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New Materials and Related New Equipment Targeting Integration of Smart Grid and Energy Grid

Ning Puqi[1, 2], Wei Tongzhen[1, 2], Xiao Liye[1, 2], Qi Zhiping[1], Yan Ping[1, 2]

1. Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China
2. University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: New materials and related new equipment, as a significant part of integration of the smart grid and the energy grid, play a critical role in promoting China's energy revolution, thereby facilitating the energy structure transformation and stimulating the innovative development of the energy industry. In the context of the integrated grid, the key technology of new materials and related new equipment and their important contributions to China's energy strategic layout and development are first discussed in this paper. This paper also reveals some dominant restraints, trends, and challenges of new materials and related new equipment based on the state-of-the-art status of the integrated grid. On this basis, several suggestions are proposed at the end of this paper, striving to facilitate the construction of new materials and related new equipment in China, and thus propel in-depth development of the integrated grid.
Keywords: new material; new equipment; integrated grid

1 Introduction

With the revolutionary changes taking place in the field of clean energy, the following four key issues must be addressed to support the development of future power grids: (1) transmission of ultra-high capacity power over a long distance; (2) maintaining a safe and stable ultra-large scale power grid; (3) ensuring decent electric power quality and power supply reliability in the grid; and (4) improving the energy efficiency of the power grid and end-user terminals [1–3]. Under such a scenario, the development of a variety of novel technologies will play a critical and irreplaceable role in resolving the potential challenges in power grid systems and providing a strong technical support for the integration of smart grids and energy grids in the future [4,5]. These technologies include superconductivity technology, new conductor materials, new insulation technologies, new semiconductor devices, new sensing technologies, and new energy storage technologies. The energy and power industries are two important basic industries contributing to the national economy. They are also the primary focus and forerunner industries outlined in the national economic development strategy [6]. However, the major energy production centers and consumers are distributed very unevenly in China. Most of the energy resources are distributed in the western and northern parts of China, while most of the end-users requiring huge amounts of energy are concentrated in the eastern coastal area. Due to such unbalanced geographical distribution of energy supply and demand, the power transmission in China exhibits cross-regional, long-distance, and large-scale features [7]. Currently, the total loss in the power grid in China is approximately 7.5%. Taking a total power generation of 5.5×10^{12} kW·h in 2014 as an example, the power loss in the power grid can reach as high as 4×10^{11} kW·h. This is equivalent to the total power generation capacity of four Three Gorges hydropower plants. Considering that an increasing amount of renewable energy will be provided to the grid system in the future accompanied by an increasing percentage of electric energy in the total end-user terminal energy consumption, the total power transmission loss will inevitably increase in the

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Corresponding author: Ning Puqi, Institute of Electrical Engineering, Chinese Academy of Sciences, Research staff. Major research fields include power device characteristics modeling, and module packaging technology. E-mail: npq@mail.iee.ac.cn
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absence of necessary technological advancements [8–10]. Therefore, achieving large-capacity, long-distance, and highly efficient power transmission through development and deployment of new material technology and new equipment is an urgent task in contemporary China [11–13].

In light of these issues, this paper focuses on exploring the integration of smart grids and energy grids in the future, analyzing the key technologies in new material and equipment development, and discussing the significance of promoting new materials and development of new equipment for China's energy sector. In addition, a brief analysis is made on the application status and existing problems of new materials and new equipment development in the energy field in both China and other nations. Based on these issues, several development recommendations are proposed with regard to the development strategy of new materials and new equipment for supporting the development of an "integrated network" strategy.

2 Emerging materials and the associated new equipment technologies targeting "integrated grid"

2.1 Emerging materials technologies targeting "integrated grid"

A distributed energy system, which combines several parts including the distributed power generation components, energy storage media, controllable loads, and converters, can regulate the local energy resources intelligently and fully leverage the complementary advantages by taking advantage of the information electronics and power electronics technologies. Therefore, it is an important research field that can provide high-quality, reliable, and controllable electric power to the local residents and the power grid. Various new materials are used as direct carriers for energy conversion, power transmission and operational control in power grid systems. Therefore, the development of new materials directly determines the operation efficiency, safety, reliability, and system cost of the microgrid. It is also the most important element in a smart grid system [4,9,14].

