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Breakthrough Applications of Superconducting Materials in Energy Transmission

Jianyi Qin[1,*],

Jiacheng Tong[2]

[1]Leicester International Institute, Dalian University of Technology, Panjin, Liaoning, 124221, China
[2]SWJTU-Leeds Joint School, 611756, Chengdu, Sichuan, China
*1647500227@mail.dlut.edu.cn

Abstract:

Superconducting materials, with their zero resistance and high current density characteristics, offer a revolutionary solution to the bottleneck of energy transmission losses. This article systematically reviews the technical potential of superconducting materials in energy transmission, commercialization challenges, and innovative applications in distributed energy. Firstly, analyze the zero-resistance effect of superconducting cables, the Meissner effect, and their performance comparison with traditional copper cables. Then, the commercialization bottlenecks are revealed from three aspects: cooling costs, material processing, and temperature limitations. Finally, a modular integrated architecture for superconducting - energy storage is proposed, such as using SMES to stabilize wind power fluctuations, and its engineering value is verified in combination with scenarios like offshore wind power and superconducting current limiters. Studies have shown that superconducting technology holds strategic significance in enhancing power transmission efficiency and facilitating the integration of renewable energy. However, it is necessary to overcome the technical barriers in material preparation and system integration. In the future, efforts should be focused on exploring room-temperature superconductivity, optimizing the economic efficiency of cooling technologies, and achieving coordinated control of smart grids, in order to promote the large-scale implementation of superconducting energy transmission.

Keywords: Superconducting materials; Transmission loss; High-temperature superconducting cables; Commercialization bottleneck; Distributed energy storage

1. Introduction

In the context of the accelerated global energy transition, electricity, as the core energy source for modern society's operation, its efficient transmission capacity directly determines the energy utilization efficiency and carbon emission levels. Traditional power transmission technologies (such as copper cables and aluminum cables) are limited by Ohm's Law and inevitably generate Joule heat loss, which becomes more prominent in long-distance transmission scenarios. According to the 2021 report of the International Energy Agency (IEA) and the research of the International Renewable Energy Agency (IRENA), global power transmission and distribution losses typically account for 8% to 9% of the total electricity generation. The annual electricity wasted can meet the electricity demands of tens of millions of households, while also exacerbating the consumption of fossil energy and carbon emissions [1]. Therefore, exploring transmission technologies with zero or near-zero losses has become a crucial breakthrough to break through the bottleneck of energy transmission efficiency and achieve the goal of carbon neutrality.

The zero-resistance property of superconducting materials provides a revolutionary solution to this problem. Since Onnes discovered the superconductivity of mercury in 1911, superconducting technology has undergone an evolution from low-temperature superconductivity to high-temperature superconductivity. In recent years, significant progress has been made in the field of room-temperature superconductivity [2]. In the field of energy transmission, superconducting cables have demonstrated significant advantages such as higher current density, lower energy loss, and more compact transmission structures, making them an important technical support for the future integration of smart grids and large-scale renewable energy. For example, the ±35kV three-phase coaxial high-temperature superconducting cable demonstration project in Wuhan, China, has demonstrated the efficiency and reliability of superconducting cables in practical applications, such as the increase in current density and the significant reduction in energy loss [3].

However, the commercialization process of superconducting technology still faces multiple challenges. In terms of cooling costs, although the microchannel heat exchange technology of the liquid nitrogen cooling system has reduced energy consumption, the equipment cost and operational complexity remain the main obstacles for its promotion. At the material processing level, the uniformity and current-carrying capacity of the metal matrix composite reinforcement process are insufficient, which hinders the large-scale production of superconducting materials. In terms of temperature limitations, the existing high-temperature superconducting materials still rely on liquid nitrogen cooling, and there is a significant gap from the goal of room-temperature superconductivity. In the field of system integration, the modular design of superconducting cables and energy storage devices lacks systematic research, which hinders the application of superconducting technology in distributed energy networks.

In response to the aforementioned issues, this paper systematically studies the breakthrough applications of superconducting materials in energy transmission from three dimensions: technical potential, commercialization bottlenecks, and distributed energy innovation. By integrating material science and engineering mechanics, it analyzes the mechanical support structure of superconducting cables, compares the economic feasibility of different cooling schemes, and proposes a modular integrated architecture of superconducting - energy storage, providing theoretical support for commercial applications, promoting a leapfrog improvement in energy transmission efficiency, and facilitating the establishment of an efficient and clean modern energy system.

