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A Transient Multi-Feed-In Short Circuit Ratio-Based Framework for East China: Insights into Grid Adaptability to UHVDC Integration

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Abstract

Amid escalating climate challenges, China's carbon neutrality objectives necessitate energy electrification as a pivotal strategy. As a critical load hub, East China demonstrates significant trends toward cleaner energy—marked by growing renewable energy penetration and accelerated cross-regional direct current (DC) transmission deployment. Ensuring stable and efficient grid operation requires rigorous assessment of the impacts of ultra-high voltage DC (UHVDC) integration on grid stability. This study introduces the transient multi-feed-in short circuit ratio (TMSCR), a novel metric for evaluating new DC transmission systems' influence on grid performance. We systematically investigate UHVDC integration within the East China power grid, emphasizing strategic DC landing point placement. Using TMSCR, the effects of diverse DC incorporation methods are analyzed. Furthermore, this research examines impacts of new DC connections on local and main grids, proposing targeted mitigation measures to enhance grid resilience. This comprehensive UHVDC impact analysis addresses a critical literature gap, providing actionable insights for East China power grid planning and establishing a foundation for subsequent grid planning and DC project feasibility studies during the '15th Five-Year Plan' period.

Keywords: UHVDC transmission; power grid planning; grid stability; cross-regional transmission; transient multi-feed-in short circuit ratio

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1. Introduction

In response to the global transition in energy and power systems, China has introduced its "Dual Carbon" strategy, targeting "carbon peaking" by 2030 and "carbon neutrality" by 2060 [1]. Carbon neutrality is not only a pivotal commitment to addressing climate change, but also a comprehensive and systemic endeavor to drive a green and low-carbon transformation of the entire society [2]. Achieving this goal requires coordinated progress across multiple sectors, including energy production and consumption, industrial restructuring, technological innovation, infrastructure development, and institutional policies. Among these, the decarbonization of the energy system is a key pathway [3,4]. This transition demands a fundamental shift from reliance on conventional fossil fuels to the adoption of clean energy [5]. While traditional coal-fired power generation provides stable baseload supply, its significantly higher carbon intensity conflicts with decarbonization objectives. In contrast, renewable energy sources produce electricity with near-zero operational emissions, positioning them as the cornerstone of China's energy transition strategy [6]. Currently, the accelerated deployment of renewable energy has become an irreversible trend, with rapid growth in photovoltaic and wind power capacity, particularly in regions with optimal geographic conditions [7]. This shift is driving substantial changes in the nation's energy infrastructure and reshaping the design of its power systems.

East China, as one of the most economically developed regions, plays a key role in optimizing China's energy structure and leading the green transformation of power systems [8]. The rapid growth of electricity demand in this region, driven by a dense population and a strong industrial base, presents significant challenges. Historically, the region has relied on local and cross-regional coal power to meet its energy needs. However, stricter environmental regulations and advances in renewable energy technologies have prompted a shift towards cleaner energy sources, with a greater emphasis on renewables [9]. This transition is vital for both environmental sustainability and economic growth, aligning with national objectives of energy efficiency and carbon emission reduction. Local clean energy development, including wind and solar power, has become a critical aspect of the region's energy strategy [10]. Nevertheless, a gap exists between the local renewable energy capacity and the region's surging electricity demand. Technological, financial, and geographic constraints limit the ability of local renewable sources to fully meet this demand [11]. Compounding this challenge, China's renewable energy resources are primarily concentrated in the northwestern regions, creating a significant spatial mismatch between renewable energy-rich areas and load centers. UHVDC transmission technology has emerged as the key solution to address this spatial imbalance. With its superior capacity and efficiency, UHVDC enables the long-distance transmission of clean energy from remote locations to demand centers like East China, effectively bridging the gap between renewable energy supply and electricity demand [12,13]. As a result, cross-regional UHVDC transmission technology has become a crucial solution to address the supply–demand imbalance in East China [14].

Recent studies have investigated various aspects of UHVDC integration in power systems. Several approaches have been proposed for grid strength assessment. An equivalent model of UHVDC systems was established in [15] to quantitatively evaluate DC power transmission stability. The work in [16] analyzed interaction patterns and stability margins of HVDC grids under varying operation conditions, employing SCR as the key indicator for system strength evaluation. Optimization schemes for renewable energy integration were developed in [17] based on SCR calculations at grid-connectable renewable power plant nodes. A generalized short circuit ratio (gSCR) was proposed in [18] through theoretical analysis of static voltage stability and grid strength relationships, providing an enhanced metric for multi-infeed LCC-HVDC system assessment. Grid adaptability to DC transmission has also received considerable attention. Dynamic HVDC system models were developed in [19] to evaluate grid adaptability under different operating conditions and technical configurations. Sequential Monte Carlo simulation was employed in [20] to systematically assess the impacts of UHVDC integration on grid reliability. Comprehensive evaluation indexes for UHVDC integration were constructed in [21], providing decision support tools for DC connection point selection. Multi-dimensional analysis of HVDC adaptability in European grids, encompassing technical feasibility, economic benefits, and policy frameworks, was presented in [22]. Despite these advances, existing grid strength assessments predominantly rely on metrics such as SCR and MSCR. While extensive engineering experience has been accumulated with these metrics, they fail to capture critical transient characteristics, presenting limitations in system strength evaluation. Furthermore, current studies on grid adaptability to UHVDC integration primarily employ idealized grid models, with limited analysis of actual grid adaptability in practical DC project implementation. Notably, the adaptability of the East China grid to large-scale UHVDC transmission integration has not been systematically investigated.

To address these research gaps, this paper proposes an evaluation method for DC system strength that considers transient characteristics, and based on the power supply and demand of the East China grid, presents the distribution of DC landing points and evaluates the adaptability of the East China grid to UHVDC integration. The main contributions are as follows:

- A novel transient multi-feed-in short circuit ratio (TMSCR) metric is proposed to assess the strength of multi-DC systems. This metric captures the transient characteristics of the system, providing an accurate evaluation indicator for system strength.
- By combining local power supply development trends with estimates of external power inputs, the optimal landing points for inter-regional UHVDC transmission are systematically identified.
- A comparative analysis of the adaptability of conventional DC and flexible DC transmission technologies in the East China power grid is conducted, considering key aspects such as grid strength and voltage stability.
- Based on local power surplus and deficit conditions, DC receiving-end integration plans of East China power grid are formulated, analyzing the impact of DC transmission integration on the local grid and proposing reinforcement measures.

The proposed methods and findings provide critical technical support for the clean energy transition in the East China region, contributing to maintaining the reliability and stability of the East China power grid under increasingly complex operating conditions.