Magnetic materials are the basic materials necessary for power grid applications. The exploration and preparation of advanced electrical and magnetic materials can greatly promote the continuous development of electrical equipment and the creation of new equipment, improve the design level and efficiency of intelligent power equipment in a power grid, and reduce the size and mass of the power equipment [15–17]. Applying magnetic materials to smart sensors in the grid system will help information collection and condition monitoring in the current grid system as well as improve the operation reliability of the new power system. Therefore, as shown in Fig. 1, the use of magnetic materials to improve the performance of smart power equipment and sensors in the grid is an important means of improving the efficiency of the "integrated grid" and ensuring its reliable operation.

High efficiency and high reliability are inevitable development trends in the future "integrated grid". Research on new conductive materials with low resistivity, high mechanical strength, good corrosion resistance, good wear resistance, good processability, and high cost performance, such as high-performance copper/copper alloy materials, copper/carbon nanotube composite materials, and carbon-metal alloy materials, will have a major impact on the development of the power grid in the future. If the electrical resistivity of the current wire can be reduced by 1/3 using these novel materials, the annual electrical power saving can reach 1×10^{11} kW·h, which exceeds the total annual power generation capacity from the Three Gorges hydropower plant [12]. In addition, deploying the novel highly conductive materials in electric wires of various electric terminals such as electric motors, electric locomotives, and household appliances will further reduce the energy consumption while alleviating energy shortages and environmental pollution issues in eastern China [6,18,19].

In the future, the voltage rating and the network scale of ultra-high voltage transmission will keep increasing. At the same time, new insulation structures and technologies will be required in gas-electric hybrid power transmission networks. These demands put forward new requirements on the structure and material composition of the insulation system of the "integrated grid". The space charge accumulation effect caused by direct current transmission will yield a distorted electric field in the local space, which can accelerate the aging of the insulating materials. The space insulation and energy transmission are constrained in wireless transmission networks, and the space charge issues in power transmission systems will affect the insulation equipment. The introduction of power electronics will lead to more frequent transient pulse over-voltages, which will change the working environment of insulated equipment [20]. Therefore, new electrical insulation materials will provide important support for the future "integrated grid".

Wide band-gap semiconductor materials, represented by silicon carbide (SiC) and gallium nitride (GaN), is a new generation of semiconductor material that was developed rapidly after the rise and wide application of the first- and second-generation semiconductor materials (represented by silicon and gallium arsenide). Compared with silicon materials, SiC and GaN exhibit a 10 times higher breakdown electric field strength and three times larger band gap [21]. Therefore, SiC and GaN devices possess an extremely low on-resistance, high switching speed, and high working frequency. In addition, the maximum theoretical operating temperature of SiC and GaN power electronic devices is more than four times that of silicon devices. Such a feature is beneficial for optimizing the heat dissipation system and further increasing the power density, both of which are in accordance with the special application requirements in a power grid [22].

Wide band-gap semiconductor devices, with their excellent performance, will be widely used for power generation, transmission, and consumption in future power grids. These materials will bring revolutionary changes to the smart grid system.

2.2 Emerging equipment technologies targeting "integrated grid"

2.2.1 Wide application of power electronics equipment based on new semiconductor devices

New power electronics equipment manufactured with new semiconductor devices will be widely used for power generation, transmission, and consumption in future power grids. Application examples include the development of green energy, next-generation power grids, rail transit, electric vehicles, large-scale energy-saving motors, consumer electronics, and other fields. A distributed energy system, which combines several parts including distributed power generation components, energy storage media, controllable loads and converters, can regulate the local energy resources intelligently and fully leverage the complementary advantages by taking advantage of the information electronics and power electronics technologies. Therefore, it is an important research field that can provide a high-quality, reliable, and controllable electric power to the local residents and power grid [19–22]. The power converter is the carrier for energy conversion, power transmission, and operation control in the grid system. It directly determines the operating efficiency, safety, reliability, and system cost of the microgrid. Therefore, it is one of the most important pieces of electric equipment in a smart grid system [3,19].