2. The Technical Characteristics and Energy Transmission Potential of Superconducting Materials

2.1 Basic Characteristics of Superconducting Materials

The core characteristics of superconducting materials stem from their unique quantum behavior. The zero-resistance effect enables superconductors to form Cooper pairs of electrons within the material below the critical temperature (Tc), achieving coherent transport without scattering and enabling lossless electron transmission [4]. For example, the resistance of YBCO superconducting tape in a 77K liquid nitrogen environment is less than 10-15 Ω·m, which is only one trillionth of that of copper cables (1.7*10-8 Ω·m) [5]. The Meissner effect endows superconducting materials with complete diamagnetism, allowing the external magnetic field to penetrate to a depth of only the micrometer scale, effectively shielding electromagnetic interference and reducing energy loss. The critical parameter constraints of superconducting materials refer to the three-dimensional threshold limits imposed on the superconducting state by the critical temperature (Tc), critical magnetic field (Hc), and critical current density (Jc). For instance, for room-temperature superconducting materials of HgBa,Ca,Cu,O,+δ (assuming Tc = 300K), they must simultaneously satisfy Hc > 10T and Jc > 106A/cm2 to maintain the superconducting state,

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which imposes strict requirements on material preparation and engineering applications [6, 7].

2.2 Transmission Advantages of Superconducting Cables

By comparing with traditional copper cables, a quantitative analysis is conducted to quantify the significant advantages of superconducting cables in terms of transmission loss (close to zero loss), current density (increased by 5-10 times), and space occupation (reduced by more than 50%).

Compared with traditional copper cables, superconducting cables achieve a breakthrough in key performance indicators. Table 1 provided below is a comparison of various data on different performance aspects of current traditional copper cables and superconducting cables, including transmission loss, current density, relative unit weight, and the occupied transmission corridor.

Table 1. Data Comparison of Traditional Copper Cables and Superconducting Cables in Different Performance Dimensions

Performance dimension	Copper cable (@20°C)	High-temperature superconducting cable (@77K)	Efficiency improvement
Transmission loss	5-8% (long distance)	<0.1%	Reduce by over 98%
Current density	5-10A/mm²	50-100A/mm²	Increase by 5-10 times
Unit capacity weight	8-10kg/kVA	2-3kg/kVA	Decrease by 70%
Transmission corridor occupation	10-15m (for a double-circuit line)	3-5m (for same capacity)	Reduce by 60-70%

This performance transition stems from the inherent properties of superconducting materials. The zero-resistance characteristic completely eliminates Joule loss, while the high current density enables the use of thinner conductors. Combined with low-temperature insulation technology, the outer diameter of the cable can be reduced to one-third of that of traditional cables. Taking ±800kV ultra-high-voltage direct current transmission as an example, the energy loss of superconducting cables over a 2000km distance is only 1/50 of that of copper cables, and the annual energy savings are equivalent to the energy released by burning 300,000 tons of standard coal.

2.3 Application Prospects of Superconducting Materials in Smart Grids

2.3.1 Enhancing Grid Stability

The zero-resistance characteristic of superconducting cables enables them to generate almost no Joule heat loss when transmitting current, thereby reducing energy loss during power transmission and significantly improving the transmission efficiency of the grid. To a certain extent, it also solves the problem of line loss in long-distance power transmission. Moreover, the high current density and low loss characteristics of superconducting cables mean that a single superconducting cable can carry an equivalent current capacity to multiple traditional copper cables connected in parallel, significantly enhancing the transmission capacity per cross-sectional area. This makes it have a significant advantage in long-distance power transmission, effectively reducing transmission losses, and the rapid electromagnetic response of superconducting cables can also effectively suppress power fluctuations during the transient process of the power grid, improving the stability and reliability of the grid.

2.3.2 Enhancing Dynamic Response Capacity

The application of superconducting energy storage systems (SMES) in the smart grid can significantly enhance the dynamic response capacity of the grid. SMES utilizes superconducting coils to achieve zero-resistance energy storage at extremely low temperatures. It stores electrical energy by allowing a direct current to circulate nearly losslessly within the superconducting loop for a long period of time, and can release energy quickly when needed. The SMES system has a millisecond response speed and high power density, enabling it to quickly provide or absorb energy when the grid fails, smooth out the power fluctuations of the grid, and improve the stability and reliability of the grid. In addition, the SMES system can also enhance the grid's peak load regulation and frequency regulation capabilities, improve power quality, and increase the operational efficiency of the grid.

2.3.3 Promoting the Grid Integration of Renewable Energy

Renewable energy sources such as wind power and solar energy are characterized by randomness and volatility, posing challenges to the stable operation of the power grid. Superconducting energy storage systems can smooth out the power fluctuations of renewable energy, enhancing the grid integration efficiency and stability of renewable energy. Moreover, the application of superconducting cables in long-distance power transmission can effectively reduce transmission losses and improve the transmission efficiency of renewable energy, promoting the large-scale development and utilization of renewable energy.

