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ORIGINAL RESEARCH

An improved fault control strategy for virtual synchronous generator with the coordination of STATCOM during unbalanced fault

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Abstract

The virtual synchronous generator (VSG) is a good solution for stabilizing the power system with high penetration of renewable energy. However, in case of serious unbalanced voltage disturbance/fault, the conventional VSG may lose voltage, inertia, and damping support characteristics to the grid and even can cause disconnection of renewable energy. This paper proposes an improved fault control strategy for VSG with the coordination of STATCOM. The proposed method can provide sufficient voltage support while keeping continuous system inertia and damping support under severe unbalanced fault. In the paper, an improved VSG and STATCOM control topology based on positive and negative sequence current control are first proposed so as to keep the damping and inertia support to grid during the grid fault. Secondly, the voltage support control method for the VSG with improved topology during unbalanced fault is introduced, which can achieve multiple control objectives, in terms of voltage support, current limitation, and active power output simultaneously. Then a coordination control scheme of improved VSG and STATCOM is developed so as to optimize the maximum control objectives in all possible scenarios, especially in the case of severe unbalanced fault. Finally, the effectiveness of the method is verified by using the MATLAB/SIMULINK simulation platform.

1 | INTRODUCTION

With the growing crisis of energy scarcity and global warming, low carbon development is gradually becoming a development strategy for countries around the world. Renewable energy generation represented by photovoltaic and wind turbines will gradually replace traditional thermal power generation, bringing challenges to the stable operation of the power system [1, 2]. Conventional synchronous generators store energy to provide inertia and damping to the grid due to the presence of the rotor. Most of the distributed generation units are grid-connected through inverters, and most of these inverter-interfaced distributed generation (IIRG) do not have the inertia and damping of synchronous generators, resulting in a relatively reduced rotating reserve capacity and rotating inertia in the power system, when the power system is susceptible to power fluctuations and faults that cause system instability [3]. Therefore, a virtual synchronous generator (VSG) control strategy has been proposed, which has an actual power source that can simulate a synchronous generator to provide rotational inertia, sag characteristics, and damping characteristics for the system. The literature [4, 5] describes the principles and implementation of voltage-controlled and current-controlled VSG. Currently, VSG have been extensively studied, and research has been conducted mainly for their steady-state operating conditions, including small-signal analysis [6, 7], parallel operation [8, 9], and inertial adaption [10–12].

Paper [13–15] proposed a positive and negative sequence independent control strategy with both active and reactive power output under fault condition, so that the VSG has a certain voltage support capability while maintaining active power output, but current limiting was not considered. Paper [16] proposed a voltage support strategy considering current limiting, which effectively raises the positive sequence voltage and reduces the negative sequence voltage by injecting positive and negative sequence reactive currents. In papers [17, 18], an improved control strategy based on positive and negative sequence voltage control is proposed, which is able to maximize the voltage support within the upper and lower limits of phase voltage operation and phase current amplitude constraints. By summarizing the above studies, it can be concluded that the VSG control strategy in the case of voltage sag has certain requirements on the inverter capacity, and cases of unachievable control objectives due to insufficient inverter capacity are frequent. Especially in case of severe faults, the reference current generated by the controller may exceed the maximum current output capacity of the inverter. Furthermore, the damping and inertia support characteristics cannot be promised during the voltage drop. Therefore, overcoming the control failure due to insufficient capacity is the primary problem that needs to be addressed by the inverter control strategy under low-voltage conditions.

Power grids containing high penetration of renewable energy sources are usually equipped with reactive power compensation devices at new energy sites with larger capacity considering the stability of operating voltage, but the original design intention is more to solve the voltage stability problem and improve the voltage operating index under non-fault [19, 20]. Compared with renewable energy generation units, STATCOM has better voltage support and voltage balance enhancement capability. Some scholars also control the STATCOM in the case of unbalanced voltage sags to achieve voltage support at the grid connection point. The literature [21, 22] describes STATCOM control methods in voltage unbalance sag scenarios. This type of method coordinates the positive and negative sequence reactive reference currents in order to improve the voltage support capability of the parallel grid and voltage reduction of the unbalance. However, this type of method still has the problem of insufficient compensation capacity under severe voltage sag. At the same time, this type of method does not consider current limiting measures, ignoring the safe operation of the inverter itself.

In order to solve the problem of insufficient voltage compensation for a single VSG and to ensure that the VSG current does not cross the limit, this paper fully explores the response characteristics and voltage support capacity of STATCOM and VSG under the condition of unbalanced voltage sag, and proposes a reactive power coordination control strategy based on STATCOM and VSG to actively support the grid voltage, while remaining damping and inertia support characteristics of STATCOM. The method can make full use of the capacity of STATCOM and VSG, and use the results of scenario differentiation algorithm to effectively support the voltage of the grid connection point of renewable energy field generations under different situations and ensure the safety of the grid connection point. The method is particularly effective in making full use of the capacity of STATCOM and VSG to actively support the parallel grid voltage, especially under fault conditions.

