

Article

Transient Voltage Stability Control of UHVDC Sending-End Grid with New Energy Integration Based on Coordinated Steady-State Prevention and Transient Self-Response

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Abstract

For large-scale new energy integrated UHVDC sending-end grids, when a bipolar blocking fault occurs in the UHVDC system under high-generation conditions, it triggers severe transient overvoltage in the sending-end AC grid. This may lead to cascading tripping of units at renewable collection stations and power plants, resulting in transient voltage instability, posing significant challenges to the secure operation and renewable energy accommodation of the sending-end power system. This paper studies transient voltage stability control methods for new energy integrated UHVDC sending-end grids, aiming to eliminate the risk of power grid transient voltage instability triggered by transient overvoltage at renewable energy collection stations. Firstly, the evolution process of transient voltage instability in the new energy sending-end grid after a UHVDC bipolar blocking fault was analyzed. Based on this, the mechanisms of excess reactive power, transient voltage propagation, and voltage instability evolution were studied. Secondly, a coordinated transient voltage control framework combining steady-state prevention and transient self-response was established, with thresholds set for coordinated control of steady-state voltage prevention and transient self-response. A coordinated transient voltage stability control strategy for new energy DC sending-end AC grids was proposed, integrating steady-state prevention and transient self-response. Simulation results show that the proposed strategy effectively eliminates transient voltage instability risks in the sending-end grid and significantly enhances the level of renewable energy transmission and accommodation.

Keywords: new energy; DC sending-end grid; DC bipolar blocking; preventive control; self-response coordination; transient voltage stability control



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1. Introduction

With the large-scale development and utilization of new energy in China's resource-rich regions, including desert areas [1,2], the new energy capacity in some power grids has exceeded 80%. Due to the sparse population and lack of industrial load in these areas, new energy power generation relies heavily on UHVDC or AC/DC transmission for long-distance power delivery, forming a typical "large capacity, small load, high-power UHVDC transmission" sending-end grid structure. Under high-generation conditions, if a bipolar

blocking fault occurs in the UHVDC system, a large amount of redundant reactive power will flow back into the sending-end AC grid. This leads to severe transient overvoltage, which propagates through AC tie lines to the local terminal grid connected to renewable energy collection stations. The voltage at wind and photovoltaic plants may exceed the upper limit of high-voltage ride-through (HVRT) [3], triggering cascading tripping of units. This further results in sustained overvoltage and transient voltage instability in the terminal grid, causing load shedding and severely impacting the secure operation of the sending-end grid and the accommodation of new energy. Figure 1 shows the new energy high-voltage ride-through curve, and Figure 2 illustrates the transient voltage curve at the bus of a renewable energy collection station under high-generation and high-power UHVDC transmission conditions during a bipolar blocking fault.

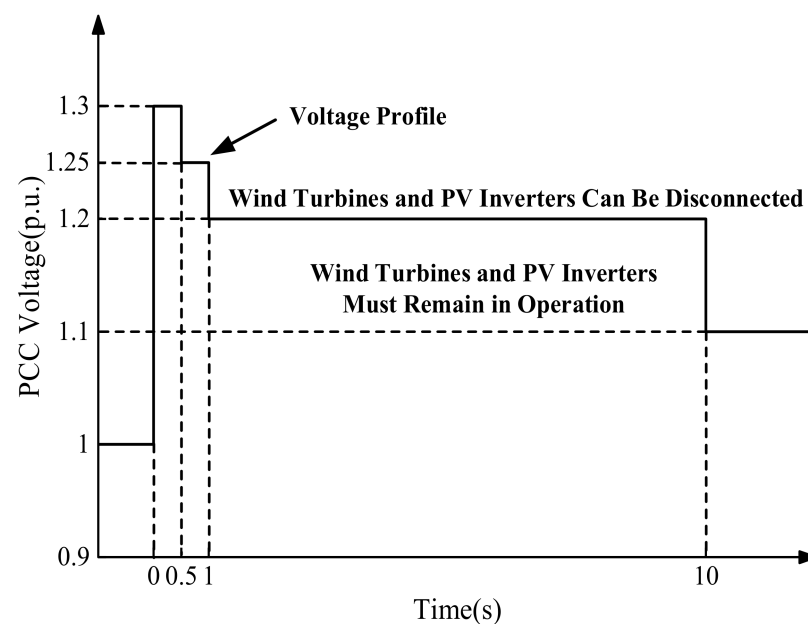


Figure 1. The high-voltage ride-through curve of new energy units.

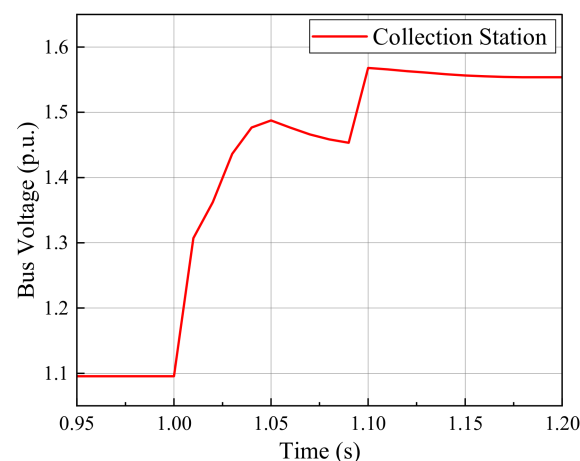


Figure 2. The transient overvoltage curve at the busbar of the new energy collection station.

From Figure 2, it can be observed that after a bipolar blocking fault occurs in the UHVDC system, the transient voltage at the bus of the renewable energy collection station in the sending-end grid rapidly rises above 1.3 p.u., exceeding the upper limit of high-voltage ride-through (HVRT) for new energy units. This causes the wind and photovoltaic units connected to the collection station to trip instantaneously, leading to sustained overvoltage at the station's bus, which remains outside the allowable range. As a result, the local

terminal grid connected to the collection station experiences transient voltage instability, triggering load shedding.

In actual operation of the sending-end grid, to prevent such voltage instability incidents in local grids connected to collection stations and ensure safe power generation from new energy units, it is essential to reduce the UHVDC transmission power during periods of high renewable generation. Table 1 shows the control relationship between UHVDC transmission power and new energy generation power in a typical new energy DC sending-end grid.

Table 1. Control relationship between UHVDC transmission power and nearby new energy generation power.

UHVDC Transmission Power (MW)	New Energy Generation Power (MW)
8000	15,450
7500	15,950
7000	16,450
6500	16,950
6000	17,450

As shown in Table 1, large-scale renewable energy generation often leads to a “reversal” phenomenon: when renewable output is high, the power transmitted via ultra-high voltage (UHV) DC systems is reduced to maintain voltage stability at the sending-end grid, severely limiting renewable power delivery and underutilizing UHV transmission capacity. Thus, there is an urgent need to study transient voltage stability control in UHV DC sending-end grids with large-scale renewable integration, and to develop adaptive control strategies. These strategies aim to enhance transient voltage stability, thereby improving both renewable power generation and UHV DC transmission capabilities.

In research on transient overvoltage in AC grids caused by DC faults, the following studies have been conducted: Reference [4] proposes a coordinated optimization control strategy for multiple dynamic reactive power sources tailored to different fault characteristics. Reference [5] analyzes the Automatic Voltage Regulation (AVR) control mechanism commonly used in VSG-DFIGs and proposes transient overvoltage suppression measures based on this analysis. Reference [6] introduces a delay-compensation control strategy for wind power systems to suppress overvoltage in sending-end AC grids with high wind penetration under commutation failure conditions. Reference [7] investigates the mechanism of transient overvoltage caused by commutation failure and proposes a constant reactive power control strategy to suppress such overvoltage in the sending-end AC system. Reference [8] examines the impact of fault initiation and clearing times on the peak transient overvoltage and proposes corresponding overvoltage suppression control strategies. Reference [9] deeply analyzes the transient overvoltage mechanism in sending AC/DC hybrid systems under commutation failure, considering active–reactive power interaction coupling. Reference [10] studies the impact of dynamic reactive compensation on wind farm transient voltage and related control strategies. Reference [11] reveals the reactive-voltage interaction mechanisms of different types of wind turbines under UHVDC commutation failure. Reference [12] analyzes the short-term voltage instability mechanism of directly driven wind farms connected to the grid using the generalized instantaneous energy function method. Reference [13] investigates the static voltage stability mechanism of receiving-end AC grids with high renewable penetration fed by DC transmission. Reference [14] analyzes the transient overvoltage mechanism caused by three-phase permanent short-circuit faults in typical renewable energy collection systems. Regarding quantitative analysis of transient overvoltage, reference [15] proposes a quantitative calculation method for transient overvoltage triggered by commutation failure in the DC side of

HVDC transmission systems, along with an analysis of influencing factors. Reference [16] analyzes the transient overvoltage characteristics in sending-end grids with large-scale DC cluster integration and proposes an optimization algorithm for solving transient overvoltage issues. Reference [17] proposes an intelligent hybrid grey wolf-particle swarm optimizer, which provides a powerful tool for solving complex engineering problems. Reference [18] puts forward an optimization method that adopts chaotic optimization to realize the optimal integration of renewable energy systems in distribution networks.