2. Analysis of Issues

2.1. Transient Multi-Feed-In Short Circuit Ratio

In the analysis of a single HVDC system shown in Figure 1, the short circuit ratio (SCR) serves as a crucial indicator to evaluate system stability. The higher the SCR value, the more robust the system is considered. Within this framework, X_s represents the equivalent reactance and U_s symbolizes the equivalent force.

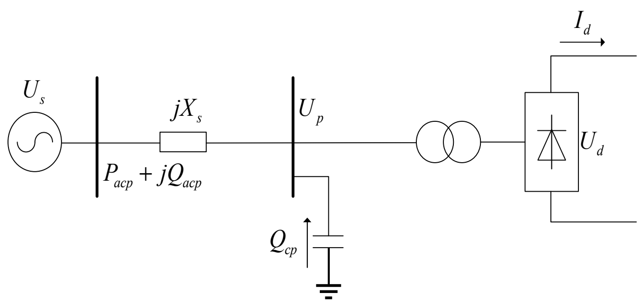

Figure 1. Representative diagram of an HVDC transmission system model.

The SCR is commonly used to evaluate relative strength because it is both simple and effective. The definition of SCR is as follows:

$$SCR = \frac{S_{ac}}{P_d} = \frac{U^2/Z_{ac}}{P_d} \quad (1)$$

In the current analytical framework, Z_{ac} stands for the Thevenin equivalent impedance, U signifies the voltage at the converter terminal, P_d denotes the transmission capability of DC line, and S_{ac} represents the short-circuit current carrying capability.

Additionally, the International Council on Large Electric Systems (CIGRE) has formulated an advanced metric known as the multi-infeed interaction factor (MIIF). This factor was crafted to quantify the level of interaction among multiple DC transmission systems connected to the same AC grid. The formula for the MIIF is presented as follows:

$$MIIF_{ki} = \frac{\Delta U_k}{\Delta U_i} \tag{2}$$

The MIIF is pivotal for a comprehensive understanding of the interconnected system dynamics, especially in configurations where several DC lines converge into a single AC network. This metric is crucial for planning and optimizing network operations, ensuring stability, and enhancing the predictability of system behavior in complex electrical environments.

Expanding on this basis, the influence of nearby DC systems is factored in by multiplying their capacity with the interaction factor, which helps redefine the MSCR. Ignoring the variations in amplitude and phase angles among node voltages, the MSCR is established and presented through Equation (3):

$$MSCR_i = \frac{1}{P_{di}\left|Z_{eqii}\right| + \sum_{j=1, j\neq i}^{n}\left|Z_{eqij}\right|P_{dj}} \tag{3}$$

In this context, P_{di} and P_{dj} indicate the nominal active power of the respective systems. Z_{eqii} and Z_{eqij} represent the impedance matrix elements. Furthermore, S_{ki} stands for the fault current withstand capability associated with the HVDC system.

The following equation can be derived by taking the bus voltage U_i as a benchmark of the system:

$$MSCR_i = \frac{1}{P_{di}\left|Z_{eqii}\right| + \sum_{j=1, j\neq i}^{n}\left|Z_{eqij}\right|P_{dj}} \tag{4}$$

The CIGRE has formulated the MIIF as a quantitative tool to assess the extent of interaction among DC systems. This factor is integral to deriving the MSCR, a critical index for evaluating a system's relative strength.

However, in assessing the system strength of a system with multiple feed-ins, as depicted in Figure 2, careful consideration must be given to the limitations associated with the use of the MSCR index [23]. Notably, discrepancies can occur where the system strength diverges from the trends predicted by the MSCR. The data delineated in Table 1 further exemplifies these inconsistencies. Such discrepancies highlight the inadequacy of the MSCR as a universally reliable metric for evaluating system strength phenomena in DC systems.

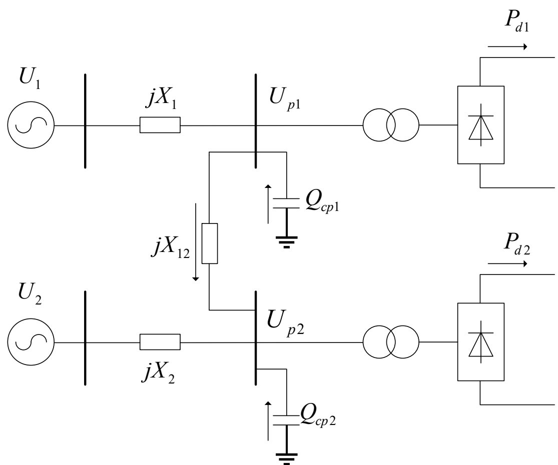

Figure 2. Model of multi-infeed system.

Table 1. Relationship between equivalent impedance and MSCR.

Parameters	Condition			
	-	-	$\lvert Z_1 \rvert \Delta P_{d1} \geq \lvert Z_2 \rvert \Delta P_{d2}$	$\lvert Z_1 \rvert \Delta P_{d1} \leq \lvert Z_2 \rvert \Delta P_{d2}$
Z_1	elevate/reduce	-	-	-
Z_2	-	elevate/reduce	-	-
Z_{12}	-	-	elevate/reduce	elevate/reduce
$MSCR_1$	reduce/elevate	reduce/elevate	reduce/elevate	elevate/reduce
U'_{p1}	elevate/reduce	elevate/reduce	reduce/elevate	reduce/elevate
$MSCR_2$	reduce/elevate	reduce/elevate	elevate/reduce	reduce/elevate

To address the inconsistency between system strength variations and MSCR evaluation results, an innovative index has been established, extending from the foundation of the MSCR. It incorporates adjustments for transient changes and reactive power, represented as ΔP_d or ΔQ_d. This index, termed TMSCR, is specifically designed to accommodate the operational needs of multi-terminal HVDC transmission systems.

$$TMSCR_i = \frac{S_{ki}}{\Delta Q_{di} + \sum_{j=1,j\neq i}^{n} \left| \frac{Z_{eqij}}{Z_{eqii}} \right| \Delta Q_{dj}} \tag{5}$$

Within this framework, the terms ΔQ_{di} and ΔQ_{dj} respectively specify the reactive power changes in the *i*-th and *j*-th circuits.

By using the bus voltage as a benchmark, Equation (5) can be reformulated as:

$$TMSCR_i = \frac{1}{\Delta Q_{di} \left| Z_{eqii} \right| + \sum_{j=1,j\neq i}^{n} \left| Z_{eqij} \right| \Delta Q_{dj}} \tag{6}$$

Equation (6) demonstrates that the specified metrics are affected by the impedance equivalence at the converter bus node, as well as by fluctuations in DC power.

