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Comparison of AC and DC Transmission Technologies and the Energy-saving Advantages of HVDC in Long-distance Transmission

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Abstract:

While fossil fuel power generation is promoting economic and social development, it has also triggered serious environmental problems. To achieve the strategic goals of carbon peaking and carbon neutrality, the large-scale development of renewable energy sources such as wind power, hydropower, and solar energy has become an important path. However, renewable energy power generation bases are usually far from load centers. Researching efficient long-distance transmission technologies is of crucial significance for the consumption of clean energy and the low-carbon development of power grids. This article systematically compares the technical characteristics and application scenarios of alternating current (AC) transmission and direct current (DC) transmission. Taking a 2000 km transmission distance as a typical scenario, based on the transmission line loss model, the energy consumption characteristics of the converter station, and the comprehensive efficiency index of the system, the energy-saving advantages of high-voltage direct current (HVDC) transmission in long-distance transmission were quantitatively analyzed. Research shows that in a 2000km transmission scenario, the line resistance loss of the HVDC system is reduced by approximately 40% compared to the AC system of the same capacity. The additional loss at the converter station can be controlled within 5% through new topology optimization, and the overall transmission efficiency is improved by 8 to 12 percentage points. Moreover, HVDC has significant advantages in reducing corridor land occupation and lowering the impact on the electromagnetic environment, providing a low-carbon and efficient technical solution for large-scale cross-regional transmission of renewable energy.

Keywords:—AC/DC comparison, HVDC, Long-distance power transmission, Energy-saving.

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1. Introduction

Energy is of vital importance to economic growth and the survival of civilization. However, the continuous growth of global energy consumption has triggered environmental crises such as global warming and the greenhouse effect, making the development of renewable energy on a large scale an inevitable choice. Renewable energy, like photovoltaic power, hydropower, and onshore wind power, are mainly distributed in the western plateaus, deserts, and other areas, which are far from densely populated regions. Whether it is the transmission of clean energy from western China or the grid connection of offshore wind power in the North Sea of Europe, both of their power transmission faces the technical challenge of long-distance transmission [1]. The study of long-distance power transmission can optimize the allocation of resources in vast areas, alleviate the power consumption pressure in high-energy-consuming regions, and promote the economic increase of power transmission areas.

The history of power transmission technology can be traced back over 100 years. In 1882, Thomas Edison illuminated Pearl Street in New York City with a direct current (DC) power supply. In 1893, Nikola Tesla illuminated the Colombian Exposition with alternating current (AC) [2]. General Electric supported Edison's DC, while Westinghouse supported Tesla's AC. Because the voltage of DC cannot be directly raised, its transmission distance is greatly limited. With the invention of three-phase AC generators and transformers, this current dispute came to an end with the popularization of AC technology. AC transmission has become the mainstream power supply method due to its relatively low transmission loss in the early stage. However, as the transmission distance extends, the competition among AC and DC transmission technologies in terms of transmission efficiency, full life cycle cost and system stability becomes increasingly prominent. Optimizing the transmission network architecture and reducing line loss rates are among the key paths to achieving the strategic goals of carbon peaking and carbon neutrality.

The advancement of high-voltage transmission technology is conducive to optimizing resource allocation and efficiently utilizing transmission corridors. In 1989, the Gezhouba - Shanghai 500kV bipolar interconnection DC transmission project in China was put into operation [3]. Research on ultra-high voltage alternating current (UHVAC) transmission technology began in the second half of the 1960s. The Soviet Union built the world's first ultra-high voltage transmission line, the 1,150kV transmission project from Siberia to Kazakhstan and the Ural, with a transmission capacity of 5,000 MW and a total length of 2,500 kilometers. In 1985, the 900km line was operating at the designed voltage of 1,150kV [3]. After 40 years of development, the two ultra-high voltage transmission methods have each found their applications, and AC/DC hybrid distribution networks have become the mainstream trend. The balance issue between the synchronous stability of AC transmission and the commutation loss of DC transmission requires research on grid structure and control strategies, systematic analysis of technical paths, and provision of feasible distribution network renovation plans.

