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The progresses of superconducting technology for power grid last decade in China

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Abstract

With the increasing development of renewable energy, it is expected that large-scale renewable power would be transported from the west and north area of China to the east and south area. For this reason, it will be necessary to develop a wide-area power grid in which the renewable energy would be the dominant power source, and the power grid will be faced by some critical challenges such as long-distance large-capacity power transmission, the stability of the wide-area power grid and the land use problem for the power grid. The superconducting technology for power (STP) would be a possible alternative for the development of China's future power grid. In last decade, STP has been extensively developed in China. In this paper, we present an overview of the R&D of STP last decade in China including: 1) the development of high temperature superconducting (HTS) materials, 2) DC power cables, 3) superconducting power substations, 4) fault current limiters and 5) superconducting magnetic energy storage (SMES).

Keywords: High temperature superconducting materials, superconducting fault current limiter; superconducting power cable; superconducting power transformer; superconducting magnetic energy storage

1. INTRODUCTION

In China, most of the power sources are located at the west and northwest of the country while most of the load centers are located in the south and east. For instance, in the year of 2014, there are about 100GW of power transported from the west and northwest to the east and south area. For this reason, it has been a basic logic to develop a wide-area power grid in which all the regional grids are interconnected in China. With the increasing development of renewable energy, it is expected that more and more power from renewable energy would be transported from the west and north area of China to the east and south area. According to a research report by a group from the Electric Power Research Institute of China [1], it would need to transport more than 500GW of power from the west and northwest to the east and south area in 2050, and the power grid of China would become a huge power system. For such a huge power system, it is becoming increasingly difficult to maintain the stability and reliability of the power grid because of the high level of fault current, and it is of great importance to keep land use to a minimum because China has a high population density and rigorous restrictions on land use. Besides, the losses of the power grid would be another problem because of the large-scale power transmission over long-distances

Superconducting power technologies, such as superconducting fault current limiters (SFCL) and superconducting magnetic energy storage (SMES) can be used to improve the stability and reliability of China's power grid. Superconducting power cables and superconducting power transformers can also be used to reduce the space required by the equipment and enhance the capacity for power transmission over a long-distance, and they are also effective to reduce the transmission losses significantly. For above reasons, the Chinese government has supported R&D into superconducting technology for power since 1996. During China's ninth five year plan from 1996 until 2000, the R&D for HTS materials and superconducting power cables had been supported, and after that, the supports under China's "863 Plan-On Superconducting Technology", the Chinese Academy of Sciences (CAS) and the Natural Science Foundation of China (NSFC) have been extended to the developments of HTS materials, power cables, the SFCL, SMES and power transformers. In this paper, we present an overview of the R&D of STP last decade in China including: 1) the development of high temperature superconducting (HTS) materials, 2) DC power cables, 3) superconducting power substations, 4) fault current limiters and 5) superconducting magnetic energy storage (SMES).

2. RESEARCH AND DEVELOPMENT OF HTS MATERIALS IN CHINA

In China, much attention of HTS materials was focused on BSSCO tape (1G) during 2000 to 2005, and great

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TABLE I
Bi2223 TAPE SUPPLIED BY INNOVA OF CHINA

Parameter / Wire category	Ic @77K, 0T	Je @77K, 0T	Max, Tensile Strength, W/ 5% Ic degradation	Critical bending Radius, W/ 5% Ic degradation	Thickness, W/ ±0.02mm tolerance	Width, W/ ±0.2mm tolerance	Application Remarks
Standard Wire	120A	12000A/cm^2	100MPa @77K	30mm	0.23mm	4.2mm	Suitable for experiments
Insulated Wire	120A	12000A/cm^2	100MPa @77K	30mm	0.25mm	4.2mm	Bukking-proof
Strengthened Wire	120A	12000A/cm^2	200MPa @77K in progress	30mm	0.35mm	4.5mm	Easy to use with high strength
Ag-Au Wire	110A	11000A/cm^2	N/A	30mm	0.23mm	4.2mm	Low thermal conductivity for current lead

progress had been made, 1G HTS tapes has been commercialized by the Innova Superconductor Technology Co.,Ltd (Innova) since 2003, the 1G tape supplied by Innova can reach a production of 200km/year. After that, most of the R&D activities for the HTS tape was then shifted to YBCO (2G) tape after 2004 in China.