Using TMSCR to assess system strength in HVDC systems enables a qualitative analysis of voltage fluctuations resulting from changes in system robustness under various conditions. Higher TMSCR values indicate improved stability of the system. The results of this analysis are presented in Table 2.

Table 2. Relationship between equivalent impedance and TMSCR.

Parameters	Condition			
	-	-	$\lvert Z_1 \rvert \Delta P_{d1} \geq \lvert Z_2 \rvert \Delta P_{d2}$	$\lvert Z_1 \rvert \Delta P_{d1} \leq \lvert Z_2 \rvert \Delta P_{d2}$
Z_1	elevate/reduce	-	-	-
Z_2	-	elevate/reduce	-	-
Z_{12}	-	-	elevate/reduce	elevate/reduce
$TMSCR_1$	reduce/elevate	reduce/elevate	elevate/reduce	elevate/reduce
U'_{p1}	elevate/reduce	elevate/reduce	reduce/elevate	reduce/elevate
$TMSCR_2$	reduce/elevate	reduce/elevate	elevate/reduce	elevate/reduce

Tables 1 and 2 illustrate that the TMSCR provides a more accurate representation of system strength in particular scenarios compared to the MSCR. The system strength assessment method based on TMSCR avoids the discrepancies between evaluation results and actual conditions that can occur with MSCR. It accurately assesses variations in system strength across multiple operating scenarios. Consequently, TMSCR is a reliable metric for analyzing system strength.

In power system studies, the electrical distance between DC transmission lines and the power system is a crucial parameter for evaluating the system's stability and reliability. Electrical distance significantly affects both the SCR and the disturbance rejection capability of the DC transmission system. In practical engineering applications, it is essential to consider the impact of electrical distance on system performance comprehensively and to strategically arrange DC transmission lines in order to optimize the overall stability and reliability of the system. When planning and designing the external DC landing points for the East China receiving-end power grid, both conventional DC transmission and flexible DC transmission should avoid placements where the electrical distance is too short. This approach not only improves system stability but also enhances the disturbance rejection capacity of the entire power system, ensuring reliable operation of the transmission network.

2.2. Analysis of Power Demand in East China

Considering the actual development of electricity demand in the early stage of the '14th Five-Year Plan', as well as economic growth, structural adjustment and electric energy substitution in the next 2–3 years [24], the maximum load forecast scenario of East China in 2030 is shown in Table 3 [25].

Table 3. The maximum load forecast scenario of East China.

Region	Maximum Load in 2030 (/10 MW)	The Average Annual Growth Rate During the '15th Five-Year Plan' Period
East China	50,091	3.4%
Shanghai	4350	1.7%
Jiangsu	17,200	2.8%
Zhejiang	14,500	3.5%
Anhui	9100	5.1%
Fujian	6650	3.5%

2.3. Power Development Plan of East China Power Grid

2.3.1. Development of Coal-Fired Power

Since 2022, China's National Energy Administration has issued two batches of "build-transfer" coal power quotas, totaling approximately 39 million kilowatts for the East China region. It is projected that over the next three years, nearly 70 million kilowatts of new coal-fired power capacity will be added to the grid, bringing the total installed capacity to 300 million kilowatts. This plan to expand the installed capacity of coal-fired power plants aims to meet the growing electricity demand while ensuring a stable power supply.

2.3.2. Development of Pumped Storage

A total of 24 pumped-storage hydroelectric plants have been approved and are under construction in the East China region, with an aggregate capacity of approximately 29 million kilowatts. Among these, the pumped-storage capacity in Jiangsu Province is about 1 million kilowatts, in Zhejiang Province about 17 million kilowatts, in Anhui Province about 5 million kilowatts, and in Fujian Province about 6 million kilowatts. The construction of these pumped-storage plants will provide significant support to the regulation capacity and stability of the regional power system. Additionally, they will enhance the grid's ability to integrate renewable energy, facilitating the optimization of the energy structure and promoting sustainable development in the East China region.

2.3.3. Development of Renewable Energy

According to an assessment of the renewable energy development progress in each province [26], in the 2030 East China region's foundational renewable energy development scenario, the region's wind power capacity is expected to exceed 100 million kilowatts, and photovoltaic capacity is projected to surpass 150 million kilowatts. The rapid growth of renewable energy is a key factor in optimizing the energy structure of the East China power grid. The significant increase in wind and photovoltaic installed capacity forecasted in this scenario reflects the region's proactive progress in advancing the development of renewable energy.

2.4. District External Electricity of East China Power Grid

The construction of cross-regional transmission channels in the East China power grid is accelerating. During the '14th Five-Year Plan' period, it is planned to start the construction of two DC transmission lines from Shaanxi to Anhui and from Gansu to Zhejiang. According to the current research on the balance of power supply and demand in East China, in order to meet the growing power demand and optimize the energy structure, East China is expected to be further connected to cross-regional UHVDC transmission during the '15th Five-Year Plan'. Through the construction of these cross-regional transmission channels, the East China power grid will enhance the transmission capacity and improve the efficiency of power resource allocation to ensure the reliability and stability of regional power supply.

3. Layout of New DC Landing Points

Only considering approved, under-construction, and clearly regulated power sources, based on the 2030 power balance forecast for East China in Table 4, there will be a significant power deficit in Shanghai, Jiangsu, and Anhui, while Zhejiang and Fujian will have a certain scale of power surplus. This data is derived from the BPA-based online simulation platform developed by the China Electric Power Research Institute (CEPRI). Based on power balance assessments under different development scenarios for 2030, the study considers the integration and layout of three external DC transmission links in Shanghai, Anhui, and Zhejiang.

Table 4. Power balance of East China in 2030.

Region	Electricity Surplus in 2030 (/10 MW)
Shanghai	−600
Jiangsu	−1600
Zhejiang	200
Anhui	−1100
Fujian	800

3.1. Layout of DC Landing Points in Shanghai

From the perspective of DC power consumption, Pudong has a larger scale of power sources arranged, while its electricity demand is relatively smaller compared to Puxi. Given the current distribution of power sources, the support capacity in the northern part of Puxi is relatively weak. Therefore, it is advisable to connect the new DC transmission entering Shanghai to the main grid framework in the northern part of Puxi.

The first landing scheme involves entering Shanghai from the west, with the landing point located in Jiading. The DC line will cross the river within Jiangsu province and pass through the southern Jiangsu hinterlands. While this scheme may face challenges in opening up new channels, it offers certain advantages in terms of construction timing.

This approach can meet power demand more quickly and shorten the power supply construction period.

The second scheme proposes entering Shanghai from the north, with the landing point situated in Chongming. While this scheme has a smaller impact on Jiangsu, it requires the construction of a specialized power tunnel across the south branch of the Yangtze River to connect to Shanghai, which is both challenging and time-consuming. Although technically more complex, this scheme minimizes interference with existing lines and supports long-term planning.

