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High-Voltage Direct Current Transmission Systems Based on Silicon Carbide MOSFETs

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Abstract. High-Voltage Direct Current (HVDC) transmission technology plays a pivotal role in modern power systems due to its capability for efficient long-distance power transmission. Compared to traditional High-Voltage Alternating Current (HVAC) transmission, HVDC systems offer significant advantages in reducing transmission losses, enhancing transmission capacity, and bolstering system stability. In recent years, the use of Silicon Carbide (SiC) materials in power electronic devices has gained widespread attention. Compared to traditional silicon-based MOSFETs, SiC MOSFETs have a higher breakdown electric field, a wider bandgap, and higher thermal conductivity. These characteristics makes them highly promising in high-voltage, high-power applications and considered a significant developmental direction for future high-performance power electronic devices. This paper will initially introduce the material characteristics of SiC, including polymorphism, wide bandgap, and diverse characteristic colors. It will also discuss the structure and main characteristics of SiC MOSFETs, including transfer, output, and breakdown characteristics. Subsequently, it will present the fundamental principles of HVDC systems and the two primary topologies: Line Commutated Converter HVDC and Voltage Source Converters HVDC. Lastly, it will discuss the advantages of SiC MOSFETs over silicon devices in HVDC, along with potential application prospects. The research findings indicate that SiC MOSFETs possess significant application potential and technological advantages in high-voltage direct current transmission, providing theoretical support and a practical foundation for the optimization of future power electronic systems.

Keywords: Silicon carbide; High-Voltage Direct Current; MOSFET; Voltage Source Converters.

1. Introduction

The concept of High-Voltage Direct Current (HVDC) transmission was first proposed by scientists in the early 20th century, but due to the limitations of technology at the time, it was not practical to implement. In the 1950s, the invention and application of the mercury arc rectifier marked a significant milestone by enabling practical implementations of HVDC technology. In 1954, the Gutenberg to Gotland project in Sweden became the world's first operational HVDC transmission project, signifying the entry of HVDC technology into the practical phase. The invention of the thyristor in the 1970s greatly propelled the development of HVDC technology [1]. Due to its high efficiency and reliability, the thyristor converter gradually replaced the mercury arc rectifier as the mainstream technology. In the late 1990s, the emergence of Voltage Source Converter (VSC) technology brought new opportunities for the development of HVDC. The VSC-HVDC system does not rely on grid voltage for commutation, offering higher flexibility and better dynamic response performance, suitable for scenarios such as urban grid interconnection and renewable energy integration. Currently, High-Voltage Direct Current technology plays a significant role in modern power systems, with advantages including efficient long-distance power transmission, reduced power losses, and improved system stability. Compared to traditional High-Voltage Alternating Current (HVAC) systems, HVDC systems demonstrate superior performance in applications such as transnational grid interconnection, long-distance bulk power transmission, and connecting remote renewable energy sources. However, as power demand grows and renewable energy sources are increasingly integrated into the grid, existing HVDC technology faces challenges in improving efficiency, reducing losses, and enhancing reliability.

In recent years, an increasing number of semiconductor manufacturers worldwide have entered the silicon carbide (SiC) market, propelling the mass production and technological innovation of SiC devices. With the refinement of the supply chain, the share of SiC MOSFETs in the power electronics market has been increasing annually. Owing to technological optimization and cost reduction, the application of SiC in the field of power electronics has garnered widespread attention. Compared to traditional silicon-based MOSFETs, SiC possesses unique physical properties, such as a wide bandgap, high thermal conductivity, and high breakdown electric field. These characteristics endow SiC with potential advantages in high-power, high-temperature, and high-frequency applications. In HVDC, SiC MOSFETs can significantly enhance system efficiency and reliability [2]. Against the backdrop of global energy transformation and carbon reduction, the prospects for the application of SiC MOSFETs in renewable energy systems, such as photovoltaic and wind power, are extensive. The demand for high-performance, high-reliability power electronic devices in these sectors has propelled the further development of SiC MOSFET technology.

