

Article

Coupling Characteristics and Construction Method of Single-AC Multi-DC Hybrid Grid

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Abstract

In regions with concentrated load centers in China, the AC transmission network is dense, leading to challenges such as difficulties in power flow control and excessive short-circuit currents. The scale effect of AC grids is approaching saturation, making it imperative to develop new AC/DC hybrid grid structures. To enhance the controllability, security, and stability of AC/DC hybrid power systems, a single-AC multi-DC hybrid grid structure is proposed in this paper. The operational characteristics of this grid are analyzed in terms of power flow control capability, N-1 overload, short-circuit current, frequency stability, voltage stability, and synchronous stability, and a method for constructing the single-AC multi-DC hybrid grid is presented. Finally, simulation analysis is conducted on a typical single-AC multi-DC case, and the results indicate that this hybrid grid structure can simultaneously satisfy the controllability, security, and stability requirements of AC/DC power systems, making it a highly promising grid configuration.

Keywords: single-AC multi-DC; AC/DC hybrid grid; operational characteristics; construction principles



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1. Introduction

In the eastern developed provinces of China, power loads are highly concentrated and the grid structure is complex [1]. With the increasing integration of DC infeed and renewable energy, the tightly interconnected provincial power grids are facing challenges such as difficulties in power flow control and excessive short-circuit currents [2,3], while the scale effect of AC grid development has approached saturation. To enhance the controllability and flexibility of provincial backbone grids, embedding DC systems into the main grid has emerged as a promising technical route [4]. DC systems offer fully controllable power transmission and contribute almost no short-circuit current [5]; therefore, constructing new AC/DC hybrid grid structures with the aid of DC systems is expected to address the challenges of power flow control and short-circuit current exceeding limits in load center areas. As a result, AC/DC hybrid grid structures have recently gained wide attention from both academia and industry, with pioneering applications in Jiangsu and Guangdong [6,7]. However, the existing AC/DC hybrid grid structures are still at an early stage of development. With the continuous improvement of the economy, the challenges of short-circuit current control and power flow regulation in load centers will further intensify, and the proportion and role of DC in backbone grids will significantly increase. Therefore, it is urgent to investigate rational approaches for AC/DC hybrid interconnection to address

grid construction challenges in load centers while minimizing potential adverse impacts on the system.

Replacing AC lines with DC systems reduces the degree of frequency coupling between the systems at both ends. In extreme cases, if the two systems rely entirely on asynchronous DC interconnection, their frequencies become decoupled, with no mutual power support, leading to a decline in frequency stability [8]. Even when AC connections are still retained, weak AC interconnection may result in poor synchronization stability between the two systems [9]. Therefore, while AC/DC hybrid interconnection is beneficial for addressing the challenges of power flow control and excessive short-circuit currents in load center grids, it may also be accompanied by issues such as deteriorated synchronization stability and frequency stability. Moreover, the intermittency and uncertainty of renewable energy sources such as wind and photovoltaic power will cause fluctuations in the power injected into the grid, while the reduction in system equivalent inertia will pose significant challenges to grid stability [10]. Reference [11] pointed out that from a stability perspective, there are three fundamental constraints that determine the reasonable scale of a synchronous grid: the frequency stability constraint, the minimum frequency constraint of low-frequency oscillations, and the constraint of the disappearance of synchronous power support. Building on these constraints, reference [12] further proposed an indicator to characterize the reasonable scale of AC/DC synchronous grids and established general principles for asynchronous partitioning of AC/DC synchronous grids. In addition to stability, the distribution of power flow between AC and DC lines is also a key factor in determining the configuration of AC/DC hybrid grids. In practical planning, it is necessary to avoid cascading failures caused by power flow transfers triggered by DC blocking [13].

To address the aforementioned challenges of AC/DC hybrid grids, scholars have proposed many effective improved control strategies from the perspective of system control. References [14,15] utilize the fast power regulation capability of flexible DC systems to enhance the frequency and synchronization characteristics of AC/DC hybrid power systems. Reference [16] reduces the risk of AC line overload under single contingencies by optimizing the power flow distribution between parallel AC and DC transmission channels. Reference [17] suggests that transmission line disconnection can serve as a control measure to prevent system collapse in hybrid grids. Although leveraging the regulation capability of DC systems can improve the security and stability of AC/DC hybrid grids, it cannot completely eliminate the associated risks. Therefore, corresponding measures must be developed from multiple aspects, including grid structure planning, operational control, and simulation verification [18–20].

At present, theoretical research on grid structure planning for AC/DC hybrid interconnections remains limited. To meet the future requirements for controllability, security, and stability in next-generation power systems, this paper proposes a single-AC multi-DC hybrid grid structure, analyzes its typical operational characteristics, and presents the principles for its construction.

2. Technical Characteristics of Single-AC Multi-DC Hybrid Grid Structures

The single-AC multi-DC hybrid network structure is shown in Figure 1, where there is only one AC channel between the sending and receiving-end systems, and all other channels are DC systems. The AC channel can consist of a single line or a parallel pair of symmetrical double lines. The single-AC multi-DC configuration is a special form of the AC/DC hybrid network structure. The operational characteristics of the single-AC multi-DC hybrid network are analyzed below from six dimensions: power flow control capability,

N-1 overload risk, risk of exceeding short-circuit current limits, frequency stability, voltage stability, and synchronization stability.