The primary difference between the two schemes lies in the choice of route. The end-reception plans and impacts on the power grid are essentially the same. The first scheme offers advantages in construction sequence and is suitable for addressing immediate needs. The second scheme, while more complex, offers benefits for long-term planning and minimizes interference with existing lines, making it more suitable for long-term development considerations.

3.2. Layout of DC Landing Points in Jiangsu

From the perspective of regional power surplus, southern Jiangsu is the load center of the province, and the peak electricity demand exceeds 9 million kilowatts in Zhenjiang and Changzhou. Although the Wuxi region has improved its supply capacity to a certain extent through the measures of first stand and then coal-to-electricity conversion, there is still a power gap, especially in the winter. Northern Jiangsu has long been equipped with a substantial number of power sources and holds significant potential for future power development, generally exhibiting a power surplus, especially in the eastern parts of northern Jiangsu. As coastal new energy and nuclear projects expand, the pressure to export electricity is increasingly growing.

Considering the assessments of electricity surpluses and deficits across various subregions within the province, as well as the existing DC connection points, the following two landing point schemes are proposed for consideration:

In the first scheme, the landing point is in the western part of northern Jiangsu. In this scheme, a small amount of electricity can be absorbed locally, and the remaining part is transmitted to southern Jiangsu through north-to-south power transmission. Although the DC line is relatively far away from the load center, this arrangement will greatly increase the power flow from north to south, which is suitable for using the power surplus in northern Jiangsu to support the power demand in southern Jiangsu.

In the second scheme, the landing point lies in the west of southern Jiangsu. This scheme can effectively alleviate the transmission pressure of north-to-south power transmission in the province, and directly introduce power into the load center area. However, as the DC lines penetrate into a densely structured grid of the load center, special attention must be paid to the impact on the regional grid's short-circuit currents and safe, stable operation.

Choosing between these two schemes requires a careful balance of several factors, including power transmission efficiency, the electricity demands of the load centers, and the safe and stable operation of the overall system. This will ensure the reliability and sustainable development of the entire power grid.

3.3. Layout of the DC Landings Points in Anhui

From the analysis of regional electricity surpluses and deficits, the northwestern and central areas of Anhui Province are experiencing significant demand growth and are facing the largest electricity deficits within the province. After the operation of the Shaanxi–Anhui DC, the deficit in central Anhui is primarily concentrated in the eastern part of

Hefei. The southern Anhui region, already hosting the Jiquan DC connection point and targeted for future pumped-storage developments, is expected to experience a significant electricity surplus.

Based on the assessment of electricity surpluses and deficits across the province, the western part of northern Anhui and the central area have been identified as the key regions for future DC power consumption. Two primary landing point schemes are proposed for consideration:

In the first scheme, the landing point lies in the western part of northern Anhui. In this scheme, part of the power is absorbed locally, and the remaining power is transmitted southward. Although the DC lines are relatively distant from the load center, this approach can be integrated with the development of the provincial main grid framework. The objective is to establish a power reception and transmission platform in northwestern Anhui, making effective use of local power resources and alleviating electricity pressure in the southern areas.

In the second scheme, the landing point lies in the eastern part of Hefei. This scheme directs DC power directly into the load center, delving into an area with a dense grid structure. This requires attention to the impact on the short-circuit current and safe and stable operation of the regional power grid. Additionally, since eastern Hefei is closer to the heavily loaded eastern cross-river channel, this approach would significantly increase the evacuation pressure on the eastern channel and requires special attention to its impact on grid operational stability.

3.4. Brief Summary

From the perspective of existing DC landing points in the region, the core area of the Yangtze River Delta has already accommodated seven DC connections, forming a pattern of intensive multi-DC feeding. A decentralized access strategy can effectively reduce the system risk caused by the failure of a single node, ensuring that the grid can maintain high stability and reliability even during severe faults. Given that the three new DC connections share the same sending end, it is recommended to adopt a decentralized access approach for these new DCs to enhance the receiving-end grid's ability to withstand severe faults.

4. Technical Route of New DC Transmission

The new DC transmission will have a certain impact on the stable operation of the regional power grid. In order to ensure the safe and stable operation of the regional power grid after the new DC transmission is integrated, an appropriate technological approach is required. This section first evaluates the impact of the newly added DC transmission on the frequency, power angle and voltage stability of the regional power grid. Furthermore, an assessment is conducted on the security and reliability levels of the regional grid after implementing flexible DC technology. The benefits of enhancing the security and reliability of the regional grid with new DC transmission using flexible DC technology are analyzed, demonstrating its potential to enhance the grid infrastructure effectively.

4.1. The Impact of New DC Transmission on Regional Security and Stability

After the addition of three DC lines in East China, the share of power electronics within the regional grid is further increased. Based on the landing point schemes discussed above, this section adopts the conventional DC combined with the addition of two synchronous compensators at each landing point load center to evaluate the impact of new DC on regional security and stability.

4.1.1. Frequency Stability Level

After the addition of new DC lines, the maximum power of a single DC line in the East China region has not exceeded 12,000 MW. A simulation of Jiquan UHVDC bipolar blocking fault under peak load conditions in the East China power grid was conducted to study the system's frequency dynamics under this scenario. The simulation was performed on the BPA-based online simulation platform developed by the CEPRI. The fault was set as an instantaneous fault at t = 0 s, resulting in a total power loss of 12,000 MW. The system's frequency response curve under this fault condition is shown in Figure 3. The curve shows a nadir of −0.34 Hz at t = 17 s, which subsequently stabilized to a quasi-steady state of −0.15 Hz after t = 45 s. The simulation results indicate that during the peak load periods of summer and winter, the East China power grid can still withstand the impact of Jiquan DC bipolar blocking. During the lighter loads of spring and autumn, the system can withstand the impact of the DC unipolar blocking fault despite the large-scale power generation of DC and new energy at the same time. If bipolar blocking occurs in the Jiquan DC transmission line, the existing frequency control system's emergency DC boosting feature can quickly restore the system frequency to safe and stable levels [27].