To compare AC and DC transmission technologies and analyze more energy-efficient methods for long-distance transmission, this paper contrasts the two transmission principles and determines the transmission scheme with more energy-saving advantages from the perspectives of loss mechanism and economic analysis.

2. A Comparison of the Principles of AC and DC Transmission Technologies

2.1 Characteristics of AC Transmission Technology

AC transmission naturally supports the synchronous interconnection of power grids, that is, the grid mode in which generators operating in parallel in the grid are interconnected at synchronous power and operate at the same rated frequency. That is, throughout the entire network, from power plants to users, the frequency of AC is the same. The voltage regulation method of AC is flexible. The voltage can be raised or lowered through a transformer, which is convenient for transmission. AC is a three-phase system, consisting of three AC circuits with the same frequency, equal electric potential amplitudes, and phase differences that are 120° apart from each other. Therefore, it requires three transmission conductors. When there is AC in a conductor, the current distribution inside the conductor is uneven. Besides, AC has the skin effect of . The output power of the power grid includes active power and reactive power. Compensating for reactive power can increase the proportional constant of active power in the power grid, reduce the design capacity of power generation and supply equipment, decrease investment, and lower line losses. The flexible voltage regulation method of AC, along with its skin effect and reactive power compensation requirements, makes it more suitable for medium and short-distance power transmission. For instance, China's first 1000kV UHVAC project, the Jindongnan-Nanyang-Jingmen line, which is 640 kilometers long, has made significant breakthroughs in key technologies such as voltage control, complete equipment development, and electromagnetic environment control [4].

2.2 Characteristics of DC Transmission Technology

DC transmission supports asynchronous interconnection, that is, two synchronous power grids connected by DC can operate asynchronously. Through back-to-back converter stations, the frequency does not need to be the same all the time and everywhere. It only transmits energy but not frequency. The converter devices for DC lines are expensive, the reactive power consumed in converter stations is high, and the converters will generate harmonics, which can affect capacitors and generators and interfere with communication systems. However, direct current transmission also has certain advantages. Firstly, the cost of line construction is low. Generally, two DC overhead transmission lines are needed, but only one is required when the ground or seawater is used as the circuit. Moreover, seawater serves as the conductor, and its resistance can be ignored, which can save a large amount of line construction costs.

In addition, the DC system has strong controllability, so it has advantage in long-distance power transmission. For instance, the ± 800-kV ultra-high voltage direct current (UHVDC) transmission project in Belo Monte, Brazil, has a total DC line length of 2,539 kilometers. It is the first UHVDC transmission line in South America and can directly transmit hydropower resources from northern Brazil to the load centers in the southeast [5].

Table 1 compares the two power transmission methods of AC and DC, each with its advantages and disadvantages. When building transmission lines, economic efficiency is the first consideration. For line interconnection, system stability must be taken into account. How to balance the two and making innovations is the key to the future development in power transmission.

Table 1. Comparison of AC and DC transmission technologies.

Transmission type	Connection method	voltage regulating mode	line loss	Number of Power Cords	Applicable distance
AC	synchronization	transformer	Inductive reactance, capacitive reactance, resistance	3	medium and short
DC	asynchronization	convertor station	resistance	2/1	long

3. Analysis of the Energy-saving Advantages of HVDC in Long-distance Power Transmission

3.1 Comparison and Analysis of Transmission Loss Mechanisms

Transmission loss refers to the energy loss caused by factors such as resistance, inductance, and capacitance during the transmission of electrical energy. Transmission losses include substation (or converter station) losses and transmission line losses. Substation losses include losses of power equipment such as transformers, reactors, and capacitors, as well as station power consumption, etc. Converter station losses also include losses of converter transformers, converter valves, filters, etc. The losses of a substation (or converter station) basically change proportionally with the variation of the transmission load. Transmission line losses mainly include resistance losses and corona losses.