In summary, in recent years, certain research achievements have been realized in aspects such as transient voltage control of new energy units and coordinated optimization methods of multiple reactive power sources, targeting the transient overvoltage problem caused by commutation failure in high-proportion new energy DC sending-end power grids. However, there are very few studies on the transient voltage instability issue of the sending-end AC power grid triggered by UHVDC bipolar blocking faults in large-scale new energy DC sending-end power grids. In particular, with the rapid development of new energy in China's new energy-rich regions and the "Desert, Gobi and Desertification" areas, the centralized integration of large-scale new energy into the power grid and its long-distance transmission via UHVDC have become a critical way for new energy consumption. When a UHVDC system suffers a bipolar blocking fault under the scenario of maximum new energy output in the sending-end power grid, a large amount of surplus reactive power (40–50% of the DC transmission power) will be injected into the sending-end AC power grid, causing severe transient overvoltage in the sending-end AC system and further leading to transient voltage instability in the terminal power grid connected to the new energy collection station. This problem has become one of the major threats affecting the safe operation of new energy sending-end power grids, yet no relevant literature on corresponding control methods has been found.

Therefore, this paper conducts research on transient voltage stability control for large-scale new energy DC sending-end power grids. Firstly, the evolution process of transient voltage instability in the new energy sending-end power grid after UHVDC bipolar blocking fault is analyzed. On this basis, the conduction mechanism of surplus reactive power and transient voltage as well as the evolution law of transient voltage instability after UHVDC bipolar blocking fault are studied. It is expounded that the severe transient overvoltage in the sending-end AC power grid caused by a DC bipolar blocking fault is the sum of a steady-state voltage and transient voltage increment, and the transient overvoltage is transmitted to the new energy collection station through tie lines between substations at all levels, which greatly increases the transient voltage instability risk of the terminal power grid connected to the new energy collection station. For this purpose, this paper carries out in-depth research on the corresponding control strategy, with the main contributions as follows:

- (1) A strategy of reducing the steady-state operating voltage to near the lower limit of the safe operation range under the scenario of large-scale new energy generation in the sending-end power grid plays a significant role in mitigating transient overvoltage.
- (2) It is proposed that after the occurrence of a UHVDC bipolar blocking fault, the coordinated control of dynamic reactive power compensation equipment in substations at all levels based on the conduction path of transient overvoltage to absorb surplus reactive power can effectively reduce the transient voltage instability risk of the local power grid connected to the new energy collection station.
- (3) A transient voltage stability control framework based on "steady-state prevention and transient coordination" is constructed. Considering that the traditional command-based control mode is no longer applicable to the millisecond-level variation characteristics of transient voltage, a self-response control idea based on local voltage

information is proposed, and the thresholds for the coordinated control of steady-state voltage prevention and transient voltage self-response are set.

- (4) A transient voltage stability control strategy for new energy DC sending-end power grids based on “steady-state prevention and transient self-response coordination” is proposed. Taking a typical new energy DC sending-end power grid as the research background, simulation verification is carried out for the control strategy proposed in this paper.

To highlight the quantitative characteristics of transient voltage, the per-unit value (p.u.) is adopted for elaboration in this paper, where the voltage reference value at all levels is the nominal voltage, and the power reference value is 100 MVA.

2. Evolution Mechanism of Transient Overvoltage Instability in Renewable Energy DC Sending-End Power Grids

2.1. Evolution Process of Transient Voltage Instability in New Energy DC Sending-End Grids

For large-scale new energy DC sending-end grids, under normal operating conditions, new energy power is collected through collection stations and cluster stations, then transmitted and accommodated via UHVDC. Figure 3 shows the wiring diagram of the new energy sending-end grid.

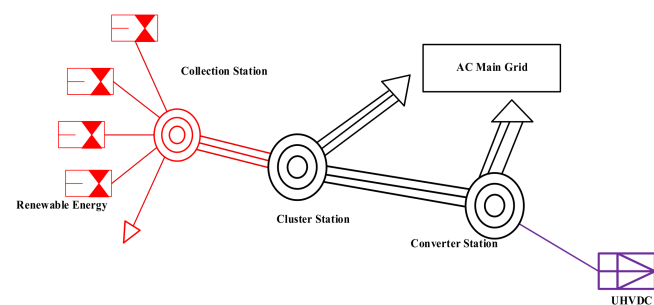


Figure 3. Typical wiring diagram of a UHVDC sending-end grid.

- (1) Reactive power flow on interconnecting lines and operating voltages at each substation in new energy sending-end grids under steady-state operating conditions

In steady-state operation of the power grid, the reactive power flow in the sending-end AC grid generally flows from the renewable energy collection stations and cluster stations stepwise into the DC converter station. The converter station’s reactive power demand is supplied partly by the sending-end grid, while the majority is provided by AC filters at the converter station. The reactive power flow on interconnecting lines between stations is shown in Table 2. Bus voltages at all levels of substations are maintained within safe allowable limits [19], as indicated in Table 3.

Table 2. Reactive power flow on interconnecting lines under steady-state operating conditions.

Interconnecting Lines	Reactive Power (p.u.)
Collection station → Cluster station	0.072
Cluster station → Converter station	0.564

Note: The reactive power transmitted from the cluster station to other physically connected power grids will not be elaborated here.

Table 3. Steady-state operating voltages at all levels of stations.

Station	Allowable Voltage Operating Range (p.u.)	Steady-State Operating Voltage (p.u.)
AC-side bus of the converter station	1.0–1.067	1.063
Cluster station	1.0–1.1	1.062
Collection station	1.0–1.1	1.095

(2) Transient reactive power and voltage propagation process after DC bipolar blocking fault

A direct current bipolar blocking fault occurs at 1 s, causing reactive power transmission from the converter station to the renewable energy collection station in the sending-end grid as shown in Table 4 and Figure 4; the transient voltage peak and increment at the converter station, renewable energy cluster station, and renewable energy collection station are shown in Table 5. The transient voltage propagation curves of each station are presented in Figure 5.

Table 4. Reactive power transfer on all levels of tie lines after a bipolar blocking fault.

Interconnecting Lines	Reactive Power (p.u.)
Converter station → Cluster station	27.405
Cluster station → Collection station	2.369

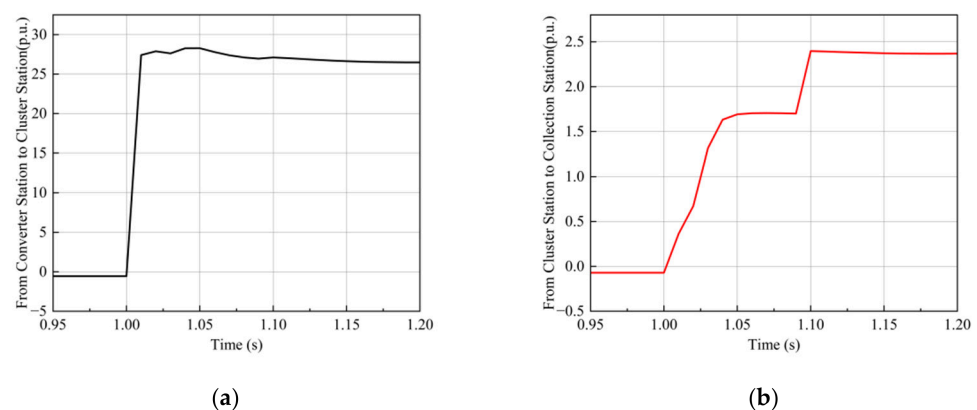


Figure 4. Reactive power propagation curves in the sending-end grid after bipolar blocking. (a) Reactive power transfer curve from converter station to cluster station. (b) Reactive power transfer curve from cluster station to collection station.

Table 5. Transient voltage peak and increment of stations after UHVDC bipolar blocking.

Station	Post-Fault Transient Voltage Peak (p.u.)	Post-Fault Transient Voltage Increment (p.u.)
AC-side bus of the converter station	1.326	0.182
Cluster station	1.273	0.133
Collection station	1.304	0.212

As shown in Table 4, after the DC blocking fault, the reactive power demand of the converter station instantaneously drops to zero, causing a large amount of excess reactive power to flow back into the AC grid, reaching the renewable energy cluster station and collection station. The surplus reactive power, as shown in Figure 4, causes a sudden rise in bus voltages across all of the stations, with the peak value equal to the sum of the pre-fault steady-state voltage and the transient voltage increment. The transient voltage peak at the renewable energy collection station bus surges to 1.304 p.u., exceeding the maximum high-voltage ride-through limit, resulting in overvoltage tripping of connected

renewable units. This leads to further voltage escalation in the local grid to 1.48 p.u., causing transient voltage instability and triggering load disconnection at the collection station after 80 ms [20].

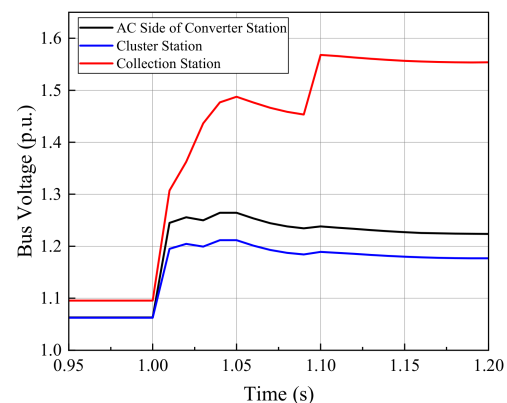


Figure 5. Transient voltage evolution curves in the sending-end grid after a DC bipolar blocking fault.

2.2. Mechanism of Excess Reactive Power and Transient Voltage Propagation After a UHVDC Bipolar Blocking Fault

- (1) Excess reactive power at the converter station's AC bus triggers a sharp transient voltage rise

At 1 s, a DC bipolar blocking fault is set to occur. After the UHVDC bipolar blocking fault, the reactive power demand of the converter drops instantaneously to zero. Due to a filter switching delay of over 200 ms, the AC filters at the converter station continue to inject capacitive reactive power, resulting in a large amount of transient excess reactive power at the AC bus of the converter station.

$$\Delta Q'_Z = Q'_f - Q'_{DT,Z} \quad (1)$$

In the formula, $\Delta Q'_Z$ is the transient excess reactive power at the converter station bus after the fault, Q'_f is the transient reactive power generated by the AC filter, and $Q'_{DT,Z}$ is the transient reactive power absorbed by the dynamic reactive power devices at the converter station after the fault.