2.2.2 Adequate monitoring and perception of the status is an important feature of the future "integrated grid"

With the development of modern power technology, power electronic devices have become an important means of power regulation. Higher requirements have also been put forward to ensure the operation reliability of power equipment. Power electronics technologies have also enabled transformation in renewable energy development from centralized grid connections to distributed power supply. The distributed grid system poses higher demands on the monitoring and sensing of the operating conditions [23]. Therefore, traditional high-voltage and high-current measurement methods will face severe challenges. The rapid development of optoelectronic technology has greatly expanded laser and fiber-based sensing technologies. Because the optical detection system naturally exhibits many advantages including good insulation, good anti-interference ability, high measurement accuracy, easy miniaturization, and distributed network, it can better meet the real-time distributed monitoring requirements in the future "integrated grid" energy systems. Therefore, the development of optical measurement, monitoring, and sensing systems is an important direction for developing the "integrated grid".

2.2.3 Energy storage is indispensable in the future "integrated grid".

Vigorous development of renewable energy has become an important national policy in China. However, due to the randomness and intermittent nature of power generation from renewable sources such as wind power and photovoltaic power generation, connecting renewable power to the grid system can bring a significant challenge to the safe, reliable, and highly efficient operation of the power grid [24]. On the other hand, China has maintained a fast economic development over a long period of time, which has resulted in a rapidly increasing power load as well as fast changes in the power load structure. The mismatch between power supply and demand has become increasingly prominent, resulting in an ever-increasing trend in both power

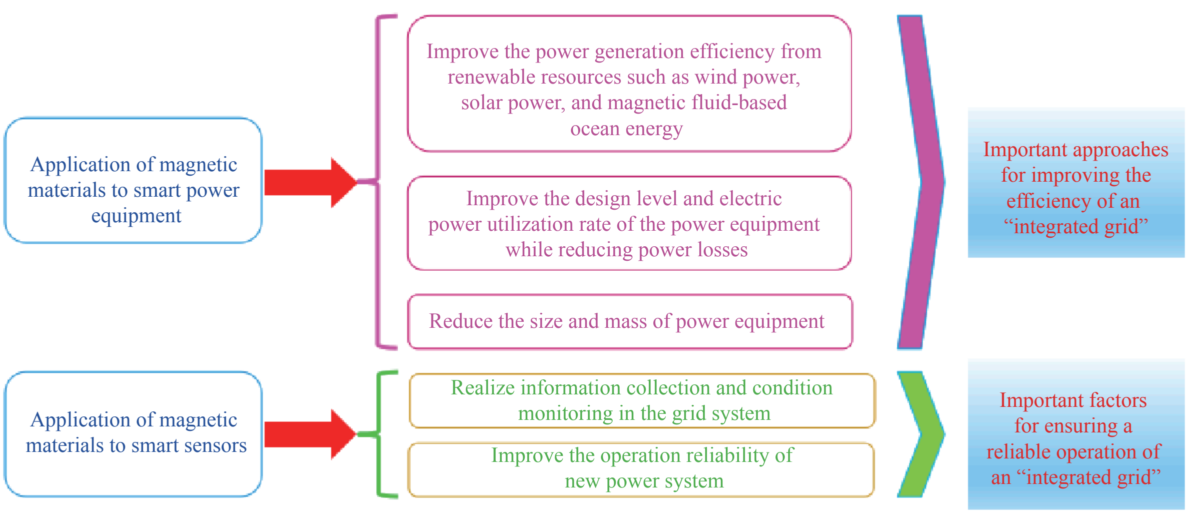

Fig. 1. The promotion effects in an "integrated grid" by new magnetic materials.

load and peak-to-valley difference. Therefore, a large storage capacity must be kept in the power system, which reduces the operation efficiency of the power system equipment [25]. Energy storage units (electric storage, cold storage, heat storage, etc.) can provide energy buffering for the power grid and the energy grid. Being a special unit in the network, it can be controlled and dispatched flexibly in the grid system. In particular, energy storage plays an indispensable role in peak clipping of the power grid, and in improving power quality, power supply reliability, the grid-connected power generation rate, and energy conversion efficiency. It is an important functional unit for realizing a safe, reliable, clean, efficient, and economical operation of the power system. It is also a critical functional unit for integrating the smart grid and the energy grid.