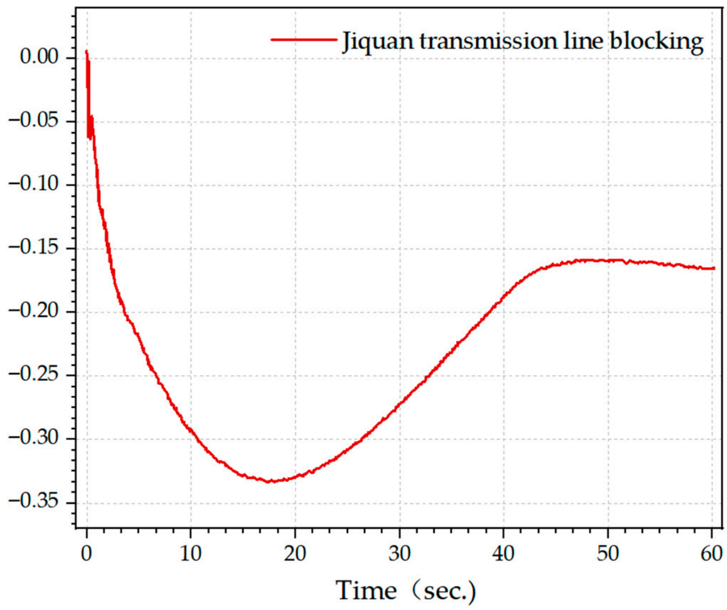

Figure 3. Frequency response curve of East China power grid following Jiquan transmission line blocking.

Under peak load conditions, the East China power grid has sufficient redundancy and stability to cope with sudden blocking events of high-power DC transmission lines. Under light load conditions, when a variety of new energy sources are connected to the grid on a large scale, the system can guarantee the reliable and stable functioning of the power grid through effective frequency control and reactive power compensation measures. The emergency DC boosting feature provided by the existing frequency control system further enhances the system's resilience in facing extreme events, ensuring that the frequency can quickly return to a stable level.

4.1.2. Transient Power Angle and Voltage Stability Level

The existing measures such as automatic voltage control (AVC), fast load shedding (FLP) and emergency power grid reconstruction can maintain the stability of transient power angle and voltage in the case of three-phase permanent faults (N-1) and line pole different name phase faults (N-2) of 500 kV and above main equipment in the whole network [28]. These stability control methods can respond quickly and effectively control the impact of faults on the stability of the system and maintain the power angle and voltage within secure parameters, thus complying with the power system's safety and stability regulations.

4.2. The Benefits of Flexible DC Technology for Improving the Level of Safety and Stability

To enhance the safety and reliability levels of regional power grids, this section concurrently evaluates the implementation of flexible DC technology at three newly added landing point load centers in East China. It also conducts a comparative analysis with the conventional DC augmented with synchronous compensators approach.

4.2.1. Voltage Stability

According to the evaluation, under the same AC fault condition, the influence range of DC commutation failure can be significantly reduced after the flexible DC technology is adopted in the new DC in the load center of the landing point. As shown in Figure 4, the number of DCs with commutation failure decreases with the adoption of flexible DC. This improvement plays an important role in improving the security and stability of the whole grid. With the continuous advancement of flexible-DC-related equipment technology, compared with conventional DC, flexible DC has gradually become more prominent in terms of economy and land occupation. As a key technology that embodies flexibility and adaptability within modern power systems [29], flexible DC meets the development needs of the new power system and becomes one of the best choices for the new DC in the regional Yangtze River Delta load center. Therefore, during the '15th Five-Year Plan' period, it is recommended that the DC of the load center should give priority to the use of flexible DC transmission technology to better meet the needs of power system development.

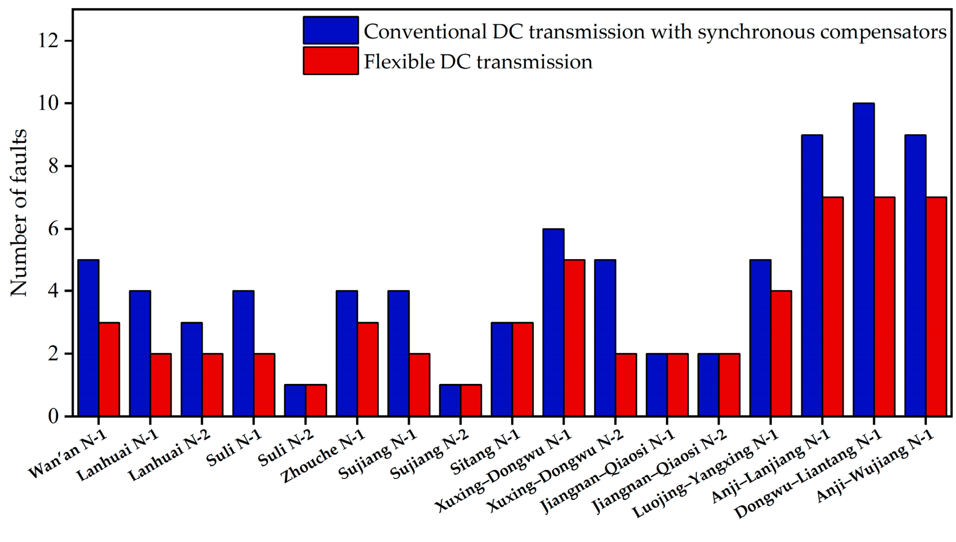

Figure 4. Comparison of commutation failures under different technical routes.

4.2.2. Analysis of TMSCR

After adopting the flexible DC technology route, in addition to addressing the issues inherent to the newly added DC itself, there is also a notable improvement in the TMSCR of nearby DC areas. As shown in Figure 5, the TMSCR of the DC connections entering Shanghai and Jiangsu has increased by about 3.2.

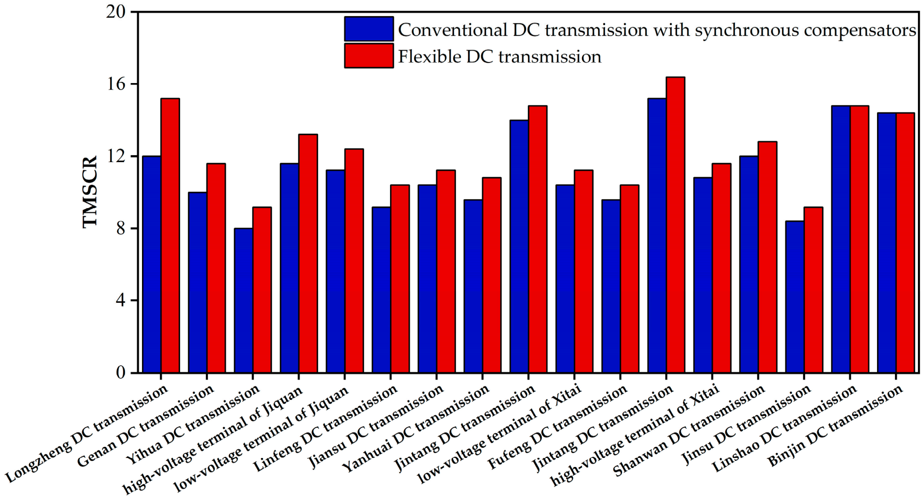

Figure 5. Comparison of TMSCR under different technical routes.