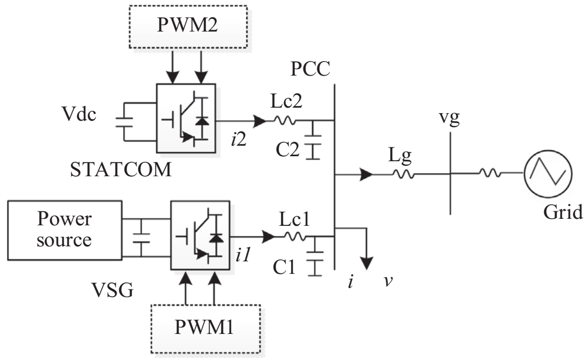

FIGURE 1 Topology of a typical renewable energy farm with STATCOM.

2 | VSG CONTROL STRUCTURE AND OUTPUT CHARACTERISTICS ANALYSIS

2.1 | VSG and STATCOM control structure

Most of the VSG and STATCOM are connected to the grid through inverters, as shown in Figure 1. Both of them have different control methods. This section first introduces the control system of VSG and STATCOM.

2.1.1 | VSG topology

The traditional voltage-based VSG cannot retain the VSG characteristics under fault, which is mainly caused by the fact that the external characteristics of the voltage-based VSG are a voltage source with active-reactive coupling and cannot control the power directly [23]. In contrast, the current-controlled VSG is based on conventional vector control technology with additional frequency regulation control, retaining the current inner-loop control structure, and the output power can be precisely controlled by controlling the current command [24]. The control structure of the VSG applied in this paper is shown in Figure 2.

When an unbalanced voltage sag occurs in the grid, a negative sequence component will appear in the current, resulting in a three-phase unbalance. In order to restore the balance of three-phase current, this paper introduces the balance current control in the classical current vector control to improve the VSG control [25], compared with the classical VSG control, the improved control adds the negative sequence current loop

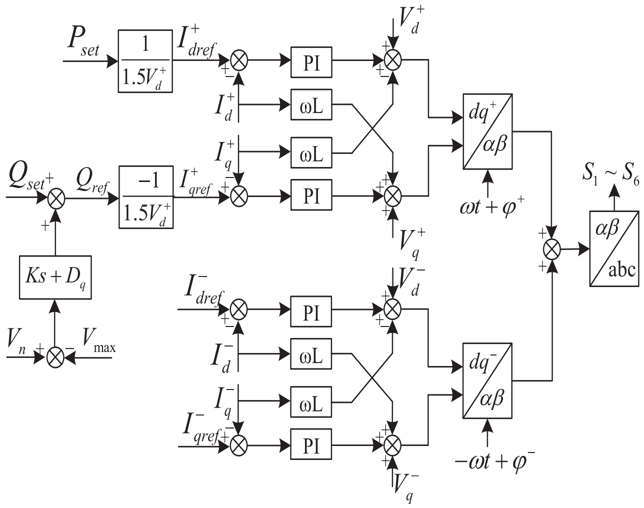

FIGURE 2 Topology of the improved VSG control. VSG, virtual synchronous generator.

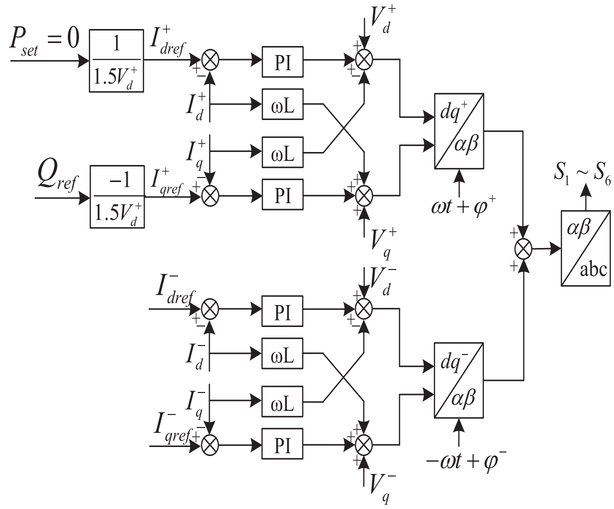

FIGURE 3 Control system of STATCOM.

on the basis of the original current loop, through the adjustment of the positive and negative sequence reference command can realize the accurate control of the positive and negative sequence components of the grid. The VSG active loop sag link is simultaneously blocked at the time of failure and the active power output is kept at the original command value to prevent the frequency flicker's negative effects on the control system.

At this point the VSG reference current can be expressed as

$$\begin{cases} I_{d\_\text{vsg}} = \dfrac{P_{set}}{1.5V_d^+} \\ I_{q\_\text{vsg}} = -\dfrac{Q_{set} + \left(D_q + Ks\right)\left(V_n - V_{\max}\right)}{1.5V_d^+} \end{cases} \tag{1}$$

V_n and V_{max} are the rated phase voltage amplitude and maximum phase voltage amplitude, respectively. K is the inertia coefficient of the reactive power control loop. S denotes the differential link. V_d^+ is expressed as the amplitude of the positive sequence voltage on the d-axis.