Excess reactive power at the converter station triggers a sharp transient voltage rise at the AC bus, with the transient voltage being the sum of the steady-state voltage and the transient voltage increment. Transient voltage at the converter station's AC bus is

$$U'_Z = U_Z + \Delta U'_Z \quad (2)$$

In the formula, U_Z is the steady-state operating voltage at the converter station's AC bus, and $\Delta U'_Z$ is the transient voltage increment at the converter station's AC bus after the fault.

The transient voltage increment at the converter station's AC bus is

$$\Delta U'_Z \approx \Delta Q'_Z / S'_{sc,Z} \quad (3)$$

In the formula, $S'_{sc,Z}$ is the short-circuit capacity at the AC-side bus of the converter station after the fault.

- (2) A large amount of surplus reactive power transmitted to the cluster station causes a transient voltage rise

After a DC fault, surplus reactive power on the AC bus side of the converter station is transmitted via the tie line to the renewable energy cluster station, causing significant reactive power surplus at the cluster station. Transient surplus reactive power at the cluster station is

$$\Delta Q'_J = \Delta Q'_Z - Q'_{DT,J} - Q'_{XJ} + Q'_H \quad (4)$$

In the formula, $\Delta Q'_J$ is the transient surplus reactive power at the cluster station bus, $\Delta Q'_Z$ is the transient reactive power injected from the converter station into the cluster station, $Q'_{DT,J}$ is the transient reactive power absorbed by the dynamic reactive power devices at the cluster station, Q'_{XJ} is the transient reactive power loss in the line between the converter station and the cluster station after a fault, and Q'_H is the transient reactive power injected from the collection station into the cluster station.

Surplus reactive power at the renewable energy cluster station causes a transient voltage rise on the bus, which is the sum of the steady-state voltage and the transient voltage increment. The transient voltage at the cluster station's AC bus is

$$U'_J = U_J + \Delta U'_J \quad (5)$$

In the formula, U_J is the steady-state operating voltage of the cluster station bus, and $\Delta U'_J$ is the transient voltage increment at the AC bus of the cluster station.

The transient voltage increment at the cluster station bus is

$$\Delta U'_J \approx \Delta Q'_J / S'_{sc,J} \quad (6)$$

In the formula, $S'_{sc,J}$ is the transient short-circuit capacity at the renewable energy cluster station bus.

- (3) A large amount of surplus reactive power transmitted to the collection station causes a transient voltage rise at the station's bus

Surplus reactive power at the renewable energy cluster station is transmitted via the tie line to the collection station, causing significant transient reactive power surplus at the collection. The transient surplus reactive power is

$$\Delta Q'_H = \Delta Q'_J - Q'_{DT,H} - Q'_{XH} \quad (7)$$

In the formula, $\Delta Q'_H$ is the transient surplus reactive power at the renewable energy cluster station bus after the fault, $\Delta Q'_J$ is the transient reactive power injected from the cluster station to the collection station, $Q'_{DT,H}$ is the transient reactive power absorbed by the dynamic reactive power compensation devices at the collection station after the fault, and Q'_{XH} is the transient reactive power loss in the line between the cluster station and the collection station after the fault.

Surplus reactive power at the collection station causes a transient voltage rise on the bus, which is the sum of the steady-state voltage and the transient voltage increment. The transient voltage at the collection station's bus is

$$U'_H = U_H + \Delta U'_H \quad (8)$$

In the formula, U_H is the steady-state operating voltage of the collection station's bus, and $\Delta U'_H$ is the transient voltage increment at the collection station's bus. The transient voltage increment at the collection station's bus is

$$\Delta U'_H \approx \Delta Q'_H / S'_{sc,H} \quad (9)$$

In the formula, $S'_{sc.H}$ is the short-circuit capacity at the collection station bus after the fault.

After a UHVDC bipolar block fault, a large amount of transient surplus reactive power and the resulting transient voltage rise are transmitted from the converter station's AC bus to the renewable energy cluster station and further to the collection station, causing a transient voltage rise across multiple substations. The transient voltage is the sum of the steady-state bus voltage and the transient voltage increment. If the transient voltage at the collection station exceeds the maximum high-voltage ride-through threshold, it may trigger immediate tripping and disconnection of connected renewable generation units.

2.3. The Transient Voltage Instability Evolution Mechanism in the Local Grid Connected to the Renewable Energy Collection Station

To highlight the key points in the qualitative analysis of the transient voltage instability evolution mechanism of the local power grid connected to the new energy collection station, a commonly used simplified dual-source equivalent model is adopted, and secondary factors such as the nonlinear characteristics of the new energy inverter are ignored, as shown in Figure 6.

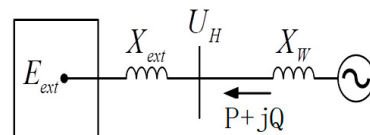


Figure 6. Dual-source parallel equivalent model of the collection station.

The network between the collection station busbar and the rectifier station is equivalent to an external system source, where E_{ext} is the equivalent electromotive force of the external system source, X_{ext} is the equivalent reactance of the external system source viewed from the collection station, X_W is the equivalent grid-connected reactance of the new energy power station, and $P + jQ$ is the power output by the new energy power station.

The equivalent system reactance viewed from the collection station busbar is

$$X_{H.S} = \frac{X_{ext}X_W}{X_{ext} + X_W} \quad (10)$$

In the formula, $X_{H.S}$ is the equivalent reactance of the system viewed from the collection station busbar, X_{ext} is the equivalent reactance of the external system source viewed from the collection station, and X_W is the equivalent grid-connected reactance of the new energy power station.

At this time, the short-circuit capacity at the collection station busbar is

$$S_{sc.H} = \frac{U_{N.H}^2}{X_{H.S}} = U_{N.H}^2 \cdot \frac{X_{ext} + X_W}{X_{ext}X_W} = U_{N.H}^2 \cdot \left(\frac{1}{X_{ext}} + \frac{1}{X_W} \right) \quad (11)$$

In the formula, $U_{N.H}$ is the rated voltage of the collection station busbar.

When the new energy power stations connected to the collection station are disconnected from the grid, the branch of the new energy power stations is out of service, and the equivalent reactance of the system viewed from the collection station busbar is

$$X'_{H.S} = X_{ext} \quad (12)$$

At this time, the short-circuit capacity at the busbar of the collection station is

$$S'_{sc.H} = \frac{U_{N.H}^2}{X'_{H.S}} = U_{N.H}^2 \cdot \frac{1}{X_{ext}} \quad (13)$$

$$S''_{sc.H} \leq S'_{sc.h} \quad (14)$$

$$\Delta U''_H \geq \Delta U'_H \quad (15)$$

After renewable energy units disconnect, the short-circuit capacity at the collection station's bus decreases, weakening the grid strength and leading to an increased transient voltage increment, which causes the collection station's bus transient voltage to rise again and remain elevated. If the duration exceeds the load tripping delay, the load will trip and disconnect from the grid, leading to the transient voltage instability of the power grid connected to the collection station [21].

3. Transient Voltage Stability Control of UHVDC Sending-End Grid with New Energy Integration Based on Coordinated Steady-State Prevention and Transient Self-Response

3.1. Steady-State Prevention and Transient Self-Response Coordinated Control Framework for Transient Voltage Stability

The study on the transient voltage instability evolution mechanism indicates that the key to transient voltage stability control in renewable energy sending-end grids is managing transient overvoltage. In scenarios of high renewable generation, if a UHVDC bipolar block fault occurs, controlling the transient voltage at the renewable energy collection station below 1.3 p.u. can effectively prevent connected renewable units from tripping offline, thereby reducing the risk of transient voltage instability in the local grid. Given that the transient voltage is the sum of the pre-fault steady-state voltage and the post-fault transient voltage increment, and considering that the increment evolves within milliseconds and requires coordinated control across multiple substations, traditional command-based control methods are no longer suitable. To address this, a "steady-state prevention and transient self-response coordinated" control framework is proposed to enable proactive and fast-acting voltage stability management.

As shown in Figure 7, in the scenario of high renewable generation and high-power DC transmission in the sending-end grid, the following occurs:

- (1) In the time dimension, steady-state voltage preventive control before the DC fault and self-responsive control of transient voltage increment after the DC fault are adopted;
- (2) In the spatial dimension, under the condition that dynamic reactive power devices at all levels of substations have sufficient regulation capacity, coordinated control of transient voltage increment is implemented at the converter station, renewable energy cluster station, and renewable energy collection station.

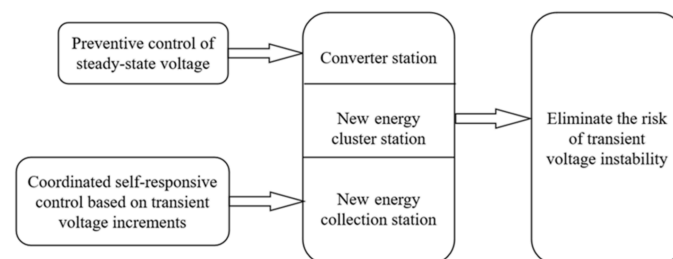


Figure 7. The control framework for transient voltage stability.

This strategy involves maintaining bus voltages at lower-end normal values during steady-state operation to achieve preventive control; after a UHVDC bipolar block fault, dynamic reactive power devices across substations collaboratively absorb surplus reactive power in a self-responsive manner, reducing the transient voltage increment and achieving optimal coordinated transient voltage control.

