Subsequently, the reactive-power-voltage control loop regulates the virtual internal voltage based on the bus voltage deviation, further boosting the inverter output voltage and thus reducing the magnitude of the critical bus voltage sag.

As shown in Figure 19, VSC2 rapidly increases its reactive-power injection after the voltage sag to support the critical-bus voltage. The peak value of reactive power is approximately 16 kvar and then approaches its pre-disturbance level once the fault is cleared. This transient process indicates that the reactive-power-voltage control loop can adjust the reactive power output quickly in response to bus voltage deviations, enabling the energy storage system to undertake voltage support tasks during faults.

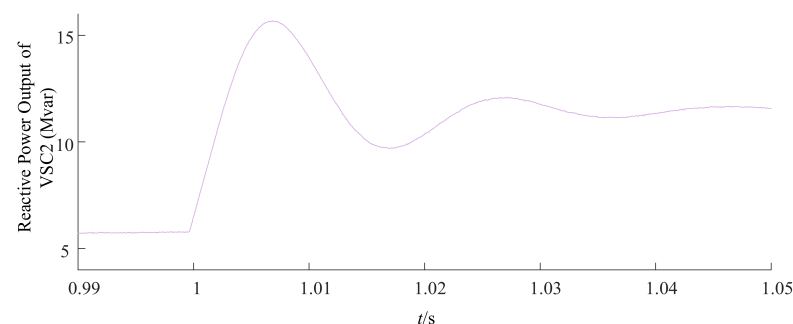
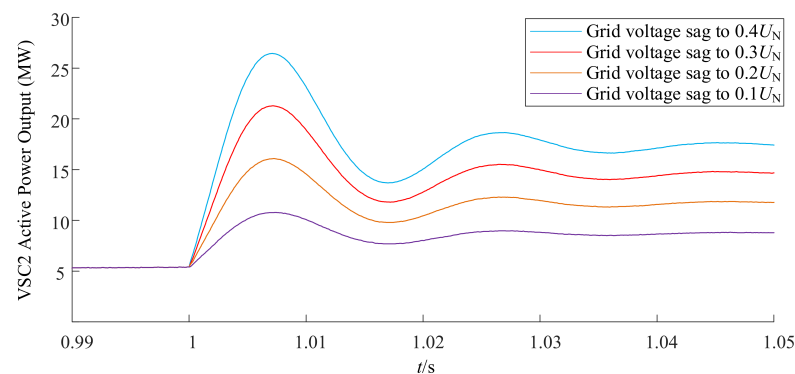
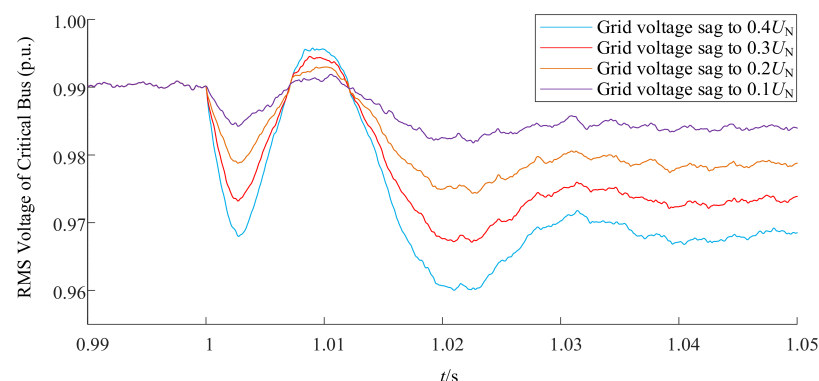


Figure 19. Reactive power output waveform of VSC2 under grid voltage sag.

The response to sag severity is further examined using four voltage levels. Four cases are designed with grid voltage sags to $0.9 U_N$, $0.8 U_N$, $0.7 U_N$, and $0.6 U_N$, respectively, each with a duration of 150 ms. The minimum value of the critical bus voltage, recovery time, and the peak reactive power of VSC2 under these cases are compared. The results under grid voltage sag conditions are summarized in Table 5, and the comparative waveforms are shown in Figures 20 and 21.

Table 5. Results under grid voltage sag conditions.

Voltage Sag Depth/ U_N	Minimum Critical Bus Voltage/p.u.	Recovery Time/ms	Peak Reactive Power/Mvar
0.9	0.982	40	11.7
0.8	0.975	40	16.8
0.7	0.967	45	22.3
0.6	0.961	48	26.5

**Figure 20.** Reactive power output of VSG under different voltage sag conditions.**Figure 21.** RMS voltage of critical bus under different voltage sag conditions.

A deeper grid-voltage sag produces a lower minimum critical-bus voltage and requires a higher peak reactive-power output from the VSG. This indicates that a more severe voltage sag requires stronger reactive power support from the system. Although the grid voltage sags to $0.9 U_N$, $0.8 U_N$, $0.7 U_N$, and $0.6 U_N$, respectively, the critical bus voltage does not fully follow the grid voltage drop in all cases. Instead, it remains at a relatively high level under the action of VSG control, demonstrating that the VSG control can provide active support to the critical bus under different voltage sag depths.

Under the aforementioned voltage sag conditions, the minimum value of the critical bus voltage remains at a relatively high level and does not significantly fall outside the equipment tolerance limits. Consequently, the voltage violation duration is relatively short, thereby lowering the likelihood of fault-induced supply interruption for critical loads.

6. Conclusions

A virtual zero-error frequency regulation strategy is developed by extending the conventional VSG power–frequency control according to the converter power-balance relation. In this strategy, the proposed method introduces an auxiliary active-power

command derived from the accumulated angular-frequency error. The additional VZFR power-compensation channel reduces the steady-state frequency deviation and drives the passive-network frequency toward its nominal value while retaining the virtual inertia and damping characteristics of the conventional VSG. The small-signal analysis further shows that the dominant characteristic roots remain in the left-half plane for $0 \leq K_\theta \leq 80$, demonstrating local small-signal stability within the investigated parameter range.

Furthermore, this paper investigates the VSG-based transient active support method for voltage–reactive-power response and analyzes the roles of the reactive-power–voltage control loop, virtual impedance, and the voltage and current dual closed-loop control in the voltage support process of the critical bus. The findings indicate that the voltage support capability of the VSG is twofold. First, immediately after the fault, the internal voltage together with the equivalent impedance limits the initial bus-voltage reduction. Second, as the transient develops, the Q – V loop modifies the internal voltage and reactive-power output to promote further voltage recovery.

The proposed strategy is finally assessed under active-load changes and grid-voltage sags of different severities to verify the active support capability of the grid-forming VSC–HVDC system based on VSG control. The simulation results show that stable frequency regulation is maintained for active-load disturbances ranging from 30 to 60 MW. Under grid-voltage sags from $0.9 U_N$ to $0.6 U_N$, the minimum critical-bus voltage remains between 0.982 and 0.961 p.u., with recovery times of 40–48 ms, while the peak reactive-power output increases from 11.7 to 26.5 Mvar. These results quantitatively demonstrate the frequency- and voltage-support capability of the proposed control within the investigated operating range.

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