2.1.2 | STATCOM topology

The control structure of the STATCOM is shown in Figure 3. The simplified model is similar to the new energy generation unit, where the DC voltage source is connected to the inverter, which is connected to the PCC bus after LC filtering, and then to the grid. The control objective of the STATCOM is to provide a stable voltage to the grid. Therefore, on the DC side, the DC voltage V_{dc} needs to be controlled so that it can absorb a small amount of active power from the AC grid to compensate for active losses. The internal loop current control link and PWM signal generation link are basically the same as the inverter type new energy.

2.2 | Analysis of output characteristics under unbalanced voltage sag

In this paper, we study the coordinated control of reactive power based on STATCOM and VSG, both of which are controlled by inverters. The inverter control system uses the real-time measured parallel grid voltage and current and the set active power reference value to calculate the reference current in the dq coordinate system to achieve the control objective of this paper. The positive and negative sequence voltage vectors at any point k of the AC system in the case of unbalanced voltage can be expressed in the dq synchronous rotating coordinate system as [26]

$$v_k = v_k^+ + v_k^- = \begin{bmatrix} V_k^+ \cos(\omega t + \delta^+) + V_k^- \cos(-\omega t + \delta^-) \\ V_k^+ \sin(\omega t + \delta^+) + V_k^- \sin(-\omega t + \delta^-) \end{bmatrix} \tag{2}$$

where v_k^+ and v_k^- denote the positive and negative sequence voltages at any point k of the AC system; V_k^+ and V_k^- denote the corresponding amplitudes of the positive and negative sequence voltages; δ^+ and δ^- are the initial phase angles of the positive and negative sequence voltages, respectively. At this time, the inverter output current in the dq coordinate system can be expressed as

$$\begin{aligned} i = i^+ + i^- &= \begin{bmatrix} I_d^+ \cos(\omega t + \delta^+) - I_q^+ \sin(\omega t + \delta^+) \\ I_d^+ \sin(\omega t + \delta^+) + I_q^+ \cos(\omega t + \delta^+) \end{bmatrix} \\ &+ \begin{bmatrix} I_d^- \cos(-\omega t + \delta^-) - I_q^- \sin(-\omega t + \delta^-) \\ I_d^- \sin(-\omega t + \delta^-) + I_q^- \cos(-\omega t + \delta^-) \end{bmatrix} \end{aligned} \tag{3}$$

where I_d^+, I_q^+ represent the positive sequence active and reactive current components, respectively, I_d^-, I_q^- represent the positive negative active and reactive current components, respectively

i^+ and i^- represent the positive and negative sequence current components, respectively. According to the topology, in the case of asymmetric voltage sag, the inverter outlet positive and negative sequence voltages can be expressed as

$$v^+ = v_g^+ + L_g \frac{di^+}{dt} \tag{4}$$

$$v^- = v_g^- + L_g \frac{di^-}{dt} \tag{5}$$

where v^+ and v^- are the PCC point positive and negative sequence voltages; v_g^+ and v_g^- are the grid-side bus positive and negative sequence voltages; L_g and R_g are the line equivalent inductance and equivalent resistance. Due to the fact that the L_g in the power system line is much larger than the R_g, and to reduce the variables and simplify the formula, set R_g to 0. Since the voltage support capability of the inverter is mainly reflected as the ability to support the PCC bus voltage, this paper needs to use Equations (3) and (4) to derive the reference current. Equations (1) and (2) are brought into Equations (3) and (4) to obtain the voltage support Equations (5) and (6) expressed in terms of positive and negative sequence magnitudes. This equation is the basis for achieving the voltage support objective below.

$$V^+ = \sqrt{(V_g^+)^2 - (\omega L_g I_d^+)} + \omega L_g I_q^+ \tag{6}$$

$$V^- = \sqrt{(V_g^-)^2 - (\omega L_g I_d^-)} - \omega L_g I_q^- \tag{7}$$

3 | INVERTER CONTROL TARGET UNDER UNBALANCED VOLTAGE SAG

To ensure that the VSG can better enhance the voltage support capacity with safety and fully utilize the output capacity of the inverter, the control objectives set in this paper are voltage support and inverter current limiting.

3.1 | Voltage support control

When the voltage is unbalanced, the three-phase voltage amplitude of the PCC bus can be expressed as

$$\begin{cases} V_a = \sqrt{(V^+)^2 + (V^-)^2 + 2V^+V^- \cos(\phi)} \\ V_b = \sqrt{(V^+)^2 + (V^-)^2 + 2V^+V^- \cos(\phi - \frac{2}{3}\pi)} \\ V_c = \sqrt{(V^+)^2 + (V^-)^2 + 2V^+V^- \cos(\phi + \frac{2}{3}\pi)} \end{cases} \tag{8}$$

Among them $\phi = \varphi^+ + \varphi^-$.