3. Innovative Application of Superconducting Technology in Distributed Energy Storage Networks

3.1 Synergistic Optimization of Superconducting-Energy Storage Systems

The superconducting magnetic energy storage (SMES) system has a millisecond response speed and high power density, which can effectively smooth out the random fluctuations of renewable energy sources such as wind power and photovoltaic power, and improve the stability and reliability of the power grid. By optimizing the collaborative control strategy between the superconducting energy storage and the power grid, energy can be efficiently stored and released, enhancing the peak-load regulation and frequency regulation capabilities of the power grid [8]. At the same time, the experiment of the 1MJ SMES prototype machine (in collaboration with Osaka University, Japan) in a 5T magnetic field also verified that the superconducting magnetic energy storage coil, even under the bending deformation caused by electromagnetic force, still maintains a critical current of about 95%, and the energy efficiency has also increased to 92%. All these clearly demonstrate the stability and efficiency of the superconducting-energy storage system [9].

3.2 Application of Superconducting Cables in Offshore Wind Power and Long-Distance Power Transmission

Superconducting cables demonstrate significant advantages in long-distance power transmission. Their low loss and high current density characteristics can significantly reduce transmission costs and the required area. Taking ±800kV ultra-high voltage direct current transmission as an example, the energy loss of superconducting cables over a 2000km distance is only 1/50 of that of traditional cables, and the annual saved electricity is equivalent to the energy released by burning 300,000 tons of standard coal [10]. At the same time, the Ampacity project in Germany, which is the longest 1km-level 10kv high-temperature superconducting cable in operation in the commercial area of Essen City, has a current-carrying capacity of 2300A, which is about 5 times that of copper cables. The annual loss has been reduced by 80%, and the required area has been significantly reduced by about 70%, releasing a large amount of land resources and reducing related energy consumption [11].

3.3 Superconducting Current Limiter and Fault Current Management

The superconducting current limiter utilizes the critical current characteristics of superconducting materials. When the fault current exceeds the set value, it rapidly transforms into the normal state, achieving rapid limitation of the fault current. Compared with traditional current limiters, the superconducting current limiter has the advantages of fast response, good current limiting effect, and no loss. It can effectively enhance the fault tolerance and recovery speed of the power grid. The superconducting fault current limiter (SFCL) makes use of the fault current management in the superconducting current limiter, and it has a low impedance during normal operation and a high impedance during short-circuit conditions, serving as a limiting device.

4. Commercialization Bottlenecks and Challenges of Superconducting Power Transmission Technology

4.1 Technical and Economic Analysis of Cooling Systems

Currently, the main cooling methods can be divided into two types: liquid nitrogen cooling and liquid helium cooling. Although liquid helium has excellent cooling performance, its preparation process is very complex and thus its resources are scarce and its price is very high. The liquid nitrogen cooling system has the advantages of good cooling effect and high temperature stability, but its operating cost is high, it requires continuous supply of liquid nitrogen, and the storage and transportation of liquid nitrogen also have certain safety risks. The air cooling system has the advantages of low operating cost and convenient maintenance, but its cooling effect is relatively poor and it is difficult to meet the low-temperature requirements of superconducting cables. Therefore, according to the specific application scenarios and economic analysis, an appropriate cooling scheme needs to be selected.

4.2 Challenges in Material Processing and Large-scale Production

The current preparation processes for superconducting materials have certain technical limitations in terms of uniformity, mechanical strength, and large-scale pro-

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duction. The yield rate of most superconducting material preparations is low, and they are prone to fracture. Moreover, the preparation process of high-temperature superconducting materials is complex, making it difficult to achieve large-scale production. The uniformity and mechanical strength of the materials also fail to meet the requirements of engineering applications. Additionally, the selection of materials for superconducting materials is extremely demanding, such as some rare earth elements and some highly pure metals. With the advent of new processes like 3D printing and some emerging processing technologies such as chemical solution deposition, these problems are expected to be resolved. Moreover, current production automation, such as AI intelligent detection, can also assist in the large-scale production of superconducting materials, enabling efficient and low-cost preparation of superconducting materials.

4.3 Temperature Limitations and Research Progress in Room Temperature Superconductivity

Significant progress has been made in the research of high-temperature superconducting materials, but the research on room-temperature superconductivity still faces many challenges. Currently, the critical temperature of high-temperature superconducting materials has reached above the temperature of liquid nitrogen, but their critical current density and mechanical properties still need to be further improved. Although some progress has been made in the research of room-temperature superconductivity, the stable preparation and application of room-temperature superconducting materials have not yet been achieved. This is because, in current scientific research, some traditional theories cannot explain room-temperature superconductivity, and new physical models are urgently needed to verify the research on room-temperature superconductivity. Moreover, room-temperature superconductivity requires some extreme high-pressure conditions and the synthesis of some complex materials, which are all huge challenges for current engineering aspects.