It can be seen that the flexible DC technical route can effectively alleviate the contradiction of multi-DC influence in the load center of the Yangtze River Delta, thereby ensuring the sustained security and stability of system operations.

5. The Influence of New DC on the Development of Main Grids and the Reinforcement Measures

The introduction of new DC transmission will have a significant impact on both the adjacent areas of the receiving-end power grid and the overall grid framework. Addressing these impacts requires meticulous planning and strategic adjustments. This section first presents specific schemes for integrating new DC connections into the power grids of Shanghai, Jiangsu, and Anhui. These schemes are designed to effectively incorporate new DC resources, thereby enhancing the reliability of regional power grids.

Building on the connection schemes of each region, this section further analyzes the specific impacts of DC integration on both the local grids and the overall main power grid of the three regions. In response to potential adverse effects, a series of solutions are proposed to maximize the benefits of DC transmission while minimizing its negative impacts on adjacent areas of the terminal power grid and the main grid, ensuring both safety and reliability.

5.1. New DC Transmission Connection to Shanghai

5.1.1. Receiving-End DC Integration Plan of Shanghai

From the perspective of power consumption, an assessment was conducted on the power surplus and deficit across various major regions within Shanghai under different peak load conditions. Based on the evaluation results, it was found that the northwest region of Shanghai still has significant potential for power demand growth during peak periods, making it an ideal area for electricity consumption. Therefore, it is proposed to connect the DC transmission to the northwest substation area of the Shanghai grid, allowing a portion of the DC power to be consumed locally in the northwest region of Shanghai. This local consumption approach not only optimizes power usage but also helps reduce the losses and cost increases associated with long-distance DC transmission.

5.1.2. Impact of DC Integration in Shanghai on the Local Power Grid and Solutions

After the adoption of flexible DC, the short-circuit current levels in the vicinity of the DC are significantly improved. Without appropriate measures, the short-circuit current at Xuxing Station, Luojing Station, and Yangxing Station will exceed the standard.

Considering the expansion of the inner-city ring network following the North and South Dual Change Four Line project and the lack of conditions for further ring-breaking in the short term, measures such as installing denominator devices and series reactors on the 500 kV side of the Shanghai-bound DC converter station can effectively control regional short-circuit current levels.

Regarding load flow distribution, the integration of DC will increase the transmission pressure on nearby channels. The integration plan partially utilizes the existing Shierchang–Yangxing and Xuxing–Yangxing channels, but the current capacity of these channels is insufficient to meet load distribution requirements. A potential solution would be to replace the two single loops of Xuxing–Luojing Station with larger capacity conductors during the process of double-loop transformation to improve channel capacity.

In terms of stability verification, the system under the integration plan can maintain stability after both N-1 and N-2 faults. However, the grid structure in the northwest area of Shanghai is relatively weak. After an N-2 fault occurs in the DC near-zone, transient instability may arise, and the system's adaptability is limited. Therefore, it is essential to focus on and implement improvement measures for voltage stability risks posed by the chain structure of the Shanghai grid.

5.1.3. Impact of DC Integration in Shanghai on the Main Grid and Reinforcement Measures

As a major city for electricity consumption in the East China region, Shanghai's strategy for receiving and distributing electricity has an important impact on the stability of the entire regional power grid. The power distribution accepted from East China is mainly incorporated into the Puxi power grid through the Dongwu and Liantang substations, and the remaining power is incorporated into the Pudong power grid through the Fenhu–Sanlin power line. This distribution strategy helps to balance the power demand and supply on both sides of the Shanghai power grid.

Shanghai's infrastructure for cross-river power transmission includes critical pathways such as Yangxing to Wai'ercang, Xinyu to Nanqiao, and Liantang to Tingwei. Among these channels, the channel from Yangxing to Waierchang bears a heavy load due to the uneven distribution of power flow. With the access of HVDC to Shanghai, it is expected to further increase the tidal current burden of the cross-river channel from Puxi to Pudong.

Despite the potential for increased load flow pressures due to the integration of the Shanghai-bound DC, the Shanghai grid has been meticulously engineered to accommodate such scenarios. It maintains grid stability through targeted local consumption strategies and sophisticated load management tactics. By absorbing part of the DC power locally, the burden and potential risks caused by long-distance transmission can be effectively reduced. In addition, under typical modes in different seasons, the power exchange across the Pudong–Puxi section meets operational requirements and has a robust margin for operational flexibility.

5.2. New DC Transmission Connection to Jiangsu

5.2.1. Receiving-End DC Integration Plan of Jiangsu

During the period of China's '15th Five-Year Plan,' significant electrical supply pressures are anticipated in the southwestern part of Jiangsu, specifically in the Nanjing South, Zhenjiang West, and Liyang districts, and the power gap in these areas is expected to further expand. In order to effectively cope with this challenge, a comprehensive power transmission and management strategy is proposed. This involves full-capacity integration into the southern Jiangsu 500 kV high voltage grid, utilizing DC transmission into Jiangsu.

The core of this strategy is the deployment of two converter stations—VSC1 and VSC2—in southern Jiangsu. The design and location selection of these two converter stations are intended to optimize the distribution and management of power flow and improve the operating efficiency of the overall power grid.

In particular, this configuration allows the power flow to be evacuated from Liyang, Jiangsu to the area at the junction of Liyang, Jiangsu and Wuhu, Anhui. This strategic layout not only effectively alleviates the electrical pressure in the Liyang area but also helps to reduce the load flow pressure on the Anhui–Jiangsu provincial interface.

5.2.2. Impact of DC Integration in Jiangsu on the Local Power Grid and Solutions

From the perspective of short-circuit current analysis, this scheme has the most significant impact on the inter-provincial short-circuit current between Anhui and Jiangsu, particularly in the Dangtu area, where the three-phase short-circuit current exceeds the standard limit. Given the structure of the nearby grid, the preliminary solution is to install a 28-ohm series reactor on the line from E'xi to the converter station to control the short-circuit current within acceptable limits [30].

In terms of load flow, during the summer peak periods when the DC is operating at full capacity, the load flow on the dual 500 kV DC converter station to Dongshanqiao line appears to be strained, whereas the 220 kV level load flow distribution is relatively more reasonable. In order to alleviate the pressure of 500 kV lines, installing series reactors along the corridor from the converter station to Dongshan Bridge or increasing the capacity of the transmission line from the converter station to Dongshan Bridge can be considered, so as to improve the transmission capacity and maintain the operational stability of the system. These measures will help to optimize the transmission of electricity during peak hours.