3.2. Steady-State Voltage Preventive Control and Transient Voltage Self-Responsive Coordinated Control Threshold Setting Method

- (1) Steady-state operating voltage control threshold setting method for substations under steady-state operation scenarios

Lowering the steady-state voltage control value helps reduce transient voltage, as indicated by Equations (2), (5) and (8). Therefore, while ensuring safe operation of the sending-end power grid, all substations should control their steady-state voltages as low as possible.

- (2) Transient voltage self-responsive coordinated control threshold setting method under transient conditions

When a UHVDC bipolar block fault drives the renewable energy sending-end grid into a transient state, due to rapid transient voltage changes and spatial characteristics across substations, each substation must not only self-respond to absorb surplus reactive power, but also coordinate actions in the sequence of converter station → renewable energy cluster station → collection station based on reactive power transmission mechanisms, to achieve optimal control of the transient voltage increment. To this end, the paper proposes a threshold setting method for transient voltage self-responsive coordinated control.

- (a) The converter station's AC bus experiences the largest surplus reactive power after a UHVDC bipolar block. Considering that the transient voltage activation threshold must exceed the system's long-term allowable overvoltage limit of 1.1 p.u. and account for the delay in dynamic reactive compensation devices at the integration station, its dynamic reactive compensation devices should act first to absorb surplus reactive power and reduce the transient voltage increment, forming the first-level defense against transient voltage instability. Thus, the transient voltage self-response activation threshold at the converter station is set to 1.11 p.u.
- (b) For the renewable energy cluster station, the activation threshold must also exceed 1.1 p.u. and consider device response delays, while ensuring it acts after the converter station to absorb reactive power and reduce the increment, providing second-level defense. Hence, the cluster station's transient voltage self-response activation threshold is set to 1.13 p.u.
- (c) As shown in Figure 1, keeping the collection station's bus transient voltage below 1.3 p.u. is critical to eliminating transient voltage instability risk. In addition to the above considerations, and building upon the first-level (converter station) and second-level (cluster station) defenses, the collection station should act after the cluster station to further absorb surplus reactive power and suppress the increment, achieving third-level defense. Therefore, the collection station's dynamic reactive compensation device activation threshold is set to 1.15 p.u.
- (d) As illustrated in Figure 1, the deactivation thresholds for the reactive compensation devices at these three levels of substations are set between 1.25 p.u. and 1.29 p.u. to ensure that the reactive power compensation devices start operating when the transient voltage reaches the activation threshold, and act during the transient voltage rising phase to absorb surplus reactive power and suppress transient overvoltage. Meanwhile, they stop operating when the transient voltage reaches the deactivation threshold and during the transient voltage falling phase. The activation condition for reactive power compensation devices at all levels of substations is set as the voltage at the next time point being higher than that at the current time point, and the deactivation condition is set as the voltage at the next time point being lower than that at the current time point. Considering the regulation capacity limit of reactive power compensation devices, the deactivation is triggered when the reactive power

regulation capability of the dynamic reactive power devices at all levels of substations is restricted, as shown in Table 6.

Table 6. The transient voltage self-response cooperative action threshold of dynamic reactive power equipment at each station.

Station	Voltage Threshold for Activation Threshold (p.u.)	Criterion for Starting Action	Voltage Threshold for Deactivation Threshold (p.u.)	Criterion for Ending Action
AC-side bus of the converter station	$V_t = 1.11$	$V_{t+1} > 1.11$	$V_t = 1.25$	$V_{t+1} < 1.25$
Cluster station 1	$V_t = 1.13$	$V_{t+1} > 1.13$	$V_t = 1.27$	$V_{t+1} < 1.27$
Collection Station 1	$V_t = 1.15$	$V_{t+1} > 1.15$	$V_t = 1.29$	$V_{t+1} < 1.29$

Note: The action ends when the regulation capacity of the dynamic reactive power equipment in stations is limited.

3.3. Transient Voltage Stability Control Strategy Based on Steady-State Prevention and Transient Self-Responsive Coordination

Based on the control framework and control thresholds, this paper proposes a transient voltage control strategy for renewable energy DC sending-end grids based on steady-state prevention and transient self-responsive coordination. The aim is to eliminate the risk of transient voltage instability in the local grid connected to the renewable energy collection station, caused by transient overvoltage at the collection station, through steady-state voltage preventive control and transient voltage self-responsive coordinated control of the DC sending-end grid.

The transient voltage control strategy for renewable energy DC sending-end grids based on steady-state prevention and transient self-responsive coordination is illustrated in Figure 8 and Table 6.

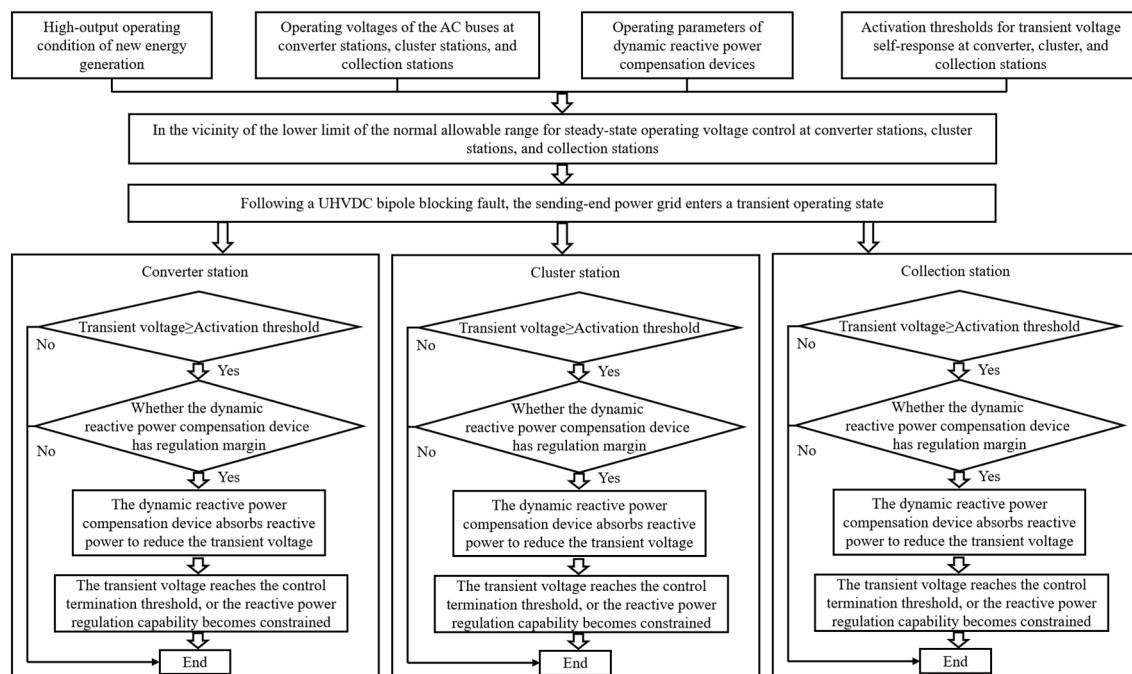


Figure 8. Transient voltage control strategy.

In the high-generation operating mode of the DC sending-end grid, steady-state voltage preventive control is first applied by regulating the AC bus voltages at the converter station, renewable energy cluster station, and collection station to the lower end of the normal allowable range, reserving sufficient voltage headroom.

When a UHVDC bipolar block fault occurs and the grid enters a transient state, transient voltage self-responsive coordinated control is activated, with each station responding sequentially based on predefined thresholds.

For the converter station, if the AC bus transient voltage ≥ 1.11 p.u. and dynamic reactive compensation devices have available regulation margin, they self-respond by absorbing reactive power to reduce the transient voltage increment, achieving first-level defense against voltage instability. Control ends when voltage reaches 1.25 p.u., the next time-step voltage is lower than the previous one, or device reactive capacity is exhausted.

For the renewable energy cluster station, if the bus transient voltage ≥ 1.13 p.u. and devices have regulation margin, they act to absorb reactive power, providing second-level defense. Control ends when voltage reaches 1.27 p.u., the next time-step voltage is lower than the previous one, or device reactive capacity is exhausted.

For the collection station, if the bus transient voltage ≥ 1.15 p.u. and devices have margin, they respond to absorb reactive power, forming the third-level defense. Control ends when voltage reaches 1.29 p.u., the next time-step voltage is lower than the previous one, or device reactive capacity is exhausted.

Ultimately, through integrated steady-state prevention and transient self-responsive coordinated control across all substations, the strategy achieves a three-level defense against transient voltage instability. This effectively eliminates the risk of voltage instability in the local grid connected to the collection station and enhances the capability of integrating and transmitting renewable energy via UHVDC systems.

3.4. Simulation Analysis

The analysis is carried out based on a typical high-proportion new energy DC sending-end power grid. The schematic diagram of the power grid configuration is shown in Figure 9. In the figure, collection station 1, collection station 2, and collection station 3 are all connected to multiple wind farms.

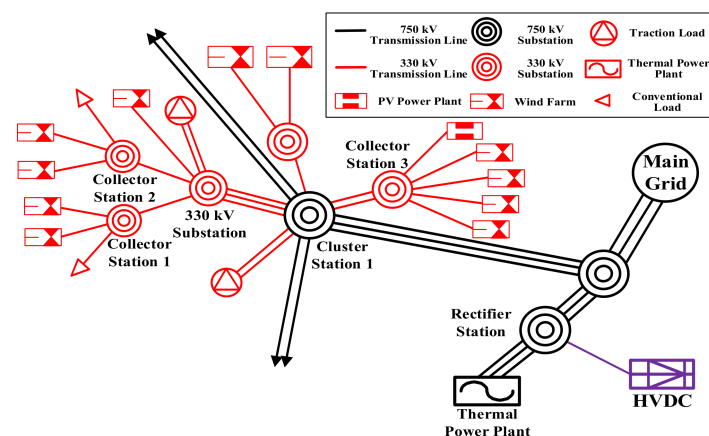


Figure 9. Schematic diagram of a typical UHVDC sending-end power grid configuration.