2.2.4 Superconducting technology that can be widely used in the future "integrated grid"

Superconducting technology can be widely used in many different applications including superconducting transmission cables, superconducting transformers, superconducting generators, superconducting motors, superconducting current limiters, and superconducting energy storage systems [14,26]. Table 1 lists the effects and impacts of various superconducting devices on the power grid. As shown in the table, a superconducting transmission cable can provide a low-loss and large-capacity power transmission strategy for the future power grid, which will help resolve the existing issues of high transmission loss and tight transmission paths. The superconducting current limiter can effectively reduce the short-circuit current of the power grid for ensuring better safety and stability of a large power grid. The superconducting energy storage systems can provide effective positive and negative compensations to the fluctuation in the power generated from renewable energy sources, thereby increasing the grid's capability to absorb renewable energy. Superconducting transformers, generators, and motors also possess irreplaceable advantages in improving the efficiency of electrical equipment and reducing its occupied area. Therefore, if superconducting technology can be widely used in the power grid, it can effectively resolve a series of major challenges in the power grid brought by the renewable energy revolution, which is of great significance to the development of the future power grid. Therefore, it is considered by the US Department of Energy as the only high-tech reserve for the power industry in the 21st century.

3 The trend and challenges in the development of new materials and the associated new equipment targeting the "integrated grid"

The following research directions are distinct and cutting-edge innovation. Once a breakthrough is made in a particular research direction, fundamental changes will be brought to the development of smart grids, which will contribute to the satisfaction of major national economic and social development requirements in energy conservation, emission reduction, and energy technology innovation. Ultimately, it will make positive contributions to resource conservation, energy consumption reduction, and environmental protection.

(1) The demand for new superconducting material and the associated equipment in an "integrated grid"

In recent years, China has made great progress in the discovery of new superconductors, the understanding of superconducting physical mechanisms, the preparation of superconducting materials, and the development of superconducting technology. These technology advancements provide a feasible technical path for tackling the major challenges brought by the new energy revolution in the power grid [27]. In recent years, the following trends were revealed in the development of superconducting power technologies: development of higher voltage levels or greater capacity; the movement of application principles toward diversification and integration of multiple functions; integration with the development requirements for smart grid technology; and tendency to develop towards DC power grid more often. Despite these trends, there are still many issues that need to be resolved in order to achieve scaled-application of superconducting materials. These include: the critical temperature of superconducting materials needs to be increased; the long-term operational reliability of the supporting equipment (mainly low temperature and cooling equipment) needs to be improved greatly; and the price of superconducting materials needs to be reduced significantly.

(2) The demand for highly electric conducting and new magnetic materials in the "integrated grid"

Research on highly electric conducting materials and new magnetic materials in China has just started to make some progress. There have not been many breakthrough results and the current research focuses include: formation and mechanism of the microstructures inside the new materials; formation mechanism and evolution pattern of new materials during processing; new material structure, organization, and performance-coupling response mechanism under high-intensity load.

(3)The demand for insulating materials in the "integrated grid"

The future direction for developing high-voltage insulation materials technology is to develop insulation materials that can operate normally in harsh environments such as higher temperatures and higher electric fields, which are in accordance with the future grid requirements. However, such a plan faces significant difficulties. Whether the difficulty comes from the balance between cost and insulation or the new requirements for future insulation materials based on environmental protection, these issues will need to be taken into consideration in future research [28,29]. However, generally speaking, the high-voltage external insulation technology in China is still de-

Table 1. The roles and influences of various superconducting devices on the future power grid.