This paper first analyzes the material characteristics of SiC MOSFETs and introduces the two primary topologies of HVDC systems: Line-commutated Converter HVDC (LCC-HVDC) and Voltage Source Converter HVDC(VSC-HVDC). Building on this foundation, the discussion delves into the potential advantages and prospective applications of integrating SiC with HVDC.

2. Characteristic of SiC MOSFET

2.1. Properties of SiC material

One of the unique properties of SiC is the polymorphic nature of its structure [3]. At present, more than 200 kinds of SiC crystals have been discovered and determined to have crystal lattice structures. Among them, there are 5 more common types: 3C, 15R, 6H, 4H and 2H.

SiC single crystal is a semiconductor material with a wide bandgap. At room temperature, the bandgap of 6H-SiC single crystal is 3.023eV, while Si and GaAs are 1.1eV and 1.4eV, respectively. At the same time, SiC has excellent thermal conductivity and voltage breakdown resistance that is 10 times that of Si [4]. By studying the band structure of 3C-SiC (2.4eV) with a relatively small bandgap until 2H-SiC (3.35eV) with a maximum bandgap, it was found that all valence band conduction band transitions of these types of SiC involve phonons. This means that these types of SiC semiconductors are all indirect bandgap semiconductors.

The light absorption between bands gives different types of SiC their characteristic colors, such as 6H-SiC appearing green, 15R-SiC appearing yellow, 4H-SiC appearing yellow green [5]. These types of SiC have uniaxial symmetry, and their various colors are caused by electronic transitions from the bottom of the conduction band to other high-energy empty energy levels. Undoped 3C-SiC appears light yellow, while doped 3C-SiC appears yellow green. This color change is due to the preferential absorption of red light within the free carrier band.

2.2. The Structure and Characteristics of Silicon Carbide MOSFETs

2.2.1. Structure of SiC MOSFET

SiC MOSFETs can be divided into n-channel and p-channel types based on the type of conductive channel, and can be classified into depleted and enhanced types based on whether there is a drain-source current when there is no gate voltage. When there is no gate voltage, a transistor with drain-source current is depleted type, whereas one without drain-source current is the enhanced type.

The structure of Silicon Carbide (SiC) MOSFETs has been optimized based on traditional silicon-based MOSFETs to fully exploit the superior characteristics of SiC materials. SiC MOSFETs frequently employ a trench gate structure, wherein vertical trenches are etched into the surface of the semiconductor material. The gate material is filled into the trenches, creating a clad structure on the sidewalls and bottom of the trench. This clad structure ensures close contact between the gate and the channel region on the trench walls. The inner walls of the trenches are typically covered with a thin oxide layer (such as silicon dioxide) for electrical isolation between the gate and the channel region. Due to the gate being clad within the trench, the electric field distribution in the channel region becomes more uniform, reducing the effect of electric field concentration, thereby enhancing the breakdown voltage and reliability of the device. This also allows for more precise and rapid control of the channel current by the gate, reducing switching delays and losses, making them suitable for high-frequency applications. Furthermore, the large contact area between the gate material and the semiconductor material in the trench aids in more effective heat dissipation, improving the thermal management performance of the device.

2.2.2. Characteristics of SiC MOSFET

The transfer characteristic of SiC MOSFETs refers to the relationship between drain current Id and gate voltage Vgs under fixed drain-source voltage Vds conditions, as illustrated in Figure 1. This transfer characteristic reflects the conduction capability at different gate voltages. By analyzing the relationship between drain current and gate voltage, key parameters such as threshold voltage and conduction characteristics can be obtained.