(1) Background

Under the steady-state operation scenario with large-scale new energy generation, the UHVDC system transmits the rated power of 8000 MW in bipolar mode. The converter station is equipped with 16 sets of AC filters totaling 4540 Mvar, along with synchronous condensers and SVCs. The reactive power required by the UHVDC system is 4000 Mvar. The new energy cluster station is connected to distributed synchronous condensers, while all of the collection stations are connected to SVCs, wind farms, and loads. To highlight the key points, this paper only presents the converter station, cluster station 1 and collection

station 1. The configuration of their dynamic reactive power devices is shown in Table 7. The threshold settings for transient voltage self-response control are given in Table 6.

Table 7. Configuration of dynamic reactive power devices in substations at all levels on the sending end.

Converter Station	Cluster Station 1	Collection Station 1
synchronous condenser: 2 × 300 Mvar SVC: 2 × 120 Mvar	distributed synchronous condenser 3 × 60 Mvar	SVC: 60 Mvar

(2) Simulation Parameter Setting

The transient voltage self-response control action threshold is shown in Table 8.

Table 8. DC fault time and self-response control action threshold of dynamic reactive power compensation equipment.

DC Bipolar Block Fault Time	Action Thresholds of Dynamic Reactive Power Compensation Equipment at Stations	Remarks
Set to 1.0 s	See Table 6	When the regulation capacity of dynamic reactive power equipment is limited, the reactive power compensation equipment terminates its operation.

The setting values for new energy unit tripping and load tripping at the collection station are shown in Table 9.

(3) Simulation calculation of control strategy

- (a) First, perform steady-state voltage preventive control. The steady-state voltages at all levels of the sending-end power grid are controlled to values near the lower limit of the normal allowable range. After control, the steady-state voltages at each substation are shown in Table 10.
- (b) Set a bipolar HVDC block fault to occur at 1 s. After the fault, the dynamic reactive power devices at the converter station, new energy cluster station, and new energy collection stations perform self-responsive coordinated control. After the control strategy is implemented, the reactive power and its increment transmitted to substations at all levels are shown in Table 11 and Figure 10; the transient voltage peak and its increment of substations at all levels after the control strategy is implemented are shown in Table 12 and Figure 11. To verify the effectiveness of the control strategy proposed in this paper, the effects without implementing the control strategy are also presented in Tables 11 and 12 and Figures 10 and 11 for comparison.

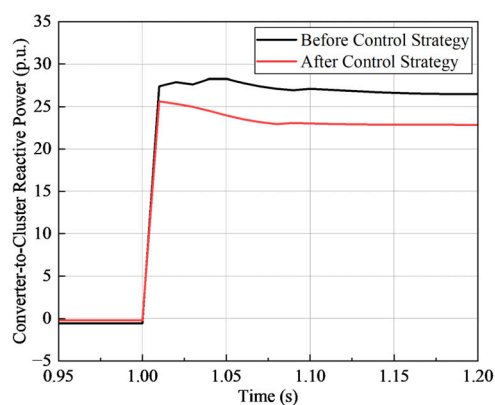
Table 9. Setting values for new energy unit tripping and load tripping at the collection station.

Source and Load Name	Tripping Voltage Setting Value (p.u.)	Delay Time (ms)
New Energy Station	1.3	0
Load	1.2	80

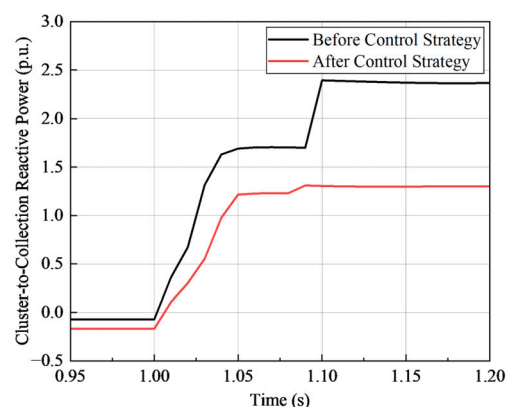
Note: The tripping setting values of new energy units at the new energy collection station are based on Reference [3], and the tripping setting values of the load are based on Reference [20].

Table 10. Steady-state operating voltage before and after control.

Station	Reference Voltage (kV)	Voltage Allowable Operating Range (p.u.)	Steady-State Operating Voltage Before Preventive Control (p.u.)	Steady-State Operating Voltage After Preventive Control (p.u.)
AC-side bus of the converter station	750	1.0~1.06	1.063	1.002
cluster station 1	750	1.0~1.06	1.062	1.002
collection station 1	330	1.0~1.1	1.095	1.024



(a)



(b)

Figure 10. Reactive power transmission curves of tie line before and after control. (a) Reactive power transfer curve between converter station and cluster station 1 before and after control. (b) Reactive power transfer curve between cluster station 1 and collection station 1 before and after control.**Table 11.** Steady-state reactive power and transient reactive power increment transmitted through tie lines before and after coordinated control.

Tie Line	Pre-Control Steady-State Reactive Power (p.u.)	Pre-Control Transient Surplus Reactive Power Increment (p.u.)	Post-Control Steady-State Reactive Power (p.u.)	Post-Control Transient Surplus Reactive Power Increment (p.u.)
Converter station → Cluster station 1	−0.564	28.274	−0.197	23.975
Cluster station 1 → Collection station 1	−0.072	1.692	−0.167	1.217

Table 12. Transient voltage peak and transient voltage increment at the busbars of all stations before and after coordinated control.

Station	Reference Voltage (kV)	Transient Voltage Peak Before Control (p.u.)	Transient Voltage Increment Before Control	Transient Voltage Peak After Control (p.u.)	Transient Voltage Increment After Control
AC-side bus of the converter station	750	1.245	0.182	1.239	0.237
Cluster station 1	750	1.195	0.133	1.191	0.189
Collection station 1	330	1.307	0.212	1.259	0.235

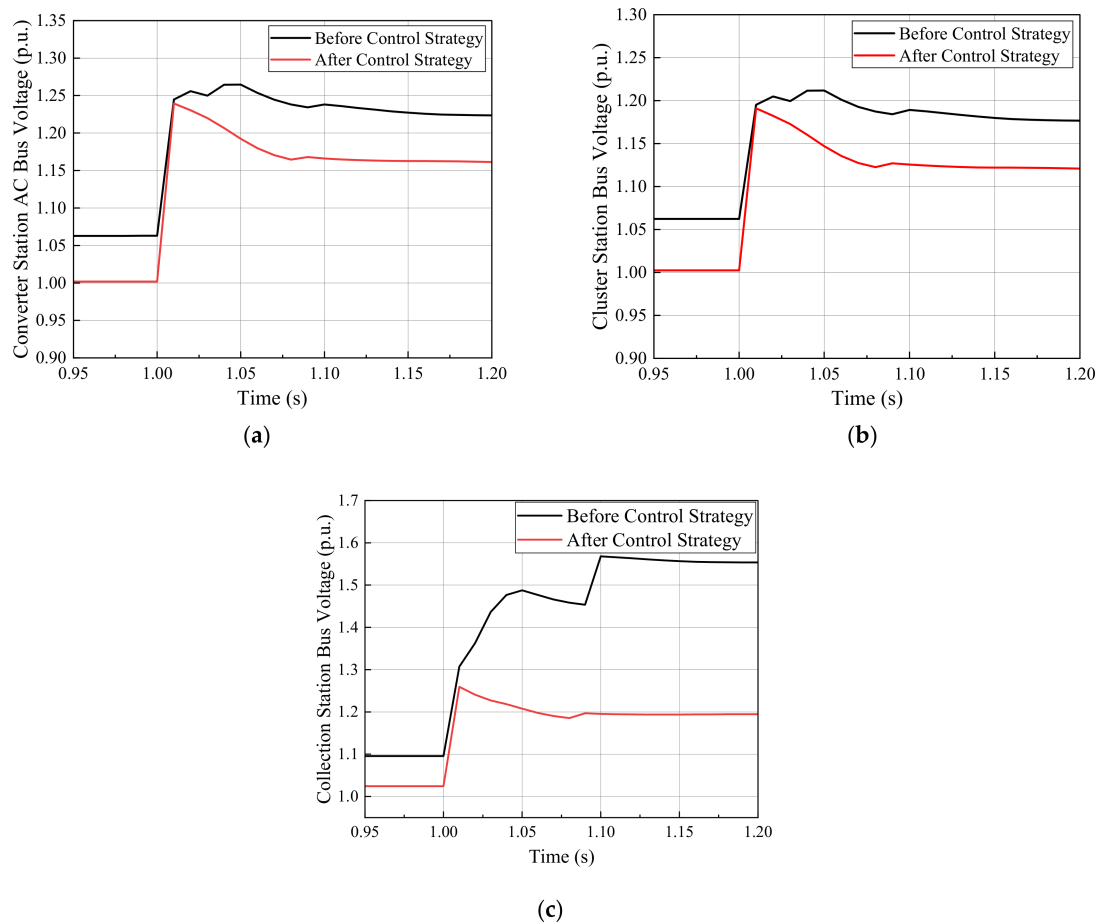


Figure 11. Transient voltage variation curves of stations before and after control following a DC bipolar blocking fault. (a) Transient voltage variation curves of converter stations before and after control. (b) Transient voltage variation curves of cluster station 1 before and after control. (c) Transient voltage variation curves of collection station 1 before and after control.