5.2.3. Impact of DC Integration in Jiangsu on the Main Grid and Reinforcement Measures

During the '15th Five-Year Plan' period, the power distribution pattern of the Jiangsu power grid will continue to feature a "coastal concentration of power export and north-to-south power flow within the province" characteristic. With the further development of power sources in northern Jiangsu, the export power flow will continue to expand. Additionally, as the load center of the province, the southern Jiangsu region has long received substantial power, especially in winter, putting considerable pressure on the power flow distribution at the cross-river transmission corridors within the province.

The layout of DC transmission into the load center has relatively little impact on the north-to-south power flow. According to forecasts, even considering the effective output at a 95% probability and the participation of energy storage on the renewable side for regulation, the power transmission demand across the river in 2030 is still expected to approach 30 million kilowatts, which exceeds the transmission capacity of the main grid as outlined in the '14th Five-Year Plan'. To address this, it may be feasible to utilize the Jiangzhen DC Phase I crossing at Wufengshan and construct subsequent Phase II and III projects. Additionally, the space beneath the Su-Tong GIL corridor could be used to build a three-line DC project from the coastal region to Suzhou, while considering further minor optimizations to the eastern main grid structure to meet power exchange demands during the '15th Five-Year Plan' period.

From the perspective of power flow patterns in southern Jiangsu, whether the DC landing point is in the western part of northern Jiangsu or the southwestern part of southern Jiangsu, the west-to-east power flow pattern will remain in place for the long term. In this configuration, the southwestern part of southern Jiangsu will not only absorb power from the east-to-west flow from Anhui and the DC surplus power from the western part of northern Jiangsu but also consume part of the power locally, with the remaining power continuing to be exported eastward. This strategy effectively balances the power demand

and supply within the region, ensuring the stable operation of the grid and the reliability of the power supply.

5.3. New DC Transmission Connection to Anhui

5.3.1. Receiving-End DC Integration Plan of Anhui

The study considers the Fubo area in northern Anhui as the landing point for the DC connection to Anhui. The nearby substations, including Shahe, Yingzhou, and Boyang, all have additional capacity for outgoing lines. Regarding the corridor resources shown in Figure 6, the third DC landing point in Anhui is also located in the Fubo area. The transmission lines primarily pass through Fuyang and Bozhou, with few restrictions except for urban planning areas. Overall, there is considerable flexibility in selecting paths for the DC and UHV transmission lines, making the proposed routes feasible.

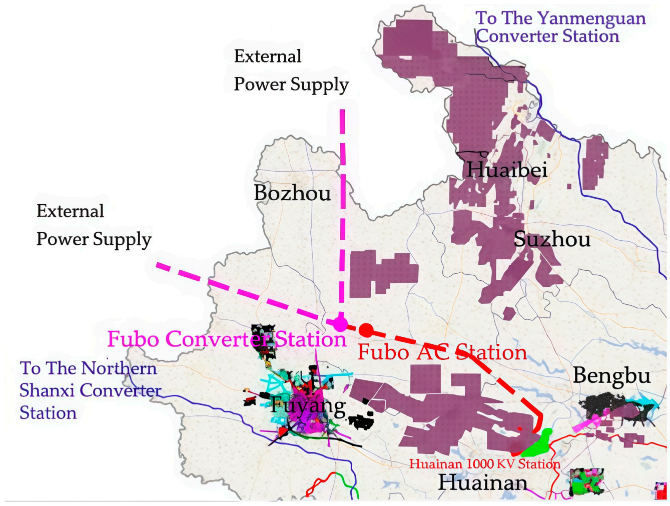

Figure 6. Schematic diagram of route corridor resources in the Fubo area.

From the perspective of DC power absorption, the Fubo area in northern Anhui experiences a DC receiving demand of 5 million kilowatts during peak periods. However, in the spring and autumn, when large amounts of renewable energy are generated alongside significant DC power transfers, the export demand from northwest Anhui increases sharply, exceeding 10 million kilowatts. Overall, DC power distribution shows a pattern of local absorption during peak periods and renewable energy export during large-scale generation. Therefore, the new DC landing point in Fubo considers two voltage-level connection modes:

Mode 1: This mode involves a layered connection at 1000/500 kV [31], with the construction of the Fubo UHV station and a double 1000 kV line from Fubo to Huainan. On the 500 kV side, a double-circuit line from Shahe to Yingzhou is considered, while the lower-end 1000 kV side connects to the Fubo UHV station. Power flow is dispersed through UHV transformers and lines. This mode, with layered connections on both the high-voltage and low-voltage sides, effectively distributes power flow, enhancing the grid's stability and flexibility.

Mode 2: This mode involves connecting entirely to the 500 kV grid, with double-circuit lines from Shahe to Yingzhou and from Yingzhou to Boyang. The power flow is primarily dispersed within the 500 kV grid, alleviating local pressure and improving power transmission efficiency through the double-circuit lines from Shahe to Yingzhou and Yingzhou to Boyang.

5.3.2. Impact of DC Integration in Anhui on the Local Power Grid and Solutions

From the perspective of short-circuit current, the power grid structure in Fuyang and Bozhou area is relatively sparse. Considering the influence of DC access, the short-circuit current in the nearby area remains within 51 kA, offering a certain margin of safety.

In terms of load flow dispersion, in the first scheme, the load flows of Fu-Bo UHV station reach 1–2 million kilowatts under the high load scenario in summer. In spring and autumn, when local new energy production is high, the upward load flows reach 160–280 MW. Moreover, the transmission capacity of the dual lines from the converter station to Shahe is inadequate and needs capacity enhancement. In the second scheme, the 500 kV power grid in the vicinity of the DC station faces significant dispersion pressure. In addition to the converter station to Shahe River, the dual-line load flow to Boyang also reaches 3.6 million kilowatts. The overload phenomenon can occur after N-1 fault, and the line capacity needs to be strengthened.

In terms of transient stability, in the first scheme, the Fubo–Huainan UHV line cannot maintain stable operation on the 1000 kV side after an N-2 fault [32]. It is necessary to take safety and stability control measures to block or quickly reduce DC power.

5.3.3. Impact of DC Integration in Anhui on the Main Grid and Reinforcement Measures

During the '15th Five-Year Plan' period, the Anhui power grid will continue to feature a bi-directional electricity exchange between the north and south. As the load center of the province, central Anhui will receive power from both southern and northern Anhui during the summer peak, while in the spring and autumn, when renewable energy generation is high, the power flow will predominantly move from north to south across the province. According to the main grid layout outlined in the '14th Five-Year Plan', the transmission capacity of the four 500 kV cross-river transmission lines will reach 10 million kilowatts.

