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Principles and Prospects of Ultra-High Voltage Direct Current Transmission Technology

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ABSTRACT

With the continuous growth of global energy demand and the large-scale development and application of clean and renewable energy, how to efficiently, safely and reliably transmit electricity from energy-rich areas to demand areas has become an urgent problem to be solved in the global energy field. Ultra-high voltage direct current (UHVDC) transmission technology refers to a technology that reduces power loss during transmission by increasing the DC transmission voltage and decreasing the transmission current. UHVDC transmission requires reactive power compensation and high-frequency filters at converter stations. This paper elucidates the basic principles and schemes of UHVDC transmission technology and explores its application prospects.

KEYWORDS

Ultra-high Voltage Direct Current Transmission; Converter Station; Reactive Power Compensation; High Frequency Filter; Future Prospects.

1. INTRODUCTION AND PRINCIPLE OF ULTRA-HIGH VOLTAGE DIRECT CURRENT TRANSMISSION TECHNOLOGY

1.1. Introduction to UHVDC Transmission Technology

Ultra-high voltage direct current (UHVDC) transmission refers to DC transmission with a voltage level of ±800kV and above. It can realize high-power long-distance power transmission and interconnection of power systems to form an efficient and stable joint power system. It is one of the most advanced power transmission technologies.

1.2. Principles of Ultra-High Voltage Direct Current Transmission Technology

The key to long-distance power transmission is reducing power loss. According to Joule's law $Q=I^2Rt$, when the transmitted electrical energy (Q) and distance are constant, the transmission time (t) and total resistance (R) are invariants. By reducing the current (I) to reduce the heat generated in the conductor, the goal of reducing power loss can be achieved.

In long-distance power transmission, the electrical energy is supplied by power plants in various regions, and the rated generating capacity of these power plants is constant. According to the power formula P=UI, when the power transmitted (P) remains constant, increasing the voltage (U) can reduce the current (I). If the current is reduced to 50% of its original value, the power loss will be reduced to 25% of its original value , demonstrating a significant reduction in line power loss .

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2. CHARACTERISTICS AND MAIN MODES OF UHVDC TRANSMISSION TECHNOLOGY

2.1. Characteristics of UHVDC Transmission Technology

Advantages of UHVDC transmission over UHVAC transmission [1], [2] :

(1) UHVDC transmission involves mainly technical issues such as network loss and voltage drop, and does not suffer from the stability problems inherent in AC transmission.

(2) UHVDC transmission overhead lines only require positive and negative conductors, have simple tower structures, narrow line corridors, low line construction costs, and low losses.

(3) UHVDC transmission cable lines have large transmission capacity, low cost, low loss, long service life, and unlimited transmission distance.

(4) UHVDC transmission can realize asynchronous interconnection of various power systems. This feature can realize cross-international power interconnection (international AC frequency is divided into 50Hz and 60Hz) .

2.2. Main Modes of UHVDC Transmission

At present, the power generation and consumption in the power system are basically AC power. When DC power transmission is adopted, it is necessary to switch between AC power and DC power. AC-DC hybrid transmission system is a power transmission method in which there are both AC line connections and DC system connections between the sending and receiving AC systems [3]. UHVDC transmission system mainly consists of rectifier stations, inverter stations, and DC transmission lines. At power transmission end, alternating current (AC) needs to be converted into direct current (the rectification process), and the power is sent to the receiving end via the DC transmission lines. At the receiving end, the direct current needs to be converted back into alternating current (the inversion process) for user consumption, as shown in Figure 1.

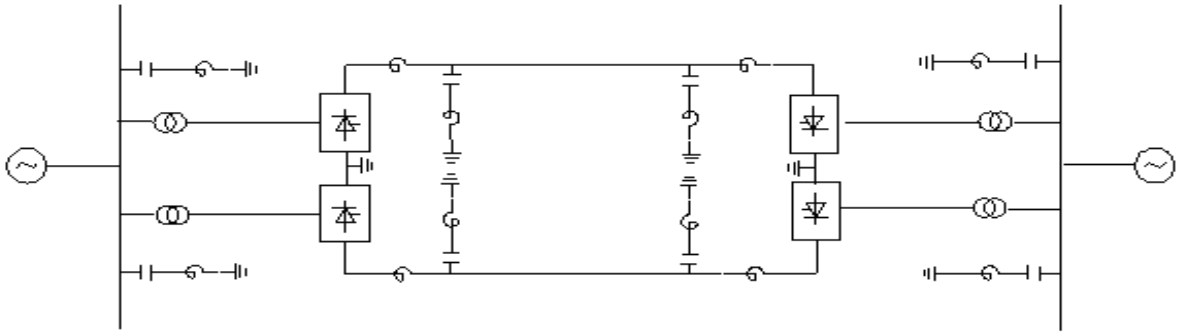

Figure 1. DC transmission system schematic diagram

3. MAIN EQUIPMENT AND BASIC DESIGN SCHEME OF ULTRA-HIGH VOLTAGE DIRECT CURRENT TRANSMISSION SYSTEM

3.1. Converter Station Equipment

3.1.1. Converter Station Structure

DC transmission converter stations are all composed of basic converter units, which can operate independently to perform AC and DC conversion. The main equipment includes converter transformers, converters, AC filters, DC filters, control systems, etc.

3.1.2. Working Principle of Converter Station

The converter is one of the main equipment in the UHVDC transmission system. It usually adopts a three-phase bridge connection method and realizes the mutual conversion between AC and DC through its regular opening and closing.

3.2. Reactive Power Compensation Device for Converter Station

3.2.1. Principle and Main Function of Reactive Power Compensation Device

The principle of reactive power compensation is to improve the power factor of the power grid by adding reactive current , so as to stabilize voltage, reduce line losses, and improve the operating efficiency and stability of the power grid system.