The usage of AC transmission cables is more than that of DC cables. With the same material and transmission distance, the loss caused by resistance is smaller. DC has no inductive or capacitive losses, but the losses in the converter are higher than those in the transformer. Optimizing cable materials and increasing transmission voltage are effective methods to reduce transmission losses.

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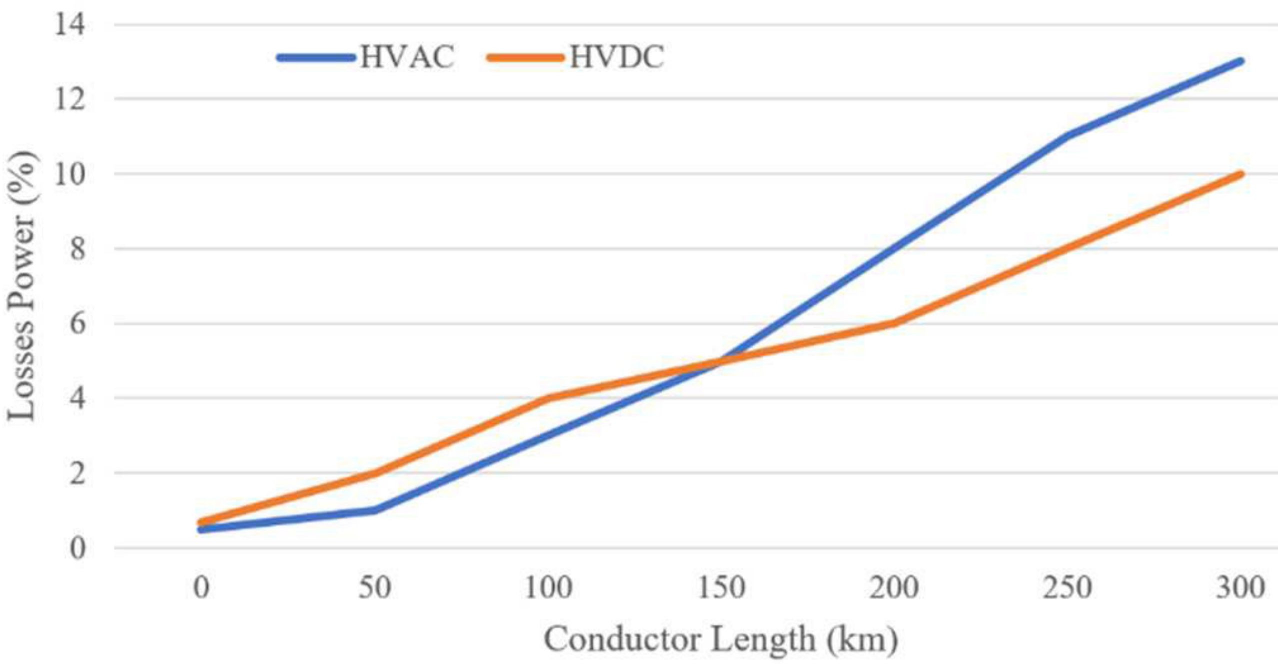

Fig. 1 HVAC and HVDC Transmission in Voltage 500 kV [6].

Langlang et al. analyzed the transmission losses at different voltage levels under a transmission power of 150MW and a transmission distance of 0 to 300 km [6]. It is found that when the distance of transmission is short, the power loss of high-voltage alternating current (HVAC) transmission is relatively small. As the transmission distance increases, its loss gradually exceeds that of high-voltage direct current (HVDC). The transmission power loss at 500kV is shown in Figure 1.