In the event of an unbalanced voltage sag, the following constraint is established to ensure that none of the three phase voltages cross the limit after voltage support.

$$V_{\max} = \max(V_a, V_b, V_c) \le V_{\text{upper}} \tag{9}$$

where V_{max} denotes the voltage amplitude of the phase with the maximum amplitude, and V_{upper} denotes the upper limit of the phase voltage amplitude constraint. Combining Equations (7) and (8), the voltage of the phase with the maximum amplitude can be expressed as

$$V_{\max} = \sqrt{(V^+)^2 + (V^-)^2 + 2V^+V^-\lambda} \tag{10}$$

where

$$\lambda = \max\left[\cos(\phi), \cos(\phi + \frac{2\pi}{3}), \cos(\phi - \frac{2\pi}{3})\right] \tag{11}$$

Equation (9) establishes the relationship between the voltage amplitude V_{max} of the phase with the maximum amplitude and the positive sequence voltage amplitude V^+. When V_{max} is raised to V_{upper}, the inverter achieves the maximum support of the positive sequence voltage while the phase voltage amplitude does not cross the limit. Let $V_{max} = V_{upper}$. From Equation (9), the corresponding positive sequence reference voltage under the maximized voltage support can be introduced as

$$V_{\text{ref}}^+ = -V^-\lambda + \sqrt{(V^-\lambda)^2 - (V^-)^2 + (V_{\text{upper}})^2} \tag{12}$$

Combining Equations (11) with (5), the corresponding reactive reference current at the maximized voltage support can be derived as follows:

$$I_{q\_\text{upper}}^+ = \frac{V_{\text{ref}}^+ - \sqrt{(V_g^+)^2 - (X_g I_d^+)^2}}{X_g} \tag{13}$$

3.2 | Current limiting control

When there is a large sag in grid voltage (e.g. fault conditions), the inverter limits the output current in order to protect its own operation.

$$\begin{cases} I_a = \sqrt{(I_q^+)^2 + (I_q^-)^2 + 2I_q^+ I_q^- \cos(\delta_I)} \\ I_b = \sqrt{(I_q^+)^2 + (I_q^-)^2 + 2I_q^+ I_q^- \cos(\delta_I - \frac{2}{3}\pi)} \\ I_c = \sqrt{(I_q^+)^2 + (I_q^-)^2 + 2I_q^+ I_q^- \cos(\delta_I + \frac{2}{3}\pi)} \end{cases} \tag{14}$$

where

$$\delta_I = \delta_I^+ + \delta_I^- \tag{15}$$

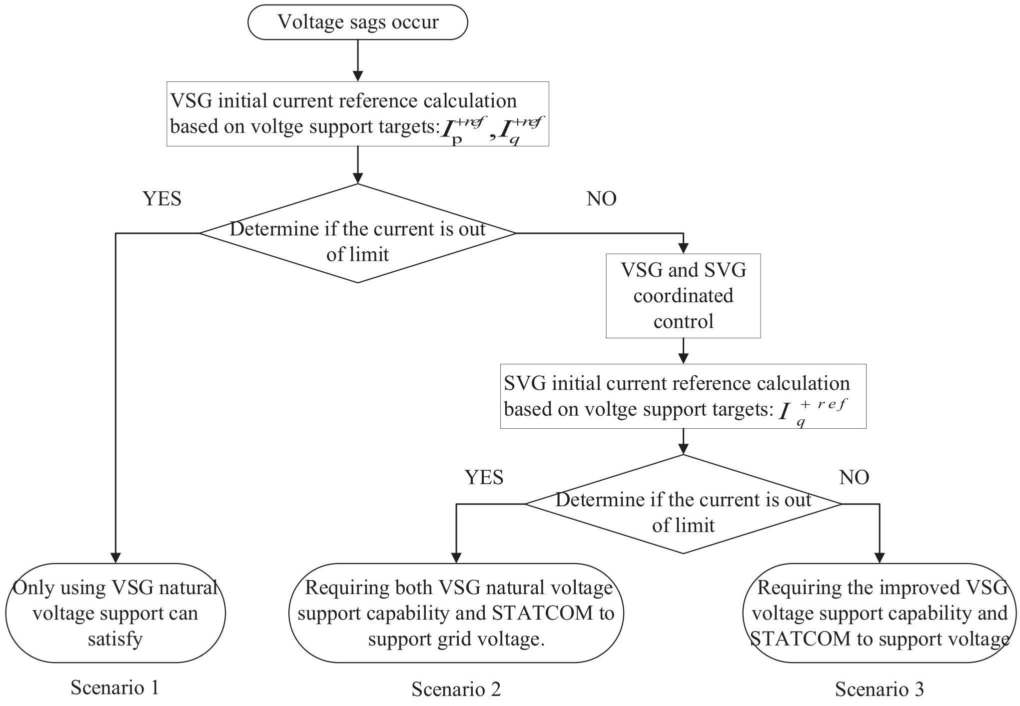

FIGURE 4 Method of scenario classification.