Application	Characteristics	The roles and impacts on the future power grid
Superconducting current limiter	Exhibits a small impedance under normal working condition and a large impedance in case of failure Integrates the detection, triggering, and current limiting functions in a single unit Fast response and recovery No side effects to the power grid	Significant reduction in short-circuit current Improvement in grid stability Improvement in power supply reliability Better protection of electrical equipment Reduced construction and retrofit costs
Superconducting cable	High power transmission density Low loss, small size, and light weight Small reactance value per unit length Cooled down by liquid nitrogen	High-capacity and high-density power transmission Satisfying environmental and energy-saving development requirements Reduce urban land use Shorten electrical distance Improving the grid structure
Superconducting transformer	High limiting capacity of a single unit Low loss, small size, and light weight Cooled down by liquid nitrogen	Reducing occupied areas Satisfying the development requirements for environmental protection and energy conservation
Superconducting energy storage system	Fast reaction speed High transmission efficiency Capable of providing high-power support to the grid system in a short period of time	Performing rapid power compensation Improving the stability of the large power grid Improving the power quality Improving the power supply reliability
Superconducting motor	High limiting capacity of a single unit Low loss, small size, and light weight	Reducing losses Reducing occupied areas Improving the stability of the power grid
Superconducting generator	High limiting capacity of a single unit Low loss, small size, and light weight Small synchronous reactance using a small synchronous generator Strong overload capability	Superconducting synchronous camera can be used for reactive power compensation Superconducting wind turbine is comparatively advantageous in large-capacity offshore wind power generation

veloping in the direction pursuing low energy consumption and cost, high safety and operational stability, and sustainable development.

(4)The demand for new power electronics devices in the "integrated grid"

At present, the mainstream high-frequency full-control devices on the market are basically monopolized by foreign countries. China has not yet mastered the key technologies in this field. Therefore, the development and application of the associated major equipment are subject to other countries and people. At the same time, the development level of the third-generation semiconductor materials and device technology is changing with each passing day globally. This trend has imposed a new round of impact on power electronics technology and industry in China [30–32]. Key research studies that need to be conducted as soon as possible include: synthesis of wide band-gap semiconductors such as SiC and GaN with large size, low defect, and high reliability; surface passivation technology for semiconductor materials; development of new semiconductor materials and analysis of their functionalities; design and fabrication of silicon-based power electronics with higher voltage levels, higher current capacity, lower on-resistance, and faster switching speed; combination expansion and series-parallel technology of multi-chip multi-module power devices; new structure, process, principle, and design of new-generation power electronic devices with wide temperature characteristics and high operating characteristics; advanced packaging, driving, and protection technologies for power electronic devices; reliability analysis and application technology of power electronic devices, etc. [33].

(5) The demand for new sensor technologies in the "integrated grid"

The research direction for new optical fiber sensing technologies is mainly oriented towards the development of nano-optics. Specifically, the sensitivity of the sensors can be further improved by enhancing the sensitivity effect using near-field, surface plasmon, photonic crystal, and other technologies [32]. In terms of applications, a significant amount of research work is still left to be done on all-fiber sensors in terms of environmental stability and temperature stability. The development of optical fiber technology can lead to the formation of a true all-fiber sensor network, where different optical sensors are connected using light. The establishment of a multi-element all-fiber power equipment state detection system is the trend of the future development in smart grids.

(6) The demand for new energy storage technologies in the "integrated grid"

China has not yet fully mastered new energy storage technology. The main bottlenecks include: ① lack of high-load compressor technology used for compressed air energy storage. The research and development of the system is still in the demonstration stage; ② lack of breakthrough in the key technologies used for flywheel energy storage such as high-speed motors, high-speed bearings, and high-strength composite materials; ③ the synthesis of key materials and the associated batching/scale technology used in chemical battery energy storage. In particular, there are still significant gaps between the most advanced technology and the current technology in China for multiple components including electrolyte, ion exchange membranes, electrodes, and module packaging and sealing; ④ lack of high-performance materials and high-power modular technology related to supercapacitors; and ⑤ lack of breakthroughs in high-temperature superconducting material for superconducting energy storage [34]. In addition, certain research on novel energy storage technology and the associated strategies on establishing intellectual properties has not received sufficient attention and support.