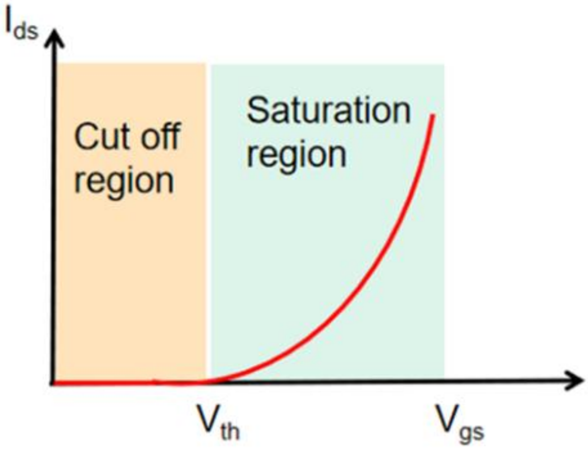

Figure 1. Transfer characteristics of SiC MOSFET [6].

The output characteristics delineate the relationship between the drain current Id and the drain-source voltage Vds under fixed gate voltage Vgs conditions for SiC MOSFETs, as illustrated in Figure 2. Through the output characteristic curves, one can comprehend the conduction performance, saturation behavior, and breakdown characteristics of the device under varying gate voltages.

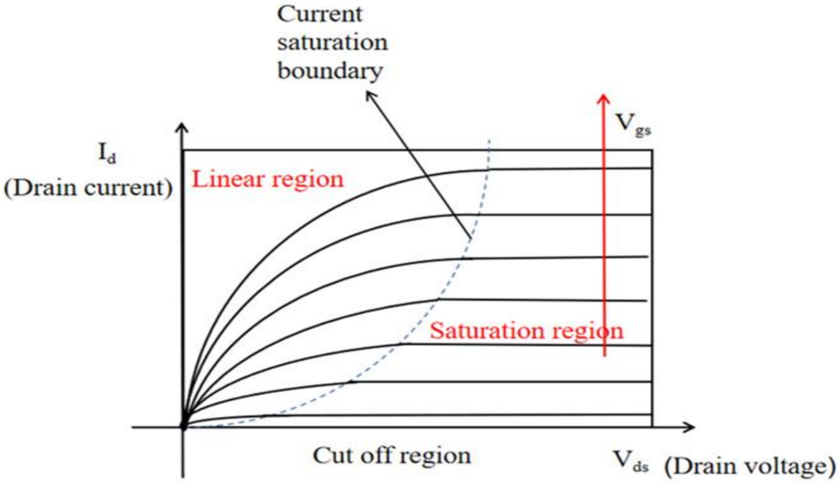

Figure 2. Output characteristics of SiC MOSFET [6].

The blocking characteristic refers to the relationship between the drain-source voltage and the drain current of a MOSFET in its off state. The blocking characteristics of SiC MOSFETs reflect their tolerance under high voltage and the magnitude of the drain current. Due to the high breakdown field strength of SiC material, SiC MOSFETs are capable of maintaining an off state under high voltage without breakdown. This endows them with a high breakdown voltage, typically ranging from several hundred to several thousand volts. The drain current of SiC MOSFETs is extremely low. This is because, in the off state, the wide bandgap characteristic of SiC reduces the number of thermally excited carriers, thereby lowering the drain current.

3. Overview of High-Voltage Direct Current (HVDC)Transmission System

Currently, there are two main types of converters used in high-voltage direct current (HVDC) transmission systems: voltage source converters (VSC), which use fully-controlled switches such as insulated gate bipolar transistors (IGBT), and line commutated converter (LCC), which use semi-controlled devices.

3.1. Line Commutated Converter HVDC (LCC-HVDC)

LCC-HVDC is currently the most widely used form of HVDC transmission system. The semiconductor valve of the converter uses thyristors, which can withstand the highest voltage (up to 10 kV) and current capacity (up to 4 kA) among power electronic devices. It plays an important role in large-capacity applications [7, 8]. The series and parallel configurations of crystal valves are mainly determined by the voltage and current requirements of the system, while also considering the balance of voltage and current, consistency of switching speed, heat dissipation and thermal management, and reliability.

The converter transformer provides the required commutation voltage for the converter to achieve pulsating current, and plays a role in insulating and isolating the AC and DC systems from each other, limiting fault currents, and buffering and suppressing lightning impulse overvoltage waves.