According to the current limiting requirement, the maximum output current of the inverter will be limited to

$$\max\{I_a, I_b, I_c\} \leq I_{\text{lim}} \tag{16}$$

Due to the need to achieve the goal of three-phase balancing of the output current, the negative sequence reference current needs to be set to zero, as

$$I_{dref}^{-} = 0 \tag{17}$$

$$I_{qref}^{-} = 0 \tag{18}$$

Since both the VSG and STATCOM are connected to the grid through the inverter, the above formulae are applicable to both the VSG and STATCOM. When an unbalanced voltage sag occurs in the grid, changing the inverter control method to support the voltage and improve the control of the unbalance may cause the inverter output current to cross the limit and threaten the safe operation of the inverter. 1.2

The inverter current rating is directly related to the inverter capacity. Therefore, the size of the inverter capacity may affect the achievement of the control target. In order to better be able to meet the voltage control target, we need to coordinate the control of the VSG and STATCOM, which can improve the voltage support capacity and ensure the operational reliability of the VSG under different voltage sag conditions, while ensuring the safe operation of the inverter.

3.3 | Active power output

In case of unbalanced voltage drop, according to the instantaneous power theory, the average active and reactive power of the inverter can be expressed as

$$\bar{P} = 1.5(V_d^{+} I_d^{+} + V_d^{-} I_d^{-}) \tag{19}$$

It can be seen from Equation (19) that the positive sequence active current and negative sequence active current can be controlled to adjust the output active power of the inverter. In order to simplify the calculation of the controller reference current and reduce imbalance, this paper set the positive sequence reactive current to zero and only considers the method of controlling the positive sequence active current to change the output active power. Therefore, when voltage sags are mild, only using VSG natural voltage support can satisfy, the VSG positive-sequence active reference current can be expressed as

$$I_{d\_\text{vsg}}^{+\text{ref}} = \frac{P_{set}}{1.5 V_d^{+}} \tag{20}$$

When the voltage sag is moderate requiring both VSG natural voltage support capability and STATCOM to support voltage. To ensure the output of active power, the VSG positive-sequence active reference current needs to be set artificially to a fixed value. When the voltage sag is sever, requiring the improved VSG voltage support capability and STATCOM to support voltage, the VSG positive-sequence active reference current needs to be set to 0.

4 | VSG COORDINATION CONTROL BASED ON SCENE DIFFERENTIATION

Considering factors such as severity of voltage sag in the grid, the system will show different operating scenarios in operation. To ensure that current limiting and voltage support can be achieved under different voltage sag, the derivation of reference currents for specific scenarios needs to be based on the division of grid operation scenarios.

In this paper, we make full use of the feature that both STATCOM and VSG can support the voltage together under different voltage sag. In the process of coordinated control, an effective system operation scenario division algorithm is first designed to provide the basis for coordinated control as shown in Figure 4. Then, the corresponding reference current injection mode under each scenario is determined according to the control objectives in different scenarios. Finally, the scenario differentiation results and the reference current injection mode are combined to achieve the control objectives.

4.1 | Operation scenario classification

$$I_{\mathrm{q}}^{+ref} = -\sqrt{(I_{\mathrm{lim}})^2 - (I_d^{+ref})^2} \tag{21}$$

V_{max} is derived from Equation (1) as follows:

$$V_{\max} = V_n + \frac{\frac{3}{2}V_d^{+} I_{\mathrm{lim}} + Q_{set}}{D_q + Ks} \tag{22}$$

Then make $V_{upper} = V_{max}$ substitute into Equations (12) and (13) to calculate the STATCOM reactive reference current I_q^{+ref}, When the calculated reference current is within the range of the maximum current I_{max} that ensure the active output of VSG and add STATCOM to coordinate control with it. On the contrary, the active power output of VSG is not ensured. STATCOM is fully utilized and VSG output is dominated by voltage support targets.

4.2 | Operation scenario differentiation and reference current calculation

(1) Scenario 1: Mild voltage sag, only using VSG natural voltage support can satisfy.

In this scenario, voltage support can be achieved by relying on the VSG output reactive power only, and the STATCOM does not need to issue reactive power, which can leave space for the output of active power. Referring to the principle of parallel grid voltage support, the reactive reference current to achieve voltage support can be calculated using Equations (8) to (13), as shown in Equations (23) and (24). Here, subscript 1 represents VSG, subscript 2 represents STATCOM.

$$\begin{cases} I_{q1}^{+ref} = -\dfrac{Q_{set} + \left(D_q + Ks\right)\left(V_n - V_{\max}\right)}{1.5V_d^{+}} \\ I_{\mathrm{d1}}^{+ref} = \dfrac{P_{set}}{1.5V_d^{+}} \end{cases} \tag{23}$$

$$\begin{cases} I_{q2}^{+ref} = 0 \\ I_{\mathrm{d2}}^{+ref} = 0 \end{cases} \tag{24}$$

Since Scenario 1 is based on the comparison of $\min\{V_a, V_b, V_c\}$ and I_{max} in Section 3.1, the resulting current reference values I_{q1}^{+ref} and I_{d1}^{+ref} outputs do not cross the limits.

(2) Scenario 2: Moderate voltage sag, requiring both VSG natural voltage support capability and STATCOM to support grid voltage.

In this scenario, using the VSG alone to support the voltage will result in the current crossing the limit, which will eventually fail to achieve the effect of voltage support and may endanger the safety of the VSG equipment at the same time. Therefore, it is necessary to coordinate the output of STATCOM and VSG to jointly support the voltage and ensure that the output current of both do not exceed the limit.