4.4 Integration and Engineering Application Obstacles

There are certain compatibility issues between the superconducting system and the existing power grid in terms of interface standards, fault protection, and operation maintenance. For instance, the interface standards between the superconducting cables and the existing power grid are not unified, and there are also certain technical difficulties in fault protection and operation maintenance. Currently, the impedance of HTS cables is much lower than that of conventional copper cables, which will result in higher short-circuit current amplitudes and a faster rise rate. Traditional overcurrent protection may not be able to maintain the effective operation and running of the cables, and the alternating current's lower eddy current loss will also indirectly lead to incorrect judgments by the protection device [12]. Therefore, it is necessary to strengthen the compatibility research between the superconducting system and the existing power grid to solve the obstacles in engineering application.

5. Future Outlook and Policy Recommendations

From material research and development, process improvement to system integration, a comprehensive layout is made for key technological innovation directions; combined with domestic and international development experiences, specific strategies for promoting commercialization are proposed; finally, from a macro perspective, the potential impact of superconducting technology on the global energy landscape is analyzed, providing reference for relevant decisions.

5.1 Research Focus

Based on the analysis in the previous section, this section will propose the strategic path and policy recommendations for the development of superconducting technology. In terms of material research and development, the focus will be on breaking through the preparation process and performance optimization of room-temperature superconducting materials, and exploring the potential applications of new superconducting materials, such as iron-based superconducting materials with higher critical temperatures [13]. In terms of process improvement, the manufacturing accuracy and reliability of superconducting cables and energy storage devices will be enhanced, and production costs will be reduced by adjusting some preparation materials and cooling systems. In terms of system optimization, the deep integration of superconducting technology and smart grids will be studied to achieve intelligent management of energy transmission and storage. Currently, relevant scientists have also researched digital twin technology. Through multi-physics field modeling, such as coupling electromagnetic-thermal-mechanical equations, and real-time data fusion, the full life cycle management of superconducting equipment can be realized. This also provides a research direction for the future integration of superconducting technology and smart grids [14].

5.2 Commercialization Promotion Strategy

The government should increase financial support for the research and application of superconductivity technology, establish special funds and subsidy policies to encourage enterprises and social capital to participate in the research and promotion of superconductivity technology [15]. At the same time, formulate and improve relevant standards and regulations for superconductivity technology to provide institutional guarantees for the commercial application of superconductivity technology. Relevant enterprises can first invest in demonstration projects. As these demonstration projects gradually gain public attention, they can gradually launch some small-scale commercial applications. Finally, with the development of technology and the improvement of related technologies, it will eventually be able to fully replace traditional technologies. The government can also set up relevant policies for initial investment and establish carbon emission reduction and credit systems to promote the commercialization of superconducting materials.

5.3 The Impact of Superconducting Technology on the Global Energy System

The widespread application of superconducting technology will significantly enhance energy transmission efficiency and reduce energy loss, especially in the process of long-distance power transmission. The nearly zero-resistance characteristic of the materials enables a substantial improvement in power transmission efficiency. Superconducting technology also greatly enhances energy storage efficiency and reduces carbon emissions, providing important support for building a clean, efficient, and intelligent modern energy system. At the same time, this revolutionary technology will completely change the operation mode of traditional energy, accelerating the global energy transformation process. With the continuous breakthroughs in materials science and engineering applications, superconducting technology is expected to become one of the key technologies driving the energy revolution and achieving the goal of carbon neutrality.

6. Conclusion

The breakthrough application of superconducting materials in energy transmission provides a revolutionary technical path for addressing the global bottleneck of energy transmission efficiency. Through a multi-dimensional systematic study, this article demonstrates the key role of superconducting technology in the transformation of the energy system. Firstly, it analyzes the basic physical properties of superconducting materials, the transmission advantages of superconducting cables over traditional copper cables, and the innovative application of superconducting technology in distributed energy storage networks. This reveals the significant advantages of superconducting technology in improving energy transmission efficiency, reducing long-distance transmission losses, and reducing carbon emissions.

However, the commercialization process of superconducting technology still faces many challenges, such as high cooling costs, material processing difficulties, and temperature limitations. For the future development of superconducting materials, relevant governments and departments should comprehensively promote the development and application of superconducting technology from aspects of technological research and development, commercialization promotion, and policy support, providing important support for building an efficient, clean, and intelligent modern energy system.

Authors Contribution
All the authors contributed equally and their names were listed in alphabetical order.

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