3.2 Economic Analysis of Power Transmission

Under the condition of equal power transmission, compared with the two long-distance power transmission methods, the line cost and land cost of HVAC are higher, while the converter station cost of HVDC is higher. Sharifabadi et al. proposed the concept of equivalent distance for power transmission, which is the distance at which the costs of two power transmission methods are the same [7]. In summary, when the distance exceeds this, it is beneficial to use DC transmission. When the distance is less than this, it is beneficial to use AC transmission. For overhead cables, this distance is approximately 800 to 1,000 kilometers, and for underwater cables, it is about 50 kilometers [8]. For instance, in 1954, Sweden completed the world's first long-distance HVDC transmission project, the 100 kV underwater cable transmission project from the mainland to Gotland Island, with a total length of 90 kilometers [9]. When longer transmission distances are required, HVDC demonstrates better economic efficiency. Take the ± 1100-kilovolt UHVDC transmission project from Zhundong to Wannan as an example. It is currently the world's highest voltage level, largest transmission capacity, longest transmission distance, and most technologically advanced ultra-high voltage transmission project. The project starts from the Changji Converter Station in Xinjiang, spans Gansu, Ningxia, Shaanxi, and Henan, and ends at the Guquan Converter Station in Anhui. It has a transmission distance of 3,293 kilometers, a transmission capacity of 12,000 megawatts, and a total investment of 37.35 billion yuan [10]. If AC power transmission is adopted, as the transmission distance increases, due to requirements for stability, over-voltage and other aspects, intermediate switch stations need to be set up, and multiple lines are required. This not only increases line investment but also substation investment, and the tot+al investment may increase by 20% to 30%, reaching approximately 45 billion yuan.

4. Technical Challenges and Future Development Directions

4.1 Bottleneck of HVDC Technology

Although HVDC has significant advantages in long-distance power transmission, its development still faces several bottlenecks. The converter is crucial in the HVDC system. In the future, with the increasing using of renewable energy at the sending end, its support and regulation capabilities, as well as its fault resistance, need to be improved. The cost of converter stations is relatively high, usually accounting for 40% to 60% of the total project investment. It is necessary to break through the modular converter valve technology to reduce the cost input. Moreover, harmonics will be generated during the commutation process, so high-precision filtering devices need to be configured. The increasingly complex power transmission system needs stronger control, protection and other capabilities.

4.2 Innovative Research Direction

Superconducting direct current transmission breaks through the physical limits of traditional conductors. Superconducting materials possess characteristics such as zero resistance, complete diamagnetism, and high critical current density. During the experimental stage, the loss is less than 0.1%, which can further reduce line losses and make zero-loss power grids possible. The operating frequency of low-frequency alternating current (LFAC) systems is often one-third of that of HVAC systems, so their capacitive reactance and inductive reactance losses are relatively small. In terms of equipment, only one AC-AC converter station is required, and the terminal cost is lower than that of HVDC. Its specific economic feasibility remains to be studied.

5. Conclusion

Ac transmission can achieve synchronous interconnection, and voltage rise and fall operations can be realized through transformers. However, there are skin effect and reactive power compensation requirements. Dc transmission has no inductive reactance or capacitive reactance losses, supports asynchronous networking, and has strong system controllability. However, it relies on converter stations and cannot directly support the existing AC power grid topology. Transmission loss is an important factor affecting the economic efficiency of transmission projects. As the transmission distance increases, the loss of HVAC gradually exceeds that of HVDC. That is, for long-distance power transmission projects, choosing HVDC will result in lower transmission losses.

Compared with the cost of substations and switch stations for AC transmission, the cost of DC converter stations is higher, while the cost of DC transmission lines is significantly lower than that of AC transmission lines. Therefore, the equivalent distance, an important engineering evaluation data for AC and DC transmission schemes, is proposed, that is, the transmission distance when the total costs of the two transmission schemes are equal. Under the current AC and DC transmission technology and equipment conditions, the distance for overhead cables is 800 to 1,000 kilometers, and for underwater cables, it is approximately 50 kilometers.

The lower power loss and lower cost input of HVDC in long-distance power transmission have been confirmed. In the future, hybrid distribution networks that integrate the advantages of AC and DC and the conversion of HVAC to HVDC by utilizing existing transmission corridors have broad prospects.

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