4 Strategic recommendations for developing new materials targeting the "integrated grid"

4.1 Promoting the integration of superconducting technology with new equipment technology and fostering new developments in the energy industry

Once a major breakthrough is achieved in superconducting technology, it will bring significant impacts in different fields including electricity, energy, transportation, communications, medical care, and scientific research. Therefore, it is recommended that the national science and technology department set up a goal for realizing practical application of superconducting power technology, strengthen the overall design, establish a strategic roadmap for near, medium, and long-term development, highlight the goal-oriented research direction, and provide long-term stable support through the national key research & development plan [33,34]. On the other hand, the nation will only be able to achieve major original breakthroughs and comprehensive improvement of technological innovation capabilities through long-term stable support for similar fundamental and forward-looking high-risk projects [35]. As an important entry point, it is recommended to start a superconducting power transmission demonstration project with higher operating temperature (e.g., exceed the temperature of liquefied natural gas) based on the existing superconductivity research in China, and to further build a 100-kilometer superconducting power transmission demonstration system through 15–20 years of efforts.

Within this project, the research focus will be on establishing the superconducting physics foundation involved in the demonstration objectives, developing key technologies for preparing high-temperature superconducting materials, developing key cryogenic and refrigeration technologies with long life and high reliability, and developing key technologies for manufacturing superconducting transmission cables. By establishing a single research project and gradually expanding to a larger influential area, this project will be able to comprehensively promote the application and development of superconducting technology in various fields in China [36].

4.2 Accelerate the research and development of high-performance conductive, insulating, and magnetic materials for complementing the weak points in the infrastructure

For combining the current national strategic requirements and the specific needs for conductive materials in smart grids, it is recommended that the following research studies be conducted: (1) prioritizing the research and development of high-performance conductive materials, insulating materials, and magnetic materials with a focus on resolving the key scientific problems in the preparation and processing of materials; (2) promoting the application and verification of new conductive materials, insulating materials, and magnetic materials in major application fields (e.g., the State Grid), and preparing large-capacity, low-energy consumption, and long-distance transmission cables and transformers [37]; (3) manufacturing new power electronic equipment based on the electrical and thermal properties of new conductive materials, insulating materials, and magnetic materials; (4) establishing a decent testing platform for characterizing the properties of new conductive materials, insulating materials and magnetic materials; establishing industrial or national standards; and strengthening discipline construction and key personnel training。

4.3 Deepening the recommendations in the field of power electronics technology devices to achieve research and development independence

In order to promote the independent innovation of power electronic technology devices and to establish a strong, complete, and independent power electronic device industry in China, the following suggestions are proposed: (1) in terms of government planning, comprehensive improvement in the status of power electronics technology should be included in the medium- and long-term national planning; (2) in terms of technology research and development, the core of the research should be focused on device development. By expanding the research field gradually from materials to devices and applications, the core key technologies will be eventually grasped and mastered comprehensively in China; (3) in terms of industrial promotion, the focus should be on the improvement of core competitiveness in the power electronics industry, which will promote a healthy development of the industry; (4) in terms of condition support, organizational leadership should be strengthened together with the establishment of a complete platform and talent system [38].

4.4 Improving the system level planning of energy storage equipment for supporting the "integrated grid"

The following five recommendations are given in terms of specific technical route planning:

(1) the distinction and connection between energy storage equipment technology and energy storage application technology must be clarified; (2) for large-scale demonstration projects connected to the power grid, the existing grid simulation system should be referred to or used to demonstrate key application technology issues, and the engineering construction should be performed after simulation study; (3) planning should be conducted based on a specific energy storage application scenario and the different levels of technology development; (4) strengthening the assessment of energy storage project application and concluding in terms of intellectual property competitiveness and technology application prospect; (5) establishing a joint innovation research institute for energy storage industry and emphasizing the industrial planning and strategies [39].

5 Conclusions

New materials and associated new equipment technologies are important foundations for supporting the integration of smart grids and energy grids in the future. This paper first introduced the main technologies associated with new materials and corresponding new equipment. Next, we analyzed several technological features and discussed the significance of new materials and new equipment for energy market reform, intelligent upgrading of the energy system, and promoting the innovation and development of the entire energy industry. Afterwards, the weaknesses and outstanding problems associated with the development of new materials and new equipment in China were analyzed and discussed in the paper. Finally, several recommendations on developing new materials and new equipment were proposed to meet the demand of the "integrated grid".

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