The landing point of the DC transmission into Anhui are selected as the Fubo area. The power surplus and deficit in the Fubo area is shown in Table 5. Under various scenarios, there is a noticeable increase in the surplus power in northwestern Anhui. Specifically, during spring and autumn, when new energy generation is high, the surplus power in northwestern Anhui will reach 15 million kilowatts. During the summer peak, the power flow from south to north will decrease, whereas in spring and autumn, when new energy generation is high, the surplus power in the Jiangbei area will increase to nearly 18 million kilowatts.

Table 5. Power surplus and deficit in the Fubo area (Unit: 10 MW).

Landing Points in Fubo	Northwestern Anhui	North-to-South Power Transmission Across the River
Summer noon peak	1100	290
Summer evening peak	800	40
High renewable energy output in spring and autumn	1550	1790

In assessing the impact of DC landing points on the north-south main grid framework, it is evident from the cross-river perspective that the Feixi–Fanchang and Hezhou–Dangtu channels are already exceeding the transmission capacity established under the '14th Five-Year Plan.' From the perspective of northwestern Anhui, in addition to the issue of north-to-south power transmission across the river, several local channels such as Yingzhou to Tangzhuang, Yuanlu to Shidian, Tangzhuang to Shouxian, and Shouxian to Gaocheng are exceeding their thermal stability limits after N-1 faults. The overloaded channels are primarily concentrated in the eastern part, prompting considerations for the addition of a new Eastern II 500 kV cross-river channel and a new UHV station in Hefei to alleviate the cross-river pressure through UHV transformers.

Regarding the impact of the Fubo DC landing point on the Hefei load center, part of the power will be transferred to eastern Hefei via the existing 500 kV grid. During the midday peak, the power received by the eastern section of central Anhui is expected to approach 10 million kilowatts. However, during the evening peak and under high-load conditions, electricity demand will increase further. Notably, the Pingwei to Feixi corridor has already experienced overloading, and the Jinniu to Chujing corridor is also operating under heavy load.

After the addition of the Hefei UHV AC station, the receiving capacity in central Anhui will be significantly improved. During the summer evening peak, the power flow reduction will reach 3.6 million kilowatts, and the flow from western Anhui to eastern Anhui will be reduced by nearly 3 million kilowatts, thereby allowing the related corridors to meet N-1 stability requirements.

The distribution of renewable energy in Anhui is depicted in Figure 7. From the perspective of its own development needs, Anhui's potential for developing clean energy sources in the future is unlikely to match the growing trend of electricity demand, resulting in a continued strong demand for external power imports. Among the regions, the Fubo area, being the most densely populated in the province, is seeing particularly rapid growth in electricity demand.

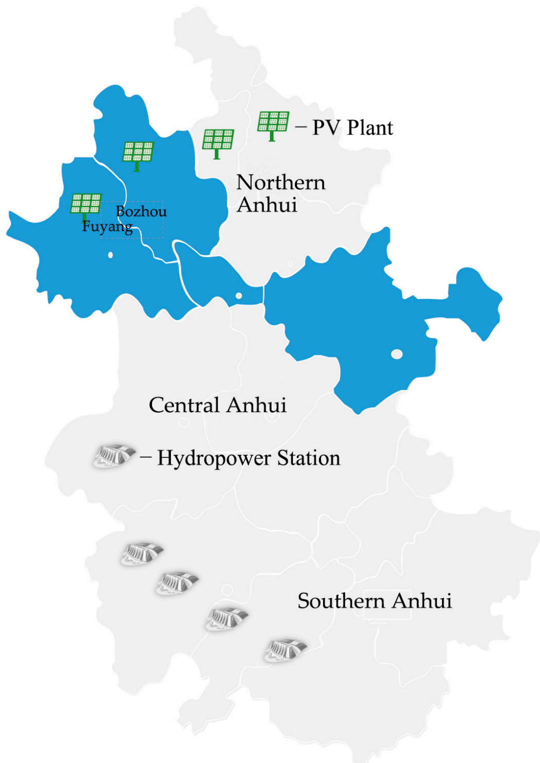

Figure 7. Distribution of renewable energy in Anhui province.

From the standpoint of resource distribution within the province, western and northern Anhui will become key areas for power development in the future, especially in terms of photovoltaic and pumped storage, both of which still have significant potential for large-scale development. The abundance of photovoltaic resources, coupled with the advancement of pumped-storage projects, will provide robust power support for these regions.

In terms of grid structure and geographical location, Anhui has already established strong external power transmission corridors. However, with ongoing socio-economic development, the difficulty of opening new channels in load-center corridors has been increasing. Nonetheless, Anhui is well-positioned to continue serving as a vital power transmission platform for the Yangtze River Delta region. By optimizing the grid structure and enhancing transmission capacity, Anhui can better meet the developmental needs of the regional economy.

Specifically, the construction of the Fubo–Huainan UHV AC transmission channel and the further extension of the UHV AC main grid to the northwest of Anhui will not only meet the growing local power demand but also lay a solid foundation for the future optimization and upgrading of regional power systems, enhancing the ability to optimize resource allocation.

6. Conclusions

As the East China power grid faces increasing electricity demand and large-scale DC integration, systematic evaluation of the grid's adaptability to UHVDC transmission becomes critically important. This paper investigates the adaptability of the East China power grid to UHVDC integration during the '15th Five-Year Plan' period. The main conclusions are summarized as follows:

- The proposed TMSCR can capture the transient characteristics of multi-DC systems, demonstrating superior assessment performance compared to the MSCR. This innovative metric provides a quantitative tool for evaluating the impact of DC transmission on grid strength and stability.
- DC landing point layout schemes are proposed for the Shanghai, Jiangsu, and Anhui, with comprehensive comparative analysis conducted considering power balance, power flow distribution, short-circuit currents, system security, and stability.
- Comparison between flexible DC and conventional DC transmission technologies is performed regarding their impacts on system voltage stability and TMSCR. The results demonstrate that flexible DC transmission offers advantages in enhancing grid security and stable operation, serving as a reliable solution for improving the efficiency and sustainability of the East China power grid.
- Assessments of DC integration plans for Shanghai, Jiangsu, and Anhui grids are conducted, analyzing the impacts on local grid security. Based on the analysis, reinforcement measures are proposed to strengthen grid security, providing guidance for safe and stable operation of the East China power grid under DC integration.

The deployment of DC transmission technology will enable the East China region to address growing electricity demands. The research findings provide critical technical support for DC transmission integration and renewable energy transition in East China, contributing to the construction of a modern power system capable of achieving decarbonization goals while maintaining grid reliability under increasingly complex operating conditions. However, this study also has limitations. The proposed TMSCR is a novel metric, and the TMSCR value ranges corresponding to strong, medium, and weak systems remain unclear. Future work needs to combine extensive practical simulations and engineering experience to establish TMSCR ranges for strong, medium, and weak systems, enabling rapid system strength assessment using the TMSCR metric.

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