During operation, the high-frequency switching action of the converter's switching devices can cause voltage and current waveform distortion, resulting in harmonic components. These harmonics can lead to increased losses in power electronic devices and transformers, causing overheating and affecting the life and reliability of the equipment. Moreover, the efficiency of the equipment will decrease, affecting the overall performance of the system. In order to reduce the impact of harmonics on equipment and systems, filters are usually installed on the AC and DC sides. The filters detect harmonic components in the power system and generate compensation currents with the same magnitude and opposite direction as the harmonic currents to eliminate the harmonics.

3.2. Voltage Source Converters HVDC (VSC-HVDC)

The VSC-HVDC system includes two voltage source converters, filters, DC capacitors, DC lines, etc. The DC capacitor can maintain the stability of the DC voltage and ensure the normal operation of the voltage source converter. Due to the high efficiency achieved by Modular multilevel converters (MMC), it is widely used in VSC-HVDC. A basic characteristic of VSC is that the polarity of the DC voltage is constant, and the direction of power transmission depends on the direction of current flow. The current always flows from the higher voltage side to the lower voltage side. VSC uses insulated gate bipolar transistor IGBT technology. Its converter works at high frequency and uses pulse width modulation PWM, which can adjust the amplitude and phase angle of the converter while maintaining a constant voltage.

The VSC-HVDC system has fast response capability, which can quickly adjust power transmission, adapt to dynamic changes in the power grid, and improve the dynamic stability of the power grid. Moreover, there is no commutation failure problem. A major risk in traditional HVDC is commutation failure, which can lead to AC network disturbances and even system collapse. However, due to the use of PWM technology to control the gate switching frequency of IGBTs, multiple on and off PWMs are performed within a single cycle, resulting in high switching losses in IGBTs [9].

4. Design and Implementation of SiC MOSFET in HVDC Systems

4.1. VSC-HVDC with SiC Semiconductor Devices

Although silicon still dominates due to its mature system (low cost), the latest progress in SiC power semiconductor technology has promoted the development of high-power fields, such as HVDC converters for transmission. Combining SiC semiconductors with high power ratings with a new sub-module (SM) topology for modular multilevel converters can achieve higher performance by improving efficiency and reducing losses. However, there is currently no packaging standard for high-power SiC modules, although the advantages of SiC MOSFET in power loss in HVDC systems have been proven [2].

When compared to equivalent Si IGBT modules, SiC monopolar devices—like MOSFETs—offer superior switching speed, reduced conduction loss, and high blocking voltage [10]. Due to its fast switching speed and easy current sharing characteristics, MOSFET is more suitable for high-frequency, low-voltage and high-current applications. In addition to having a direct impact on efficiency, the ability of silicon carbide to handle higher operating temperatures can also be used to gain additional freedom for cooling design.

The high blocking voltage characteristics of MOSFETs can reduce the number of series and parallel components, simplify circuit design, and reduce system complexity and cost. SiC MOSFET power devices are suitable for MMC. They outperform silicon IGBTs not just in terms of on-state performance but also in terms of blocking voltage and switching speed. Moreover, basic surge and short-circuit capabilities have been proven, but there is still a gap between the robustness and reliability of SiC MOSFET and Si IGBT [11].

Fast DC breakers and robust power devices may be enough in certain applications to manage DC faults and the ensuing surge currents. In this case, the classic half-bridge (HB) topology may still be the most feasible option because it is simple and has low power consumption. SiC MOSFETs' parallel connection allows them to arbitrarily lower conduction losses, whereas Si IGBTs with' inherent potential prevents them from doing so. By reducing losses, more research directions can be provided for achieving cooling and temperature reduction. For example, using air-cooled radiators instead of coolant. Today, SiC MOSFET modules have an operating temperature of 175°C, and additional developments may further drive this temperature up. In addition, high-rated power devices will not have problems handling DC fault surge currents. And due to economies of scale, SiC MOSFET modules may significantly reduce costs in the coming years. This design approach increases semiconductor spending, which must be weighed against its benefits, namely reduced cooling costs, reduced complexity, and improved reliability.