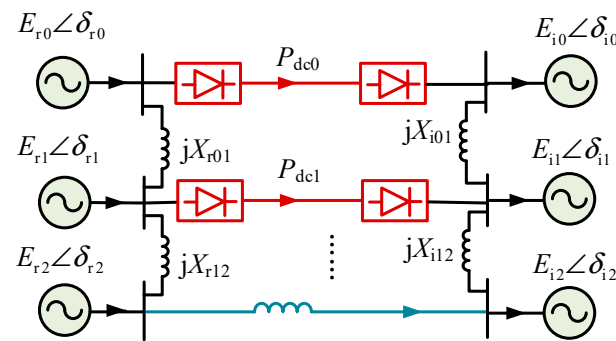


Figure 1. Diagram of single-AC multi-DC hybrid interconnected network.

In this figure, P_{acj} represents the active power transmitted by the j -th AC line in the AC channel. P_{dci} is the power transmitted by the i -th DC line. E_{rj} , E_{ij} , δ_{rj} , δ_{ij} represent the electromotive forces and power angles of the systems at both ends of the j -th transmission line. X_r , X_i denote the tie reactances between transmission lines.

2.1. Power Flow Controllability

For a fully AC synchronous interconnected network structure, the sending-end and receiving-end systems can adjust the power exchanged between them by varying generation output or load. Therefore, the total power transmitted across the AC transmission channel is controllable. However, adjusting the power distribution among different lines is difficult, as it requires changing the locations of generation and load. In practice, generation and load distribution are determined by real-world factors, and the unit startup sequence is dictated by economic dispatch results. Thus, for a fully AC synchronous interconnected network with n AC interconnection lines, the dimension of uncontrollable power can be considered $n-1$. For an AC/DC hybrid network structure, assuming that m of the n lines are DC lines, the DC system's power is controllable, so the dimension of uncontrollable power in the AC/DC hybrid network is $n-m-1$.

In the single-AC multi-DC hybrid network, the active power transmitted by the AC lines is expressed as in (1). The total power exchanged between the sending-end and receiving-end systems is controllable, and the power transmitted by the DC lines is also controllable. Therefore, according to (1), the power transmitted by the AC lines is controllable as well, and the sectional power flow is fully controllable.

$$P_{acj} = \frac{P_{\text{sum}} - \sum_{i=1}^m P_{dci}}{n_{ac}} \quad (1)$$

where P_{acj} represents the active power transmitted by the j -th AC line in the AC channel. P_{sum} is the total power transmitted across the section. P_{dci} is the power transmitted by the i -th DC line. n_{ac} is the number of AC lines, and m represents the number of DC lines.

2.2. N-1 Overload Risk

In an AC/DC hybrid network structure, if any single AC or DC line experiences a fault, the power flow shifts to the remaining AC lines, while the power on the remaining DC lines remains unchanged. For a single-AC multi-DC hybrid network, after an N-1 fault on an AC line, the power flow does not transfer to the DC system. However, following an N-1 fault on a DC line, the power flow shifts to the AC lines. Therefore, in this network structure, it is necessary to ensure that the maximum transmission power of a single DC line does not

exceed the power margin of a single AC channel, as shown in (2). For example, for a 500 kV AC line, the maximum current is approximately 3 kA, so the maximum transmission power of a single DC line must not exceed 1500 MW. If the single AC channel consists of a parallel double-circuit line, the maximum transmission power of a single DC line must not exceed 3000 MW.

$$P_{\text{dcmax}} < n_{\text{ac}} \times P_{\text{acmax}} - P_{\text{acsum}} \quad (2)$$

where P_{dcmax} refers to the maximum transmission power of a single DC line. P_{acmax} refers to the maximum transmission power of a single AC line, and P_{acsum} represents the total power transmitted by the AC lines.

2.3. Risk of Exceeding Short-Circuit Current Limits

The introduction of DC lines into an AC network helps increase the electrical distance between generation and load nodes, thereby reducing short-circuit currents. Under the same transmission capacity, the higher the degree of DC integration, the lower the risk of exceeding short-circuit current limits. Therefore, compared with a fully AC synchronous network, the short-circuit current risk in an AC/DC hybrid network is mitigated. For a single-AC multi-DC network structure, the AC electrical connection between the sending-end and receiving-end systems is significantly weakened, which can largely alleviate short-circuit current issues. Additionally, by evaluating the contribution of each channel in the transmission section to the short-circuit current at each node of the sending-end and receiving-end systems, the AC line with the lowest overall contribution can be retained, while the remaining channels are implemented as DC lines. Specifically, all possible single-AC multi-DC configurations of the transmission section are examined, and the short-circuit current margin under each configuration is assessed using (3). The configuration with the largest short-circuit current margin is then selected.

$$\mu_{\text{ss}} = \min \left(\frac{I_{\text{max}h} - I_{\text{ssh}}}{I_{\text{max}h}} \right) \quad (3)$$

where μ_{ss} is the minimum short-circuit current margin in the system. $I_{\text{max}h}$ is the maximum allowable short-circuit current at node h . I_{ssh} is the actual short-circuit current at node h , and $\min()$ denotes taking the minimum value among all nodes.