Under steady-state operation, as shown in Table 11, the reactive power flow in the sending-end grid is directed from the renewable energy collection station through the cluster station to the converter station, with a small amount of reactive power transmitted across each tie line. Most of the reactive power demand of the UHVDC system is supplied by reactive compensation devices connected to the converter station. As indicated by Table 11 and Figure 10, after a UHVDC bipolar blocking fault, a large amount of surplus reactive power is generated at the converter station's AC bus and flows backward through tie lines, passing through Renewable Cluster Station 1 to the collection station, both before and after control implementation. However, the reactive power flow transmitted is significantly reduced after control.

As shown in Table 12 and Figure 11, surplus reactive power transmitted from the converter station to the sending-end grid causes a sudden rise in transient bus voltages across all stations, with the peak value equal to the sum of steady-state voltage and transient voltage increment. Before control implementation, the bus voltage at collection station 1 surges to 1.307 p.u., exceeding the maximum high-voltage ride-through limit of wind farm units [3], triggering cascading tripping of wind turbines. As shown in Figure 11, this leads to a further voltage escalation at the collection station bus to 1.48 p.u., resulting in transient voltage instability and load disconnection after a 80 ms delay [20]. After control is applied, the transient bus voltage at collection station 1 is reduced to 1.259 p.u., which remains within the high-voltage ride-through capability of renewable units, ensuring safe

operation. The voltage then steadily decreases to 1.195 p.u., effectively eliminating the risk of transient voltage instability.

In summary, after implementing the coordinated steady-state preventive and transient self-responsive control strategy, the transient overvoltage in the sending-end power grid caused by a bipolar HVDC block fault is effectively reduced, the risk of transient voltage instability is eliminated, and the capacity for new energy delivery and accommodation is enhanced.

(4) Comparative Analysis of Different Control Strategies

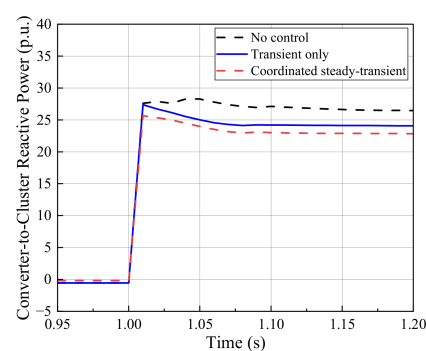
To further illustrate the effectiveness of the proposed “steady-state prevention and transient self-response coordination” control strategy in suppressing transient overvoltage, a simulation comparison is conducted between the strategy that only considers transient voltage control and the proposed strategy on their transient overvoltage control performances.

Under the scenario of maximum new energy output, a bipolar block fault of the UHVDC system is set to occur at 1 s. The transient control parameters of the two control strategies are shown in Tables 8 and 9 mentioned above.

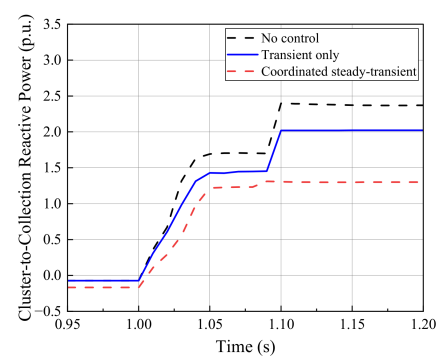
- The steady-state voltages of substations at all levels under different control strategies are shown in Table 13.
- After the DC bipolar block fault occurs, the dynamic reactive power equipment in the converter station, cluster station and collection station performs self-responsive coordinated control according to the respective control thresholds. The reactive power and reactive power increment transmitted to substations at all levels under different control strategies are shown in Table 14 and Figure 12; the transient voltage and transient voltage increment of substations at all levels under different control strategies are shown in Table 15 and Figure 13.

Table 13. Steady-state operating voltage of each substation under different control strategies.

Station	Reference Voltage (kV)	Allowable Operating Range of VOLTAGE (p.u.)	Steady-State Voltage Without Control (p.u.)	Steady-State Voltage Under Only Transient Control (p.u.)	Steady-State Voltage Under Coordinated Control (p.u.)
AC-side bus of the converter station	750	1.0~1.06	1.063	1.063	1.002
Cluster station 1	750	1.0~1.06	1.062	1.062	1.002
Collection station 1	330	1.0~1.1	1.095	1.095	1.024



(a)



(b)

Figure 12. Reactive power transmission curves of tie lines under different control strategies after bipolar block. (a) Reactive power transmission curve between the converter station and cluster station 1. (b) Reactive power transmission curve between cluster station 1 and collection station 1.

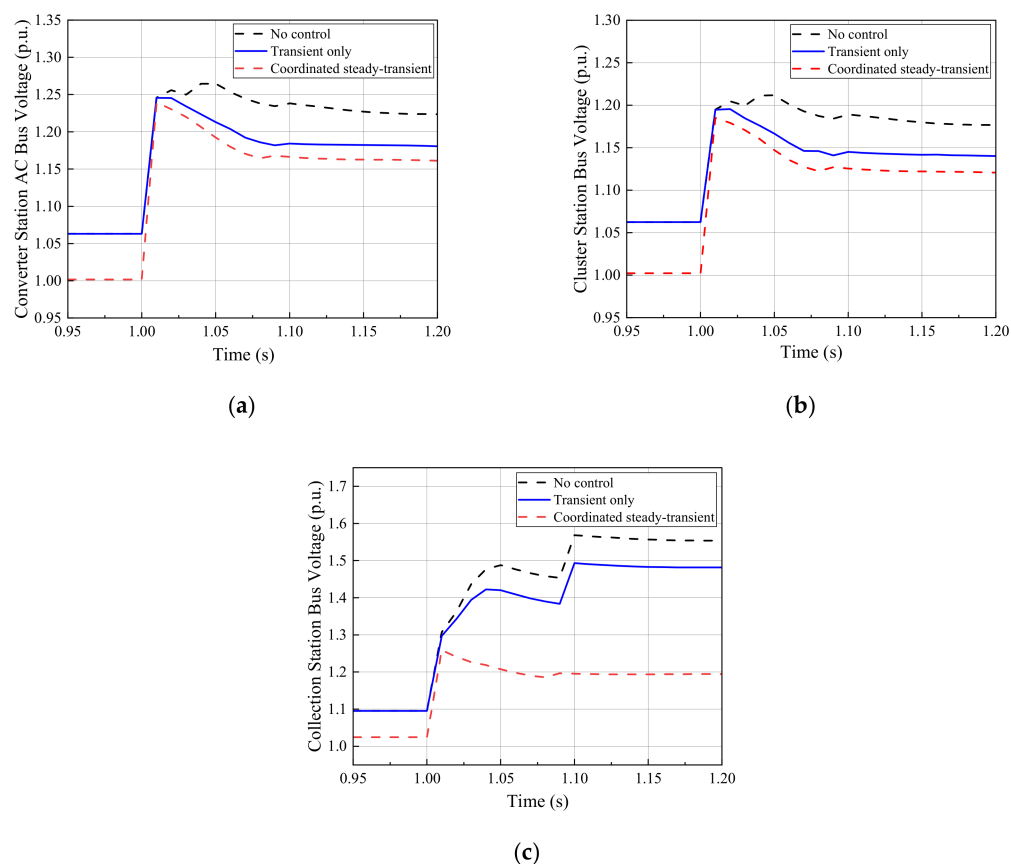


Figure 13. Transient voltage variation curves of stations under different control strategies after bipolar block. (a) Transient voltage variation curve of the converter station. (b) Transient voltage variation curve of the cluster station. (c) Transient voltage variation curve of the collection station.

Table 14. Reactive power and reactive power increment transmitted by tie lines under different control strategies.

Tie Lines	Steady-State Reactive Power Without Control	Transient Reactive Power Increment Without Control	Steady-State Reactive Power Under Only Transient Control	Transient Reactive Power Increment Under Only Transient Control	Steady-State Reactive Power Under Coordinated Control	Transient Reactive Power Increment Under Coordinated Control
Converter station → Cluster station 1	−0.564	28.274	−0.564	27.952	−0.197	25.828
Cluster station 1 → Collection station 1	−0.072	2.469	−0.072	2.092	−0.167	1.472

Table 15. Transient voltage peak and transient voltage increment of busbars in stations at all levels under different control strategies.

Station	Reference Voltage (kV)	Transient Voltage Peak Without Control	Transient Voltage Increment Without Control	Transient Voltage Peak Under Only Transient Control	Transient Voltage Increment Under Only Transient Control	Transient Voltage Peak Under Coordinated Control	Transient Voltage Increment Under Coordinated Control
AC-side bus of the converter station	750	1.245	0.182	1.245	0.182	1.239	0.237
Cluster station 1	750	1.195	0.133	1.195	0.133	1.185	0.183
Collection station 1	330	1.307	0.212	1.297	0.202	1.259	0.235

As can be seen from Table 13, under the steady-state operation scenario, the reactive power flow in the sending-end grid under different control strategies always flows from the new energy collection station to the converter station via the cluster station. However, the steady-state operating voltage under the proposed “steady-state prevention and transient self-response coordination” control strategy drops from 1.095 p.u. (the steady-state voltage under the transient-only control strategy) to 1.024 p.u., which sets the first line of defense for suppressing transient voltage. As shown in Table 14 and Figure 12, after the bipolar block fault occurs in the UHVDC system, a large amount of surplus reactive power is generated at the AC bus of the converter station under different control strategies, and is transmitted to new energy collection station 1 through the tie line via the new energy cluster station. The reactive power increment transmitted under the proposed “steady-state prevention and transient self-response coordination” control strategy is significantly lower than that under the transient-only control strategy.