According to the more serious voltage sags, first rely on VSG to support the voltage and ensure the output of active power, reactive current as in Equation (21), STATCOM to join for coordinated control as in Equation (13), current distribution as in Equations (25) and (26). Here, subscript 1 VSG, subscript 2 represent the STATCOM.

$$\begin{cases} I_{q1}^{+ref} = -\sqrt{(I_{\mathrm{lim}})^2 - (I_d^{+ref})^2} \\ I_{\mathrm{d1}}^{+ref} = 0.52 \end{cases} \tag{25}$$

$$\begin{cases} I_{q2}^{+ref} = I_{\mathrm{q}}^{+ref} \\ I_{\mathrm{d2}}^{+ref} = 0 \end{cases} \tag{26}$$

(3) Scenario 3: Sever voltage sag, requiring the improved VSG voltage support capability and STATCOM to support voltage.

In this scenario, using either the STATCOM alone or the virtual synchronizer to support the voltage will cause the current to cross the limit. In order to support the voltage to the maximum extent, STATCOM and VSG all generate reactive power and the

TABLE 1 Simulation parameter setting.

VSG parameter		STATCOM parameter	
Parameters	**Value**	**Parameters**	**Value**
Base power S_{B1}	15 kVA	Base power S_{B2}	15 kVA
DC-link voltage V_{dc1}	1000 V	DC-link voltage V_{dc2}	1000 V
Filter inductance L_{f1}	30 mH	Filter inductance L_{f2}	30 mH
Filter capacitor L_{c1}	40 uF	Filter capacitor L_{c2}	40 uF
Grid resistance R_{g1}	0 ohm	Grid resistance R_{g2}	0 ohm
PS proportional gain of proposed controller k_{p1}^{+}	120	PS proportional gain of proposed controller k_{p2}^{+}	100
PS integral gain of proposed k_{i1}^{+}	0.1	PS integral gain of proposed k_{i1}^{+}	0.1
NS proportional gain of proposed controlle k_{p1}^{-}	10	NS proportional gain of proposed controlle k_{p2}^{-}	10
NS integral gain of proposed controller k_{i1}^{-}	0.01	NS integral gain of proposed controller k_{i2}^{-}	0.01

TABLE 2 Simulation scenario setting.

Determined scenario	$V_g^+/(\text{p.u.})$	$V_g^-/(\text{p.u.})$	$\delta^+ + \delta^-/(°)$
1	0.8	0.2	3.7
2	0.5	0.27	6.3
3	0.2	0.25	6.3

V_k^+ andV_k^- denote the parallel grid amplitudes of the positive and negative sequence voltages.

TABLE 3 Results of scenario classification.

Determined scenario	Voltage sag level
1	Mild voltage sag, only using VSG natural voltage support can satisfy
2	Moderate voltage sag, requiring both VSG natural voltage support capability and STATCOM to support grid voltage
3	Sever voltage sag, requiring the improved VSG voltage support capability and STATCOM to support voltage

current is assigned as Equations (27) and (28). Here, subscript 1 VSG, subscript 2 represent the STATCOM.

$$\begin{cases} I_{q1}^{+ref} = I_{\text{lim}} \\ I_{\text{d}1}^{+ref} = 0 \end{cases} \tag{27}$$

$$\begin{cases} I_{q2}^{+ref} = I_{q}^{+ref} \\ I_{\text{d}2}^{+ref} = 0 \end{cases} \tag{28}$$

The calculation results of the positive sequence component reference values are brought into the VSG with the STATCOM current inner loop for control to achieve the above control objectives.

5 | CASE STUDIES AND EVALUATION

To verify the effectiveness of the proposed control strategy under different operation scenarios and the enhancement effect of the coordinated control method on the reactive voltage support control strategy. Based on MATLAB/Simulink, a simulation system with VSG and STATCOM for grid-connected operation of renewable energy generation shown in Figure 1 is established. The maximum allowable output current of the inverter $I_{lim} = 1.2p.u.$, the upper limit of phase voltage operation is set to 1.1 p.u., and the specific parameters are set as shown in Table 1.

In the simulation, it is set up at $t = 0.2 - 0.4$ s when the grid-side bus occurs unbalanced drop. Before and after (before $t = 0.2$ s and after $t = 0.4$ s) the fault occurs, the VSG uses the conventional VSG control strategy, and the STATCOM control objective is to maintain a constant voltage at the grid-side grid. During the fault occurrence, the control strategy switches to the voltage support strategy in this paper. The line rated voltage is 15 kV and the line inductance $L_g =$ 4 mH.

5.1 | Scene differentiation method validation

After the voltage sag occurs, the voltage sag degree is evaluated according to the comparison of positive sequence reactive reference current magnitude and phase current magnitude limit (Equations (14) to (16)), and the scenario differentiation is realized. The determind scenario settings and scenario differentiation results are shown in Tables 2 and 3.

5.2 | Simulation results in specific scenarios

(1) Scenario 1: Mild voltage sag, only using VSG natural voltage support, can satisfy.