2.4. Analysis of System Frequency Stability

With the increasing penetration of renewable energy and the corresponding phase-out of synchronous generators, the system's inertia level gradually decreases, leading to a deterioration in frequency stability under disturbances of the same intensity. For both fully AC synchronous network structures and AC/DC hybrid network structures, as long as there remains an AC line connection between the two systems after any N-1 line fault, no power imbalance will occur across the system, and the risk of frequency instability can be avoided. In contrast, in a fully DC asynchronous interconnected network structure, an N-1 fault of a DC line will cause a power surplus in the sending-end system and a power deficit in the receiving-end system, resulting in frequency fluctuations.

In a single-AC multi-DC hybrid network, any N-1 or N-2 fault in the DC system will not cause a power deficit between the sending- and receiving-end systems, as the DC transmission power will be transferred to the AC line. Therefore, DC faults do not pose a threat to the frequency stability of a single-AC multi-DC interconnected system. However, when an N-1 or N-2 fault occurs on the AC line and the sending-end and receiving-end systems completely lose their AC connection, the power previously transmitted by the AC line will not be taken over by the DC system, resulting in a power deficit between the two systems. For a single-AC multi-DC network, the maximum possible power deficit that may

occur between the sending and receiving ends is represented by P_{acmax} , as expressed in (4). Since the AC line power is fully controllable, P_{acmax} can be restricted to a very small range, or even reduced to zero.

$$P_{acsum} = \sum_{j=1}^{n_{ac}} P_{acj} \quad (4)$$

where P_{acmax} represents the maximum possible power deficit between the sending- and receiving-end systems. n_{ac} is the number of AC lines, and m represents the number of DC lines. P_{acj} represents the active power transmitted by the j -th AC line in the AC channel.

2.5. Analysis of System Voltage Stability

For the single-AC multi-DC network structure, the increasing degree of DC integration weakens the electrical connections among regional AC networks and reduces the voltage support capability of converter buses, thereby significantly increasing the risk of commutation failures. Consequently, voltage stability becomes a critical concern in single-AC multi-DC structures, which can be evaluated based on the strength of the AC system's voltage support capability. To address insufficient voltage support in power grids, flexible DC transmission technology is widely adopted in engineering practice, as it effectively enhances system voltage support strength and reduces the risk of commutation failure. Therefore, it is necessary to assess the voltage support strength of the single-AC multi-DC network structure to determine the appropriate DC technology route and ensure voltage stability.

Considering the recent large-scale integration of renewable energy into power systems, the voltage stiffness index suitable for non-synchronous generation sources can be applied to evaluate system strength, as shown in (5) [21]. If the index exceeds the threshold $K_{vtg \min}$, the access point system is considered relatively strong.

$$K_{vtg} = \frac{U_{sys}}{U_{sys0}} = \frac{\lambda_{SCR}}{\sqrt{1 + \lambda_{SCR}^2}} \geq K_{vtg \min} \quad (5)$$

where λ_{SCR} denotes the short-circuit ratio of the grid at any node corresponding to the connected device. U_{sys} represents the voltage magnitude at the network port. U_{sys0} is the open-circuit voltage at any node when the device is not connected to the grid, and $K_{vtg \min}$ is the minimum allowable voltage stiffness value under engineering safety standards.

2.6. Analysis of System Synchronization Stability

In a single-AC multi-DC network structure, the AC connection between the sending-end and receiving-end systems is relatively weak. Under the condition of equal power transmission on the AC interconnection line, the synchronous stability of a single-AC multi-DC network is relatively poorer compared with that of a fully AC or conventional AC/DC hybrid configuration. However, for a single-AC multi-DC network, the stability of the sending- and receiving-end systems can be ensured in two ways.

On the one hand, the power transmitted by the AC line, P_{acsum} can be reduced, or even set to zero, in which case the synchronous stability between the sending-end and receiving-end systems can be effectively improved. On the other hand, under severe faults, the protection device of the AC interconnection line continuously monitors the phase angle difference between the two ends, and once the phase angle difference reaches a certain threshold (6), the AC line is automatically tripped, allowing the sending-end and receiving-end systems to operate asynchronously without the need to maintain synchronism.

$$\Delta\theta_{ac} \geq \theta_{th} \quad (6)$$

where $\Delta\theta_{ac}$ denotes the phase angle difference between the two ends of the AC interconnection line, and θ_{th} is the phase angle difference threshold.

In conventional AC/DC hybrid grids, the strong coupling among multiple AC channels causes disturbances to AC tie-line power during faults, leading to an expanded fault range. In contrast, the single-AC multi-DC structure, equipped with an active AC line-shedding device, can promptly disconnect the AC line once the rotor angle difference between the two ends of the transmission corridor reaches a certain threshold, thereby enabling asynchronous operation of the sending and receiving grids, avoiding angle instability, and providing more flexible control of synchronization stability.