As shown in Table 15 and Figure 13, in the transient scenario after the UHVDC bipolar block fault, the transient voltage at the bus of each substation rises sharply, and its peak value is the sum of the steady-state voltage and the transient voltage increment. Without control measures, the bus voltage of new energy collection station 1 surges to 1.307 p.u., exceeding the maximum high-voltage ride-through limit of wind turbine units and leading to cascading off-grid of wind farm units. Under the transient-only control strategy, the bus voltage of new energy collection station 1 still rises to 1.297 p.u. and continues to increase in the later stage, which will also cause cascading off-grid of wind farm units. In contrast, with the proposed “steady-state prevention and transient self-response coordination” control, the transient voltage at the bus of new energy collection station 1 is 1.259 p.u., and the voltage continues to decrease to 1.195 p.u. in the later stage, which effectively eliminates the risk of transient voltage instability caused by cascading off-grid of wind farm units and load tripping.

In conclusion, compared with the strategy that only implements transient voltage control, the proposed “steady-state prevention and transient self-response coordination” control strategy is more effective in suppressing the transient overvoltage of the sending-end grid caused by DC bipolar block faults and eliminating the risk of transient voltage instability.

(5) Simulation Analysis Under 50% New Energy Generation Proportion Scenario

To further illustrate the adaptability of the proposed “steady-state prevention and transient self-response coordination” control strategy across different new energy generation scenarios, this paper takes doubly fed wind turbines as the research object. Considering that the probability of maximum wind power output scenarios is relatively low and most operation scenarios are non-maximum output ones, the 50% new energy generation proportion scenario is selected. A comparison is conducted between the case without control strategies and the case adopting the proposed “steady-state prevention and transient suppression coordination” transient voltage control strategy, so as to verify the effectiveness of the proposed strategy in suppressing transient overvoltage under different new energy generation scenarios.

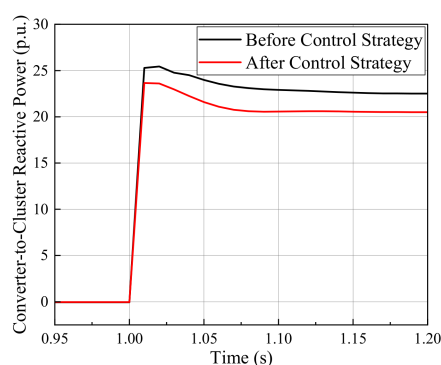
The 50% new energy generation proportion operation scenario is adopted, and other control parameters are shown in Tables 8 and 9.

- (a) First, carry out steady-state voltage preventive control. The steady-state voltages at all levels of the sending-end grid are controlled near the lower limit of the normal allowable range. The steady-state voltages of substations at all levels are shown in Table 16.
- (b) A DC bipolar block fault is set to occur at 1 s. After the fault, the dynamic reactive power equipment in the converter station, new energy cluster station and new energy

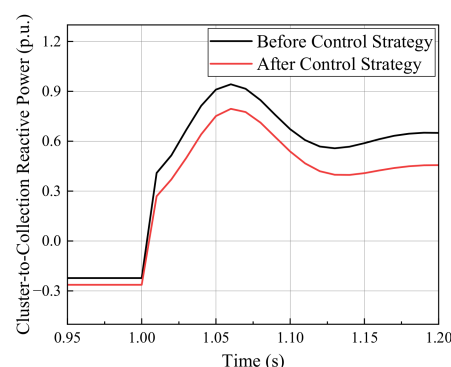
collection station performs self-responsive coordinated control according to the respective control thresholds. The reactive power and reactive power increment transmitted by tie lines at all levels are shown in Table 17 and Figure 14; the transient voltage and transient voltage increment of substations at all levels before and after control are shown in Table 18 and Figure 15.

Table 16. Steady-state operating voltage of stations before and after the control.

Station	Reference Voltage (kV)	Allowable Operating Range of Voltage (p.u.)	Steady-State Voltage Without Control (p.u.)	Steady-State Voltage with Control (p.u.)
AC-side bus of the converter station	750	1.0~1.06	1.063	1.004
Cluster station 1	750	1.0~1.06	1.062	1.003
Collection station 1	330	1.0~1.1	1.095	1.007



(a)



(b)

Figure 14. Reactive power transmission curves of tie lines before and after the control after bipolar block (50% scenario). (a) Reactive power transmission curve between the converter station and cluster station 1. (b) Reactive power transmission curve between cluster station 1 and collection station 1.

Table 17. Reactive power and reactive power increment transmitted by tie lines before and after the control.

Tie Lines	Steady-State Reactive Power Without Control	Transient Reactive Power Increment Without Control	Steady-State Reactive Power Under Coordinated Control	Transient Reactive Power Increment Under Coordinated Control
Converter station → Cluster station 1	−0.056	25.35	−0.065	23.7
Cluster station 1 → Collection station 1	−0.223	1.167	−0.263	1.058

Table 18. Transient voltage peak and transient voltage increment of the busbars in stations at all levels before and after the control.

Station	Reference Voltage (kV)	Transient Voltage Peak Without Control (p.u.)	Transient Voltage Increment Without Control (p.u.)	Transient Voltage Peak with Control (p.u.)	Transient Voltage Increment with Control (p.u.)
AC-side bus of the converter station	750	1.212	0.149	1.196	0.192
Cluster station 1	750	1.161	0.099	1.139	0.136
Collection station 1	330	1.189	0.094	1.157	0.15

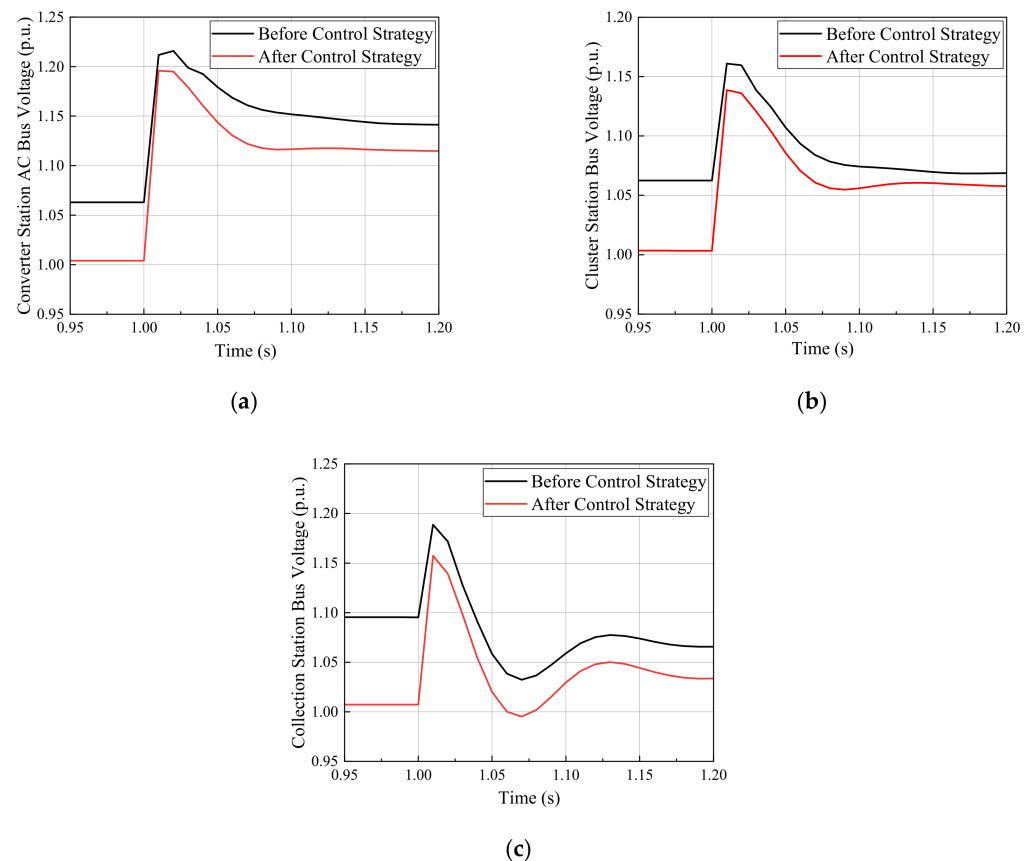


Figure 15. Transient voltage variation curves of stations under different control strategies after bipolar block (50% scenario). (a) Transient voltage variation curve of the converter station. (b) Transient voltage variation curve of the cluster station. (c) Transient voltage variation curve of the collection station.

As can be seen from Table 16, under the steady-state operation scenario, the reactive power flow in the sending-end grid always flows from the new energy collection station to the converter station via the cluster station before and after the control strategy is implemented. However, the steady-state operating voltage under the proposed “steady-state prevention and transient self-response coordination” control strategy drops from 1.095 p.u. (the steady-state voltage without control) to 1.0007 p.u., which sets the first line of defense for suppressing transient overvoltage. As shown in Table 17 and Figure 14, after the UHVDC bipolar block fault occurs, a large amount of surplus reactive power is generated at the AC bus of the converter station under different control strategies, and is transmitted to new energy collection station 1 through the tie line via new energy cluster station 1. The reactive power increment transmitted under the proposed “steady-state prevention and transient self-response coordination” control strategy is significantly lower than that under the no-control scenario.