The active output of the VSG is controlled by the balanced current under asymmetric fault [27], when $t = 0.2$ s, a mild voltage sag (scenario 1) ($V_g^+ = 0.8$ p.u., $V_g^- = 0.2$p.u.) fault occurs at the grid side bus.

From Figures 5a and 5b, it can be seen that under the voltage support control strategy, the adjustment of the voltage of each phase of the parallel grid can be completed by controlling the positive and negative sequence voltage of the parallel grid, and the maximum magnitude of the parallel grid voltage is propped

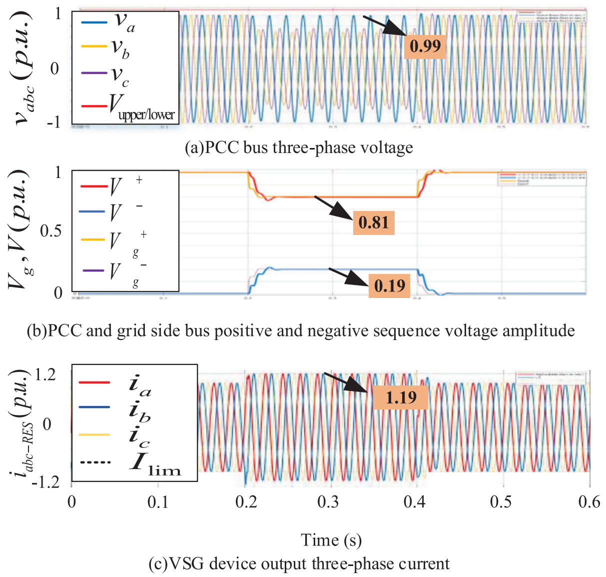

FIGURE 5 Output performance of VSG under scenario 1. VSG, virtual synchronous generator.

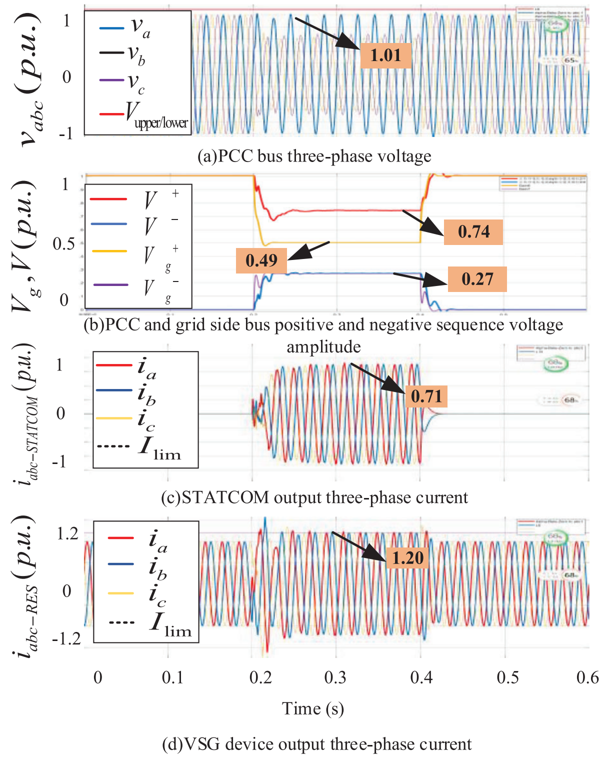

FIGURE 6 Output performance of VSG under scenario 2. VSG, virtual synchronous generator.

up to 0.99 p.u. The voltage support meets the set requirements. From Figure 5c, it can be seen that based on the judgment of Equations (13) and (14), voltage support can be achieved by relying only on the VSG output reactive power when the voltage sag is not severe, and the VSG output current does not cross the limit, the VSG reactive current output is 0.

(2) Scenario 2: Moderate voltage sag, requiring both VSG natural voltage support capability and STATCOM to support grid voltage.

When $t = 0.2$ s a severe voltage sag occurs at the grid side bus ($V_g^+ = 0.5$ p.u., $V_g^- = 0.27$ p.u.), the active current reference value is likewise I_d^+ taken as 0.53 p.u.

From Figures 6a and 6b, it can be seen that under the voltage support control strategy, the adjustment of the voltage of each phase of the parallel grid can be completed by controlling the positive and negative sequence voltage of the parallel grid, and the maximum magnitude of the parallel grid phase voltage is maintained at 1 p.u. to meet the voltage support setting target requirements. As can be seen from Figures 6c and 6d, based on the judgment of Equations (13) and (14), it is determined that the scenario is a serious voltage sag, and the positive and negative sequence reactive reference currents under the control strategy of this scenario rely on the STATCOM and VSG to coordinate the control to achieve. Through the control algorithm and optimization process in this paper, not only the VSG current limit requirement is satisfied, and active power output is ensured.

(3) Scenario 3: Sever voltage sag, requiring the improved VSG voltage support capability and STATCOM to support voltage

The active current reference value I_d^+ is also taken as 0 in the control of the VSG, when $t = 0.2$ s a severe voltage sag occurs at the grid side bus ($V_g^+ = 0.2$ p.u., $V_g^- = 0.25$ p.u.).