In terms of power flow characteristics, since the number of uncontrollable dimensions in an AC/DC hybrid transmission section is $n-m-1$, the single-AC multi-DC configuration enables full controllability of section power flows. By appropriately coordinating the power allocation between AC and DC lines, it can effectively avoid the risk of N-1 line overload. Regarding short-circuit current risk, as the degree of DC penetration in the transmission section increases, the suppression effect becomes more pronounced, ensuring the safety of short-circuit currents while expanding transmission capacity. Moreover, when frequency or synchronization disturbances occur between the systems at both ends of the section, the proposed scheme can employ an active line-shedding strategy to promptly disconnect a single AC line, thereby enhancing system transient stability. Therefore, compared with conventional AC/DC hybrid sections, the single-AC multi-DC structure offers significant advantages in terms of power flow controllability, operational stability, and mitigation of security risks. This structure better aligns with the future development requirements of controllability, security, and stability in modern power grids.

3. Construction Scheme of the Single-AC Multi-DC Hybrid Network Structure

From a technical perspective, controlling the power of AC lines in the single-AC multi-DC network to zero can effectively reduce N-1 overload risks and improve system frequency stability and synchronism stability. The construction method of the single-AC multi-DC network under this condition is shown in Figure 2.

Based on the above analysis, the construction principles of the single-AC multi-DC network structure can be summarized as follows.

- (1) Following the principle of maximizing the short-circuit current margin (3), select a single AC channel in the transmission section, while adopting DC transmission technology for the remaining channels.
- (2) Use the potential power deficits at the sending and receiving-end systems caused by N-1/N-2 AC line faults (4) to verify system frequency stability and determine the maximum allowable transmission power of the AC lines.
- (3) Apply (2) to determine a reasonable allocation of AC and DC transmission power, ensuring that DC system N-1/N-2 faults do not cause AC line overloads.
- (4) Determine the DC technology route and calculate the system strength under the AC/DC hybrid structure using (5). If the system strength meets engineering requirements, a conventional DC technology route is adopted; otherwise, a flexible DC technology route with voltage support capability may be considered.
- (5) Establish an active disconnection strategy for the AC interconnection lines. When the phase difference at both ends of an AC interconnection line reaches a certain threshold, the AC line is actively disconnected, allowing asynchronous operation between the sending and receiving-end systems.

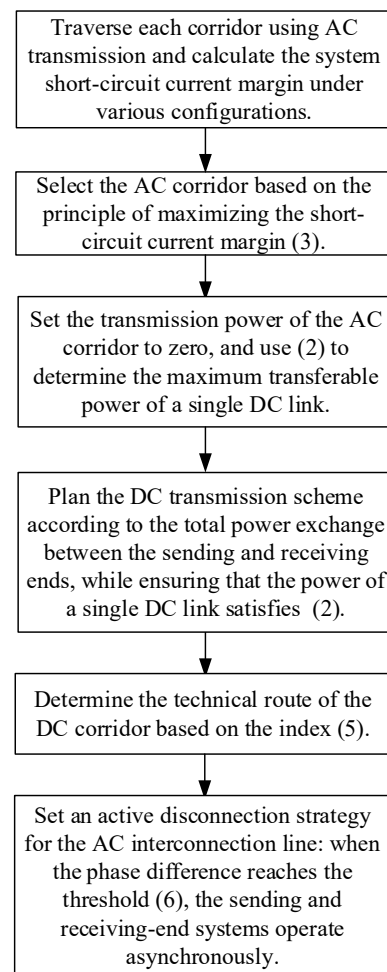


Figure 2. Construction method of single-AC multi-DC hybrid interconnected network.

4. Case Analysis

A typical single-AC multi-DC case is constructed using the IEEE two-area four-machine system. Specifically, two IEEE two-area four-machine systems are interconnected through three transmission channels, as shown in Figure 3. The load levels of the sending and receiving-end systems are adjusted so that the exchanged power between the two systems reaches 4000 MW. First, the location of the AC channel needs to be determined based on the system short-circuit current margin. With the transmission distance and AC line reactance parameters fixed, each transmission channel is traversed using the AC interconnection scheme, and the minimum short-circuit current margin of the system under different schemes is obtained, as shown in Table 1.

Through calculation, if channel 1 is selected as the AC channel, the short-circuit current margin of system is 18%. If channel 2 is selected as the AC channel, the system achieves the maximum short-circuit current margin 26%, with the lowest risk of short-circuit current exceeding the limit. And if channel 3 is selected as the AC channel, the maximum short-circuit current margin of system is 16%. According to the flow chart of the planning scheme for the AC/DC hybrid transmission section with single AC channel and multiple DC channels shown in Figure 2, the configuration of the AC and DC channels in the section structure at the first step is carried out based on the principle of maximizing the short-circuit current margin. Therefore, channel 1 and channel 3 are selected as DC transmission channels, while channel 2 is chosen as the AC transmission channel to construct the single-

AC multi-DC network structure, as illustrated in Figure 4. The main parameters of the two DC systems are provided in Table 1.