3.2.2. Reactive Power Compensation Device Scheme

Since the operation of the converter is always accompanied by the consumption of reactive power, every converter station must be equipped with a reactive power compensation device [4] .The reactive power compensation device adopts a group operation mode. The grouping scheme needs to comprehensively consider factors such as total compensation, voltage control, reactive power exchange, filtering performance, and equipment layout; the group capacity should be optimized according to the system's transient voltage change rate and steady-state voltage regulation requirements to finally determine the optimal group capacity configuration scheme for the converter station.

3.3. Filter Device

3.3.1. Causes of Power Line Carrier Interference (PLCI)

The main causes of power line carrier interference (PLCI) generated by UHVDC transmission systems are:the opening and closing of converter valves, corona discharge on conductor surfaces, and spark discharge due to loose connections or poor contact. The converter is a typical nonlinear device that achieves AC-to-DC (rectification) or DC-to-AC (inversion) conversion through the regular opening and closing of its converter valves, while also generating a large number of harmonics.

3.3.2. Causes of Radio Interference (RI)

Radio interference in UHVDC transmission systems mainly comes from the opening and closing of converter valves, line corona discharge, and partial discharge of insulators [5].

(1) Radio interference generated by the converter valve

When the converter valve opens or closes, a sudden voltage change occurs between the valve anode and cathode. This sudden voltage change propagates in two modes: 1) High-frequency electromagnetic interference propagates into space via dipole radiation. This interference is shielded by the valve chamber and does not generate radio interference outside the valve chamber; 2) High-frequency oscillations occur with the valve's equalizing capacitance and closely adjacent stray capacitances and inductances. These high-frequency oscillating currents enter the AC/DC switchyard through the converter transformer and smoothing reactor, causing radio radiation interference to electrical equipment and AC/DC lines within the switchyard.

(2) Corona discharge of the line generates radio interference.

When the surface electric field strength of a line exceeds the corona induction voltage of air, corona discharge will occur and line interference will be generated. The magnitude of radio interference is related to the line voltage level, air medium, and climatic conditions.

(3) Partial discharge of insulators generates radio interference.

If the voltage across an insulator exceeds its flashover value, it will discharge and generate radio interference.

3.3.3. Converter Station AC Side Filter

During commutation, the converter will generate harmonics. When the converter valve turns on or off, High-frequency interference is caused by voltage surges in the converter valve. At the moment the converter valve is triggered, the inter-electrode voltage changes rapidly due to the thyristor turning on, which in turn causes a rapid change in current. At the same time, the transient response of the damping circuit and the rapid change in the voltage to ground of the converter valve components will also generate additional high-frequency currents, which will lead to the generation of high-frequency harmonics.

The hazards of high-frequency harmonics to power system equipment can be categorized into two types: The first type involves the generation of superimposed harmonic voltages in electrical equipment, causing voltage increases and potentially leading to malfunctions in control and protection devices. The second type involves harmonic currents flowing through power lines inducing harmonic potentials on nearby telephone lines, interfering with communication systems. Therefore, filters must be installed on the AC side of converter stations to prevent these hazards.

3.3.4. DC - Side Filter of Converter Station

Harmonics on the DC side of the converter station are mainly generated during the converter process and are unavoidable. These harmonic currents cause the following three hazards.

(1) Harmonic currents flowing through all equipment except filters on the DC side will cause these equipment to heat up, thus increasing the equipment's rated value requirements and operating costs.

(2) Seriously interferes with the communication of open-line telephone lines near the line corridor.

(3) It leads to a significant decline in the operating performance of the line system.

The most commonly used DC filter is the dual-coordinated filter, the structure of which is shown in Figure 2.

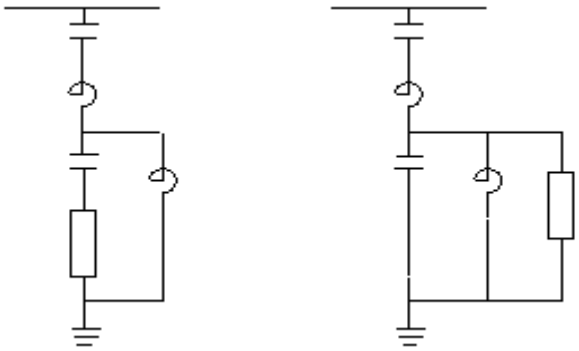

Figure 2. Wiring diagram of a dual-tuned filter

4. THE CONCLUSION OF ULTRA-HIGH VOLTAGE DIRECT CURRENT TRANSMISSION TECHNOLOGY

With the continuous growth of global energy demand and the large-scale development and application of clean and renewable energy [6], how to efficiently, safely and reliably transmit electricity from energy-rich areas to demand areas has become an urgent problem to be solved in the global energy field. Ultra-high voltage direct current transmission technology, with its significant advantages, will become the key to solving this problem. China has successfully built and operates the world's largest number of UHVDC transmission lines. Europe, North America, and other regions are also actively

promoting the research and application of UHVDC transmission technology. For example, Europe's Super-Grid project uses UHVDC transmission technology as its core to create a transnational, cross-border, and transregional "super grid" as the main framework for its future power grid .

UHVDC transmission technology plays a pivotal role in the global "Internet of Power" process . It not only provides crucial technical means for the efficient, safe, and reliable transmission of electricity but also serves as a significant driving force for the construction of a global energy Internet. In the future, we need to conduct in-depth research on the economic, environmental, and safety aspects of UHVDC transmission, and strengthen international cooperation and exchange, which is of great significance for truly achieving the optimization of the global energy structure and sustainable development.

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