From Figures 7a and 7b, it can be seen that under the voltage support control strategy, the adjustment of the voltage of each phase of the grid can be completed by controlling the positive and negative sequence voltages of the parallel grid, maintaining the maximum magnitude of the parallel gridphase voltage at 0.77 p.u. and not meeting the voltage support setting target requirements. As can be seen from Figures 7c and 7d, based on the judgment of Equations (13) and (14), the scenario is determined to be a very serious voltage sag, and although the current oscillates in a short period of time, the oscillating current is negligible within the controllable range. In this scenario, the VSG and STATCOM are fully used for voltage support, not to the voltage support requirements.

5.3 | Comparison of individual VSG voltage support effects

To verify the improvement of voltage support capability by coordinated control of STATCOM device and VSG. In the face of voltage sag also targeting the upper phase voltage limit for voltage support, only the output characteristics of the VSG are changed to support the voltage without introducing the STATCOM device, and when the calculated reactive reference current crosses the limit, make VSG full reactive power generation

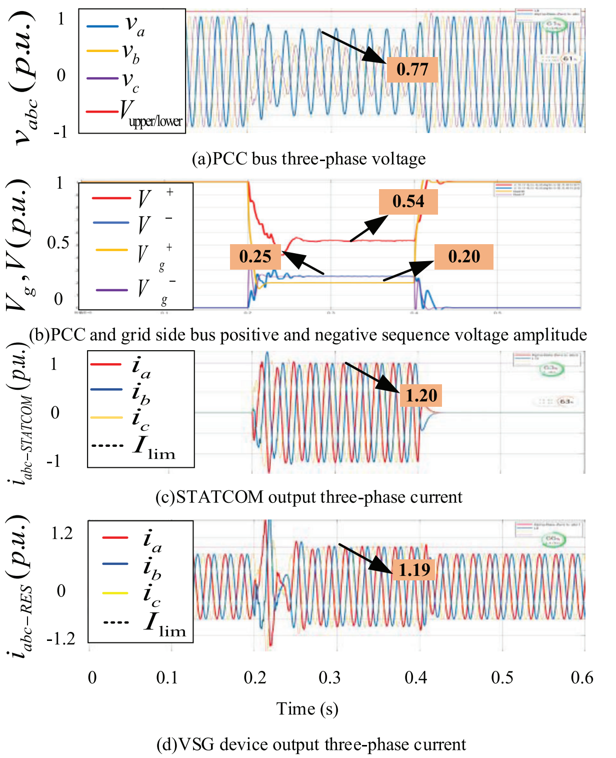

FIGURE 7 Output performance of VSG under scenario 3. VSG, virtual synchronous generator.

TABLE 4 Simulation scenario setting.

Determined scenario	Voltage sag level	V_g^+/(p.u.)	V_g^-/(p.u.)
1	Mild voltage sag	0.8	0.2
2	Moderate voltage sag	0.5	0.27
3	Sever voltage sag	0.2	0.25
4	Severe voltage unbalance	0.48	0.4

TABLE 5 Results of scenario classification.

Determined scenario	PCC bus voltage amplitude (VSG)	PCC bus voltage amplitude (improved VSG)	PCC bus voltage amplitude (improved VSG and STATCOM)
1	1.09	0.98	/
2	0.77	0.92	1.01
3	0.45	0.59	0.77
4	0.87	0.95	1.01

to ensure the safety of inverter operation, but the established voltage support effect is affected.

Here we set four scenarios:Mild voltage sag, Moderate voltage sag, Sever voltage sag, and Severe voltage unbalance. The determined scenario settings and scenario differentiation results are shown in Tables 4 and 5.

6 | CONCLUSION

In response to the problem that both STATCOM and VSG can actively support grid voltage during severe voltage sag, but there are output capacity limitations and insufficient active support capability, this paper proposes a control strategy based on the actual configuration of renewable energy generations that coordinates the STATCOM and VSG to improve the voltage support capability and achieve the following results:

(1) The proposed voltage support coordination control strategy achieves voltage support and ensures that the phase voltage amplitude does not cross the limit and other objectives in accordance with the parallel grid voltage operation requirements of the VSG.
(2) The coordination control strategy is based on using the scenario differentiation method, comparing the demand for reactive power under voltage sag and the output capacity of STATCOM and VSG, fully considering the actual support capacity of each device itself, and using this as the standard to set the reference current value.
(3) Coordinating the control methods of STATCOM and VSG not only safely supports the parallel grid voltage and enhances the voltage support capability, but also brings out its damping characteristics by making full use of the VSG.

AUTHOR CONTRIBUTIONS

I am the main author responsible for the simulation construction, Liang Ji is responsible for the whole management and responsible for the technical direction, Yifan Ding participated in part of the technology, Qiteng Hong made field suggestions, Xiao Chang is responsible for language modification, Botong Li is responsible for the paper revision, Enyu Jiang and Ling Mao are responsible for data collection.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The simulation results based on MATLAB/Simulink verified the effectiveness of the proposed strategy.

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