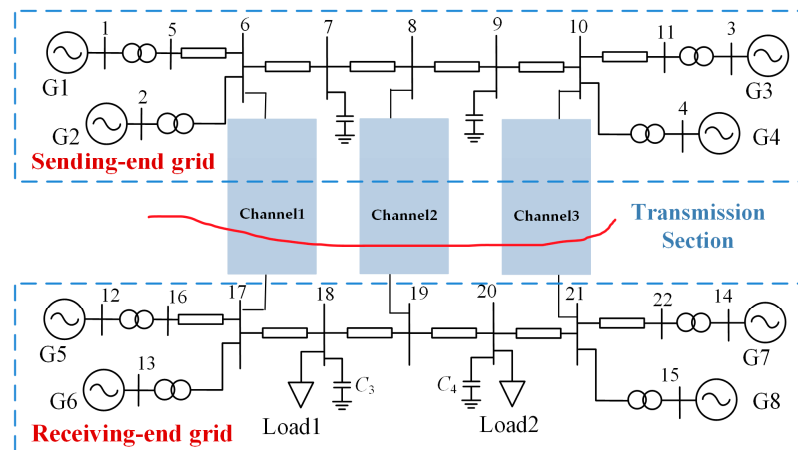


Figure 3. Typical case of three-channel interconnection system.

Table 1. Short-circuit current margin indicators that do not meet the requirements.

Parameter	Rated Power /MW	Number of Poles	Voltage Level /kV	Technology Route
HVDC 1	2000	2	500	LCC
HVDC 2	2000	2	500	LCC

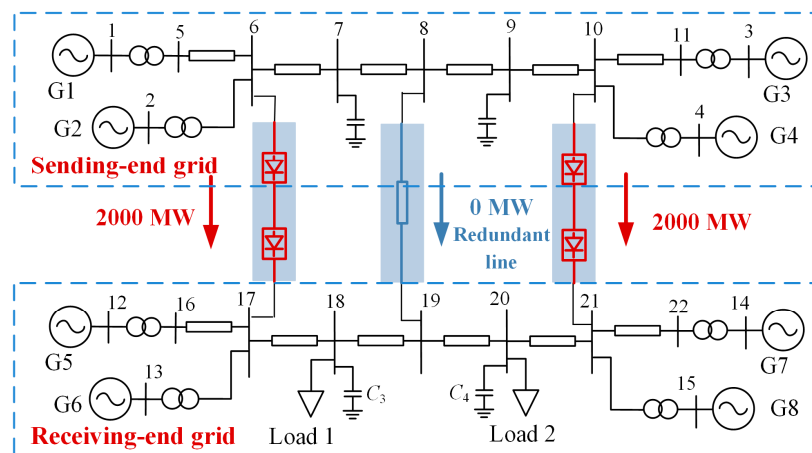


Figure 4. Typical case of single-AC multi-DC system.

First, the frequency stability of the system under the single-AC multi-DC interconnection scheme is analyzed. A fault is applied by causing a DC fault and blocking HVDC1 at 0.5 s, resulting in the frequency variations in the sending and receiving-end generators as shown in Figure 5, while the changes in AC line power flows are shown in Figure 6. As observed from Figures 5 and 6, when HVDC1 experiences a DC blocking, the power that would have been transmitted by HVDC1 is rapidly transferred to the AC interconnection lines. The frequency deviation of the sending and receiving-end generators is very small and returns to the nominal value after minor fluctuations over a short period. Therefore, under the single-AC multi-DC transmission scheme, the interconnection provided by the AC lines can effectively prevent DC blocking from impacting the system frequency at the sending and receiving ends.

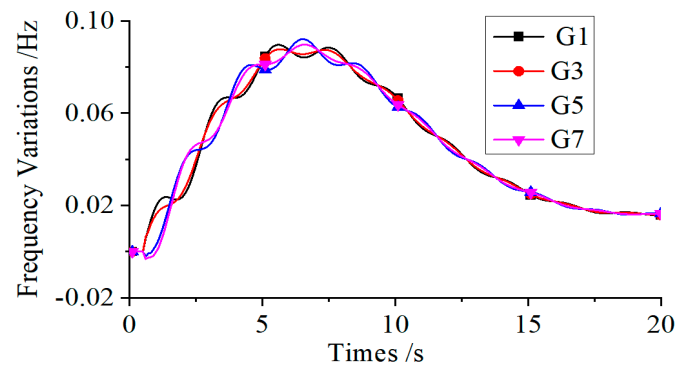


Figure 5. Frequency response curves under the HVDC1 blocking.

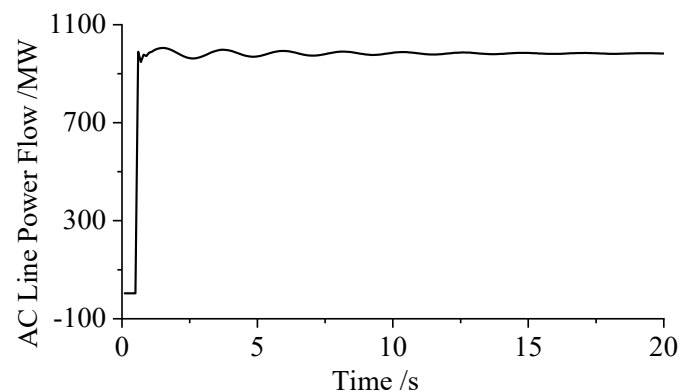


Figure 6. Active power variation in the AC tie line under the HVDC1 blocking.