4.2. SiC MOSFET in the DC/DC converters for future HVDC offshore wind farms

In long-distance, high-power power transmission and interconnected power grids, HVDC has significant advantages over HVAC. There are no capacitive and inductive effects of AC power in HVDC transmission, so line losses are lower. In long-distance transmission, the loss of HVDC is significantly lower than that of HVAC. Moreover, when the distance exceeds a certain threshold (usually more than 500 kilometers), due to lower losses and fewer line equipment (such as no need for intermediate substations and capacitive compensation equipment), the overall transmission cost of HVDC is lower than that of HVAC.For a complete offshore wind farm, a strategy to significantly reduce costs by removing the AC collector platform using a fully DC collector has recently been proposed [12]. It utilizes a VSC-HVDC system, requiring the use of a high-voltage high-power DC/DC converter. SiC MOSFET can meet this requirement. Because there is currently no SiC MOSFET high-voltage power module on the market, the loss model of SiC MOSFET power module can only be inferred from chip data sheets by paralleling chips. The research report compares the power loss of IGBT power module based on silicon insulated gate transistor and SiC MOSFET power module based on SiC MOSFET at 3.3 kV. Experiments show that compared with Si IGBT, SiC

MOSFET can significantly reduce switching loss at different power levels. However, when the power level increases, the conduction loss is higher. Moreover, converters based on SiC-MOSFET can significantly improve efficiency.

It is calculated that if considering an energy cost of 150 \$/MWh, the money saving reaches 1.2 M\$ each year. However, in the current market, the production cost of SiC MOSFET power modules is much higher than that of Si. This hinders the large-scale use of SiC MOSFETs. However, with the development of technology, the production cost will gradually decrease until it can be accepted by the market. Therefore, the use of SiC MOFET in the future will bring significant economic benefits to offshore wind farms.

5. Conclusion

This paper reviews the current state of research, technological advantages, application examples, and future directions of high-voltage direct current transmission systems based on SiC MOSFETs.

Silicon Carbide MOSFETs (SiC MOSFETs) exhibit significant potential in high-voltage, high-power applications due to their exceptional material properties, including wide bandgap, high thermal conductivity, and high breakdown electric field. Compared to traditional silicon-based MOSFETs, SiC MOSFETs demonstrate faster switching speeds, lower on-resistance, and superior thermal performance, significantly enhancing the efficiency and reliability of HVDC systems.

High Voltage Direct Current (HVDC) technology has seen extensive application and development due to its advantages in long-distance and large-capacity power transmission. In particular, the VSC-HVDC system based on Silicon Carbide MOSFETs (SiC MOSFETs) exhibits outstanding performance in terms of flexibility and dynamic response, making it suitable for applications such as weak grids and grid integration of renewable energy sources.

In the future, the development of SiC MOSFET technology will focus on reducing manufacturing costs, achieving mass production, enhancing device reliability and lifespan, exploring new application scenarios, and promoting environmental friendliness and sustainable development. Specific measures include improving material growth techniques and manufacturing processes, and conducting long-term high-stress condition operation tests to assess the performance variations and failure modes of SiC MOSFETs under different environmental and operational conditions. Additionally, there is a need to develop more advanced packaging technologies to enhance the heat dissipation and mechanical strength of the devices, reducing failures caused by thermal and mechanical stresses. Furthermore, research on the application of SiC MOSFETs in smart grids, the development of efficient power converters and intelligent control systems, is essential to improve the stability and flexibility of the power grid. Through system-level optimization design, the technological advantages of SiC MOSFETs can be fully exploited to enhance the overall efficiency and reliability of power transmission and distribution systems. Lastly, intensifying research on the application of SiC MOSFETs in the grid-connection of renewable energy sources such as wind and solar power is crucial to improve energy conversion efficiency and reduce system losses. Through these efforts, SiC MOSFET technology is expected to play a more significant role in high-voltage direct current transmission and power electronics, driving the efficiency enhancement and energy structure optimization of global power systems, providing solid technical support for achieving sustainable energy goals.

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