As shown in Table 18 and Figure 15, in the transient scenario after the UHVDC bipolar block fault, the transient voltage at the bus of each substation rises sharply, and its peak value is the sum of the steady-state voltage and the transient voltage increment. Without control measures, it can be seen from Table 18 that the AC bus voltage of the converter station surges to 1.212 p.u., the bus voltage of new energy cluster station 1 rises to 1.161 p.u., and the bus voltage of new energy collection station 1 reaches 1.189 p.u. Compared with the maximum new energy output scenario, the transient voltage peaks of all substations decrease significantly, and the transient voltage peak of the new energy collection station does not exceed the maximum high-voltage ride-through limit of wind turbine units, so

cascading off-grid of wind farm units will not occur. However, the transient voltage peaks of all substations exceed the action thresholds of dynamic reactive power equipment. The reactive power compensation equipment in each substation performs self-responsive coordinated actions, reducing the transient voltage peak of the new energy collection station to 1.157 p.u., and the voltage continues to drop within the normal allowable range in the later stage.

In conclusion, under the 50% new energy generation proportion operation scenario, the proposed “steady-state prevention and transient self-response coordination” control strategy still has feasibility and effectiveness in suppressing the transient overvoltage of the sending-end grid caused by DC bipolar block faults.

4. Conclusions

This paper focuses on transient voltage stability control in large-scale renewable energy HVDC sending-end power grids, where bipolar block faults in UHVDC systems easily trigger transient voltage instability. This paper reveals the transient voltage instability evolution mechanism in renewable energy collection stations within renewable energy HVDC sending-end power grids, and proposes a transient voltage stability control strategy based on coordinated steady-state prevention and transient self-response. The conclusions are as follows:

- (1) For large-scale renewable energy-intensive UHVDC sending-end power grids, when a bipolar block fault occurs in the UHVDC system under high-renewable-generation conditions, the key factor triggering transient voltage instability in the terminal power grid connected to renewable energy collection stations is the transient voltage at the collection station exceeding the maximum overvoltage ride-through limit of the renewable energy units. Therefore, the key to eliminating transient voltage instability risk in the sending-end grid is to control the transient voltage at the collection station below the maximum overvoltage ride-through threshold.
- (2) UHVDC bipolar block faults trigger severe transient overvoltage in the sending-end grid, which is closely related to the steady-state voltage of the sending-end grid before the DC fault. Therefore, during steady-state operation of the sending-end grid, controlling substation bus voltages near the lower limit of the normal allowable range can reduce the transient voltage increment after a UHVDC fault, achieving transient voltage preventive control.
- (3) After a UHVDC bipolar block fault, the sending-end grid enters a transient state. Due to the rapid change in transient voltage and spatial characteristics across substations, traditional command-based control methods are no longer suitable. Substations at all levels should adopt threshold-based self-responsive coordinated control.
- (4) The coordinated control of steady-state prevention and transient self-response in renewable energy HVDC sending-end grids can effectively prevent chain disconnection of renewable energy units at collection stations caused by UHVDC bipolar block faults, thereby eliminating the risk of transient voltage instability in local grids and enhancing the integration and consumption capacity of renewable energy via UHVDC transmission.

This paper only analyzes the transient voltage instability mechanism in high-penetration renewable energy HVDC sending-end grids under typical operating conditions, without fully considering the impact of more complex operating conditions and uncertainties. In terms of control methods and strategies, this study does not consider multiple control factors such as the sensitivity optimization of action thresholds, the self-response control of new energy converters to transient voltage, and the adaptability of the proposed method under different conditions, which has certain limitations. Subsequent research will

further explore complex operating conditions including multi-type fault scenarios, extreme new energy output fluctuations and control uncertainties, and conduct in-depth studies on relevant mechanisms, various control methods and their adaptability under different conditions, so as to improve the practicability and universality of the method proposed in this paper.

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References

1. Li, M.J.; Guo, Q.; He, J.B.; Wang, X.; Wu, P.; Liu, M. Typical Test System of UHV AC and DC Network with High Penetration of New Energy (1): Test System for Analyzing Voltage and Power Angle Stability. *Power Syst. Technol.* **2023**, *47*, 3935–3943.
2. Sun, H.D.; Xu, S.Y.; He, J.B.; Wang, Y.; Li, W.; Zhao, B. Overvoltage of the Power System Integrated with High Proportion of Power Electronics (I): Definition, Classification and Relevant Requirements. *Proc. CSEE* **2024**, *44*, 22–33.
3. GB/T 19963.1-2021; China Electricity Council. Technical Rules for Wind Farm Integration into Power Systems—Part 1: Onshore Wind Power. China Standards Press: Beijing, China, 2021.
4. Sun, S.Q.; Yuan, Z.H.; Chen, D.Z.; Li, Z.H.; Tang, X.J.; Song, Y.T.; Zhou, G.H. Research on Coordinated Control of Dynamic Reactive Power Sources of DC Blocking and Commutation Failure Transient Overvoltage in New Energy Transmission. *Energies* **2025**, *18*, 2349. [[CrossRef](#)]
5. Wang, S.Y.; Wang, Q.C.; Zeng, Z.; Jiang, W.; Chen, J.Y.; Wang, Z.J. Overvoltage Suppression Strategy for VSG-Based DFIGs Under Commutation Failures of HVDC Transmission Systems. *Energies* **2024**, *17*, 5989. [[CrossRef](#)]
6. Jin, X.; Nian, H. Overvoltage Suppression Strategy for Sending AC Grid with High Penetration of Wind Power in the LCC-HVdc System Under Commutation Failure. In *IEEE Transactions on Power Systems*; IEEE: New York, NY, USA, 2020; Volume 36, pp. 10265–10277.
7. Yin, C.Y.; Li, F.T. Reactive Power Control Strategy for Inhibiting Transient Overvoltage Caused by Commutation Failure. In *IEEE Transactions on Power Systems*; IEEE: New York, NY, USA, 2021; Volume 36, pp. 4764–4777.
8. Tong, W.; Lin, P.; Jiaming, W.; Zengping, W. Overvoltage Suppression Under Commutation Failure Based on Improved Voltage-Dependent Current Order Limiter Control Strategy. In *IEEE Transactions on Industry Applications*; IEEE: New York, NY, USA, 2022; Volume 58, pp. 4714–4922.
9. Shi, Y.P.; Yin, C.Y.; Li, F.G.; Han, L.; Liu, J.; Zhang, Y. Transient overvoltage mechanism and control strategy considering active and reactive interaction when there is a fault in the sending end AC system. *Power Syst. Prot. Control.* **2024**, *52*, 117–128.
10. Lv, Q.G.; Xu, Z.; Li, H.; Xiao, J.; Wang, S. Effects of Dynamic Reactive Power Compensation on Wind Farm Transient Voltage and Its Control Strategy Research. *Electr. Power Constr.* **2015**, *36*, 122–129.
11. Jin, Y.D.; He, J.B.; Li, G.H.; Liu, C.; He, G.Q.; Zhang, Y. Commutation Failure of UHVDC System for Wind Farm Integration (Part II): Characteristics and Mechanism Analysis of Transient Reactive Power and Voltage of Wind Powers in Sending Terminal Grid. *Proc. CSEE* **2022**, *42*, 4738–4748.
12. Li, D.D.; Wu, X.W.; Sun, M.X.; Zhao, Y.; Luo, D.; Zhong, W.; Liu, Y. Analysis of short-term voltage stability of a large-scale direct-drive wind farm integrated into a weak AC grid based on the generalized instantaneous energy function method. *Power Syst. Prot. Control.* **2025**, *53*, 24–36.
13. Zhao, W.; Huang, Z.Y.; Pan, Y.; Xu, P.; Li, F.Q.; Li, G.Y. Static Voltage Stability Analysis of Receiving-end Grid with DC Infeed High Penetration Renewable Energy. *J. North China Electr. Power Univ.* **2022**, *49*, 11–19.

14. Yu, S.Q.; Sun, D.W.; Wu, L.L.; Li, Y.; Wang, X.; Deng, X.; Song, J. Transient overvoltage mechanism after short circuit fault removal of renewable energy collection system. *Electr. Power Autom. Equip.* **2023**, *43*, 179–185.
15. Cao, Z.; Li, X.; Yao, R.; Fan, X.; Shi, X.; Wang, X. Calculation Method of Transient Overvoltage of sending-side Grid Caused by Commutation Failure. In Proceedings of the 2019 IEEE 3rd International Electrical and Energy Conference (CIEEC47146), Beijing, China, 7–9 September 2019; IEEC-2019667. pp. 1952–1956.
16. Niu, S.B.; Cui, W.; Zhang, W.C.; Wang, Y.; Huang, M.; Wang, C. Study on Transient Overvoltage Optimization Strategy of Dc Cluster in Sending-End Grid Considering Multi-Energy Matching. *Acta Energiæ Solaris Sin.* **2025**, *46*, 103–113.
17. Shaikh, M.S.; Lin, H.; Xie, S.; Dong, X.; Lin, Y.; Shiva, C.K.; Mbasso, W.F. An intelligent hybrid grey wolf-particle swarm optimizer for optimization in complex engineering design problem. *Sci. Rep.* **2025**, *15*, 18313. [[CrossRef](#)] [[PubMed](#)]
18. Shaikh, M.S.; Dong, X.; Wang, C.; Wang, C.; Xie, S.; Lin, H. Optimized Integration of Renewable Energy Systems Using Chaotic Optimization in Distribution Systems. In Proceedings of the 2025 International Conference on Electrical Engineering and Informatics (ICEEI), Kuching, Malaysia, 13–15 November 2025; pp. 1–6.
19. GB/T 40427-2021; Technical Guidelines for Power Systems Voltage and Reactive Power. Standardization Administration of China: Beijing, China, 2022.
20. GB/T 38969-2020; Technical Guidelines for Power Systems. Standardization Administration of China: Beijing, China, 2020.
21. GB 38755-2019; Code on security and stability for power system. Standardization Administration of China: Beijing, China, 2020.

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