Next, the impact of AC interconnection line faults between the sending and receiving-end systems on system frequency stability is examined. A three-phase metallic short-circuit fault is applied to the AC interconnection line at 0.5 s and lasts for 0.1 s, after which the AC line is disconnected and the short-circuit fault is cleared. The resulting frequency variations in the generators are shown in Figure 7. As seen in Figure 7, during the short-circuit fault, the frequencies of all generators rise rapidly. Once the fault is cleared, the frequencies gradually decrease and eventually return to their nominal values. It is worth noting that the process shown in Figure 7 reflects the primary frequency response caused by the temporary obstruction of power delivery to the generators due to the short-circuit fault.

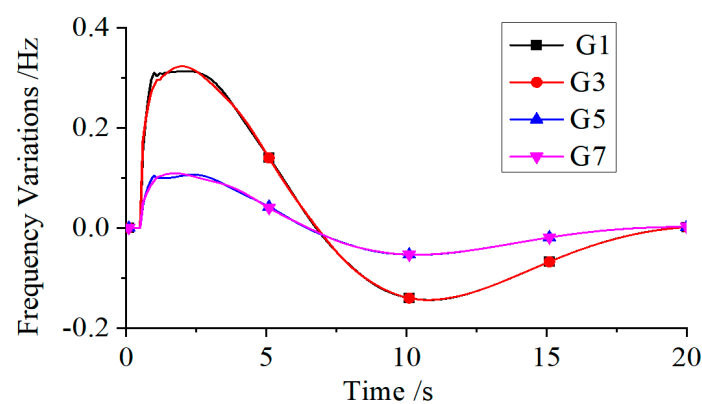


Figure 7. Frequency response curves under the short-circuit fault and disconnection condition.

To illustrate this, the AC interconnection line is disconnected without introducing a short-circuit fault, and the generator frequency variations are shown in Figure 8. From Figure 8, it can be seen that, in the absence of a short-circuit fault, opening the AC inter-

connection line has negligible effect on the frequencies of the generators, because under steady-state conditions the AC line does not carry significant power.

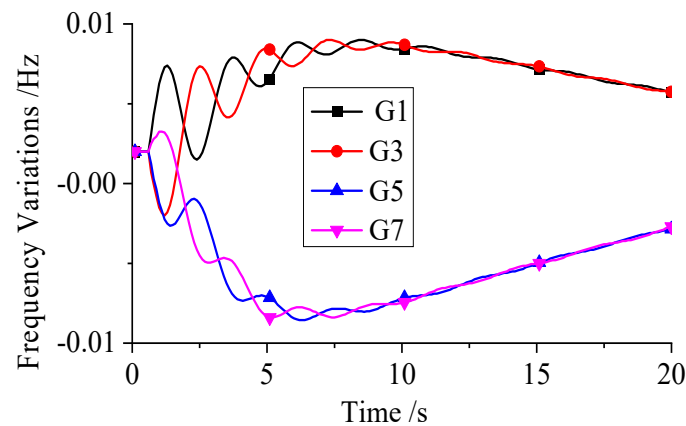


Figure 8. Frequency response curves under the disconnection condition.

From the above analysis, it can be concluded that under the single-AC multi-DC interconnection scheme, neither AC nor DC faults create unbalanced power in the system, effectively enhancing system frequency stability.

The feasibility of the single-AC multi-DC interconnected scheme is analyzed from the perspective of synchronous stability. Compared with a fully AC synchronous interconnection scheme, the AC coupling between the sending and receiving systems is weakened under the single-AC multi-DC scheme, which can lead to a deterioration of system synchronous stability if no countermeasures are taken. A short-circuit fault is applied on the line between bus 6 and bus 7 in the sending-end system and cleared after 0.1 s. The rotor angle responses of all units in the system are shown in Figure 9. As seen in Figure 9, without any mitigating measures, the short-circuit fault causes the units in the sending and receiving systems to lose synchronism, with the phase difference continuously increasing. Ultimately, the units lose synchrony, and the system's synchronous stability cannot meet the requirements for stable operation.

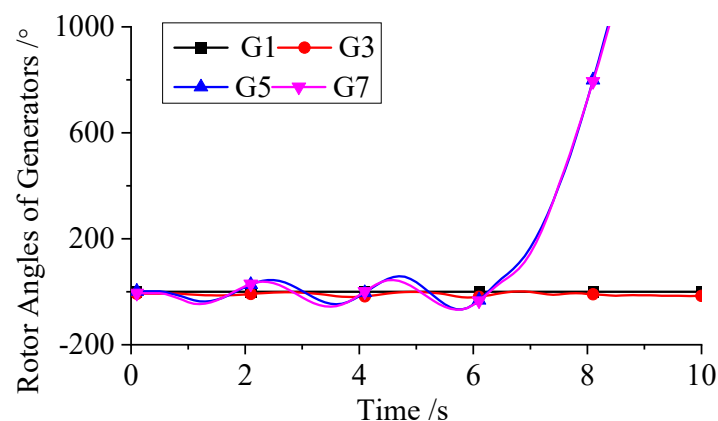


Figure 9. Angle response curves under the short-circuit fault in the sending-end system.

Although the inherent structure of a single-AC multi-DC system can negatively impact system synchronous stability, the single-AC multi-DC configuration has the advantage of being able to flexibly switch to an asynchronous interconnection mode. In the case of a single-AC multi-DC interconnection scheme, if the AC tie line is actively disconnected, the sending and receiving systems enter an asynchronous interconnection state, and the issue of synchronous stability no longer exists.

To verify the impact of active AC tie line disconnection on system stability, for the system shown in Figure 4, the AC tie line is actively disconnected when the phase difference between its terminal buses reaches 40° . Applying the same short-circuit fault at the sending-end system again, the phase difference between the AC tie line terminal buses reaches 40° at 1.5 s, causing the tie line to disconnect. The simulation results are shown in Figure 10. As can be seen from Figure 10, after the AC tie line is actively disconnected, the frequencies of the generating units in the sending-end and receiving-end systems gradually return to their rated values, and the system tends toward stability. Therefore, by utilizing the active disconnection capability of the AC line, the single-AC multi-DC interconnection scheme can effectively prevent loss of synchronism between the sending and receiving systems.

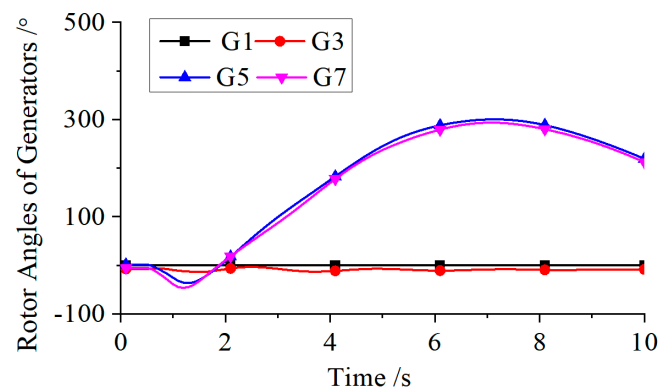


Figure 10. Angle response curves under the active disaggregation.

Furthermore, after the transmission section planning, simulation results show that the voltage stiffness indices at the key nodes all exceed 0.95, indicating that the system has sufficient voltage support capability. In summary, the voltage stability, frequency stability, and synchronous stability of this single-AC multi-DC transmission structure all meet the engineering operational stability requirements.

5. Conclusions

This paper addresses critical challenges in power grids located in load center areas, where dense AC networks often lead to difficulties in power flow control and the occurrence of excessive short-circuit currents. To overcome these issues, a novel single-AC multi-DC hybrid grid structure is proposed. This innovative configuration aims to enhance both the operational flexibility and the overall stability of power systems, providing a feasible solution for modern high-demand load centers. The main conclusions of this study are summarized as follows:

- (1) The technical advantages of the single-AC multi-DC hybrid structure are comprehensively analyzed from six key dimensions: power flow controllability, N-1 overload risk, short-circuit current risk, voltage stability, frequency stability, and synchronous stability. The analysis demonstrates that this hybrid structure not only improves the controllability of power flows compared to conventional AC-dominated grids but also effectively mitigates risks associated with line overloads and short-circuit currents. Moreover, the results show significant enhancements in voltage regulation, frequency response, and synchronous stability, highlighting the superior performance of the single-AC multi-DC structure across all evaluated technical aspects.
- (2) To validate the effectiveness of the proposed configuration, simulation studies are conducted on a representative single-AC multi-DC test system. The results indicate that the system can leverage the active disconnection capability of AC lines to dynamically transition into an asynchronous operational mode when necessary. This capabil-

ity allows the grid to compensate for potential deficiencies in synchronous stability, thereby substantially improving the overall controllability, operational flexibility, and security-stability of the power network. These findings confirm that the single-AC multi-DC hybrid structure is a promising approach for enhancing the resilience and adaptability of modern power grids in load center regions.

In the future, research will continue to explore the coordination between the optimal planning of the single-AC multi-DC structure and high-proportion renewable energy, so as to provide more comprehensive technical support for power grid upgrading and transformation and to realize the unification of power sources and the grid.

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References

1. Liu, L.; Cheng, H.; Wu, Y.; Chen, H.; Zhang, N.; Wang, Z. Research Progress and Prospects of Transmission Expansion Planning Method for High Proportion of Renewable Energy. *Autom. Electr. Power Syst.* **2021**, *45*, 176–183.
2. Chi, Y.; Liang, W.; Zhang, Z.; Li, Y.; Jin, S.; Cai, X.; Hu, J.; Zhao, S.; Tian, W. An Overview on Key Technologies Regarding Power Transmission and Grid Integration of Large Scale Offshore Wind Power. *Proc. CSEE* **2016**, *36*, 3758–3771. [\[CrossRef\]](#)
3. Deng, B.; Wen, Y.; Yu, L.; Jiang, X. Short-circuit Current Suppression Strategy for Receiving-end Power Grid Based on Coordination of Current Limiter Configuration and Network Structure Optimization. *Autom. Electr. Power Syst.* **2024**, *48*, 151–161.
4. Wang, Z.; Ling, J.; Zheng, J.; Wang, C.; Kong, X.; Liu, Z.; Feng, X. Optimized DC Fault Transient Control Strategy for Embedded Symmetric Unipolar LCC-HVDC. *Power Syst. Technol.* **2025**, *49*, 1541–1550. [\[CrossRef\]](#)
5. Yi, Y.; Shen, Y.; Lin, Z. Characteristics and Analysis Methods of AC Short-circuit Current Contributed by VSC-HVDC. *High Volt. Eng.* **2018**, *44*, 2150–2158. [\[CrossRef\]](#)
6. Wang, Z.; Huang, J.; Sun, W.; Sun, F.; Lan, T.; Diao, R. Intelligent analysis method for dynamic response of receiving system with embedded HVDC. *Electr. Power Eng. Technol.* **2024**, *43*, 77–85. [\[CrossRef\]](#)
7. Luo, S.; Liu, R.; Jin, C.; Zuo, Z.; Lin, Y.; Zhang, D.; Zhou, Q.; Wang, D. Risk and countermeasures of high-frequency resonance for back-to-back HVDC in Guangdong Power Grid. *South. Power Syst. Technol.* **2023**, *17*, 1–9+21. [\[CrossRef\]](#)
8. Wang, Y.; Qiu, F.; Lei, M.; Ji, Y.; Wang, C. Frequency support strategy for VSC-BTB based DC segmented system with large capacity renewable energy integration. *Power Syst. Technol.* **2023**, *47*, 959–968. [\[CrossRef\]](#)
9. Li, Y.; Xia, S.; Ma, L.; Zhao, K.; Li, X. Transient power angle stability evaluation and interpretability analysis of AC/DC hybrid power system. *Electr. Power Constr.* **2024**, *45*, 1–9.
10. Le, C.; Bei, B. Impact of new energy access on power grid stability and counter measures. *J. Xiangtan Univ.* **2022**, *44*, 121–126.
11. Xu, Z.; Dong, H.; Song, P.; Cheng, B. Three basic constraints for reasonable size of synchronous grids. *Electr. Power Constr.* **2015**, *36*, 77–84.
12. Dong, H.; Xu, Z.; Qian, Y.; Si, D.; Song, P.; Xing, F. General principle of asynchronous segment for AC/DC synchronous power systems. *High Volt. Eng.* **2017**, *43*, 2167–2174. [\[CrossRef\]](#)
13. Shen, Z.; Sun, H.; Zhong, W.; Wang, A.; Zhao, B.; Xu, S. Key event based analysis of evolution law of cascading failures in power system with high proportion of renewable energy. *Autom. Electr. Power Syst.* **2022**, *46*, 57–65.

14. Peng, F.; Huang, W.; Xu, S.; Li, Y.; Guo, Z.; Liu, T. Asynchronous automatic control strategy for MMC-HVDC system. *South. Power Syst. Technol.* **2023**, *17*, 20–26. [[CrossRef](#)]
15. Shu, H.; Shao, Z.; Zhao, W.; Bao, G. Research on emergency power control of AC-DC hybrid power system with flexible DC. *Trans. China Electrotech. Soc.* **2023**, *38*, 5590–5604. [[CrossRef](#)]
16. He, S.; Liu, J.; Wang, Q.; Zhou, Z.; Chang, A.; Xiao, Y.; Liang, W.; Lin, S.; Dong, P. Distributionally robust optimization for the power allocation of AC/DC parallel transmission channels. *J. Electr. Power Sci. Technol.* **2023**, *38*, 225–236. [[CrossRef](#)]
17. Yu, F.; Liu, C.; Zhang, Y. Research on influence of transmission line breaking control on transient stability of AC/DC hybrid power system. *J. Northeast. Electr. Power Univ.* **2023**, *43*, 85–91. [[CrossRef](#)]
18. Lv, P. Research on HVDC operation characteristics under influence of hybrid AC/DC power grids. *Power Syst. Technol.* **2022**, *46*, 503–510. [[CrossRef](#)]
19. Huang, Y.; Zhang, J.; Wang, G.; Xu, Z. Transient stability analysis and improvement of isolated renewable energy bases with VSC-DC transmission. *CSEE J. Power Energy Syst.* **2025**, 1–11, early access. [[CrossRef](#)]
20. Xiao, H.; Gan, H.; Yang, P.; Li, L.; Li, D.; Hao, Q. Robust submodule fault management in modular multilevel converters with nearest level modulation for uninterrupted power transmission. *IEEE Trans. Power Deliv.* **2023**, *39*, 931–946. [[CrossRef](#)]
21. Xu, Z. Reasonable definition and calculation method of power grid strength under the background of new power system. *High Volt. Technol.* **2022**, *48*, 3805–3819. [[CrossRef](#)]

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