2.1. The first generation HTS tape (Bi2223 tape)

Because the length of 1G tape can reach one kilometer easily, and the physical performance can satisfy some requirements for applications for cable, transformer, FCL etc, a project for the 1G commercialization were supported by “863 Plan-On Superconducting Technology” in 2002. This project was sponsored by Innova Superconductor Technology Co.,Ltd（Innost） and Northwest Institute For Non-ferrous Metal Research(NIN). The remarkable technological breakthrough had been achieved for Bi2223 superconducting wire in both Innost and NIN in 2005: 200 meter length of BSCCO/Ag superconductor wire with a critical current exceeding 150A & Je of 15kA/mm^2 at 77K, self-field. Now Innova can provide long Bi2223 tape with different specifications (see table 1).

2.2. The second generation HTS tape(YBCO tape or Coated Conductor)

Although 1G HTS tape meets the electrical and mechanical requirements for application, it contains about more than 75% of silver, making tape cost a barrier to broad acceptance of HTS devices. 2G HTS tape in which the element of the main material is Fe or Ni provides the opportunity to lower the price-performance ratio toward that of copper. In the late of Tenth Five-year Plan, R&D for 2G tape obtained more attention in China. In 2004, a 10m length 2G tape project was started by Ministry of Science and Technology (MOST), it was sponsored by Beijing General Research Institute for Non-ferrous Metals (GRINM). The researcher of GRINM used the rolling-assisted biaxially textured substrates (RABiTS) process to prepare the substrate, sputtering method to epitaxial grow the Y_2O_3 and CeO_2 buffer layers, pulsed laser deposition to grow YBCO superconductor layer. In 2006, the researcher at GRINM successfully fabricates a 10 m 2G tape with critical current of 50A.

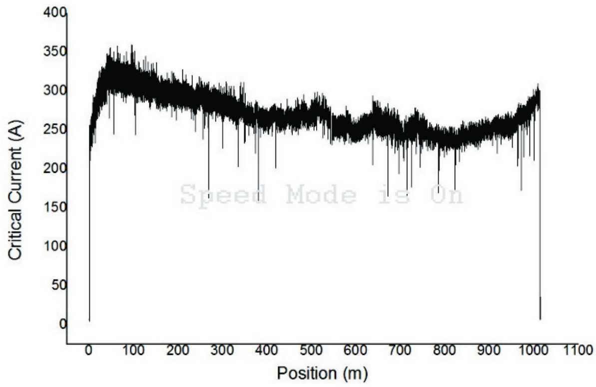

Fig. 1. Longitudinal Ic profile from a 1000 m 2G tape prepare by SAMRI.

In 2008, another project for R&D of 2G tape was sponsored by Shanghai Jiao Tong University. They also employed RABiTS+PLD process to fabricate the 2G tape, and the structure was YBCO/CeO_2/Y_2O_3/CeO_2/Ni. In 2010, critical current value of 194 A/cm had been achieved in 100 m long tape.

In 2011, a research project was started by Science & Technology Department of Jiangsu Province, and Suzhou Advanced Materials Research Institute (SAMRI) was responsible for the project. In 2012, a major industrialization project from Shanghai Municipal Science and Technology Commission was executed by Shanghai Jiao Tong University, Shanghai Superconductor Tech. Co., Shanghai University, etc. In this project, the lab research goal is: Jc > 3.5 MA/cm^2, Ic > 1000A/cm-width, and Pilot-line goal is: L > 1000 m, Ic = 300~500A, Jc > 3.0 MA/cm^2.

In 2014, both Suzhou Advanced Materials Research Institute and Shanghai Jiao Tong University can fabricate 2G tape with length up to 1000m. Figure 1 shows the performance of the 1000 m 2G tape developed by SAMRI.

3. RESEARCH AND DEVELOPMENT OF SUPERCONDUCTING EQUIPMENTS FOR POWER IN CHINA

Since 2004, the R&D on the superconducting technology for power in China has been supported by three separately funded government agencies, they are China's Ministry of Science and Technology (MOST), through a project named "863 Plan-On Superconducting Technology", the Chinese Academy of Science (CAS) and the Natural Science Foundation of China (NSFC). In addition, China's power companies and power equipments companies, such as State Power Grid Company (PGC), the South Power Grid Company (SGC), the Changtong Power Cable Company (CPCC), TBEA Group, Zhongfu Group etc. also supported the R&D for superconducting power equipments. In this section, we present the progresses of major projects as follows:

3.1. The 360m/10kA superconducting DC power cable

With the quick developments of renewable energy, it is expected that HVDC power transmission would be widely used for the future power grid. In order to demonstrate the possible application of a superconductor in DC power transmission, a 360m/10 kA HTS DC power cable project was started in 2007. This project is supported by MOST and the Zhongfu Group, an aluminum production company, and sponsored by the Institute of Electrical Engineering, CAS.

The cable is a warm-dielectric type, and Bi-2223 HTS tapes were used to fabricate the conductor. The conductor consists of 5 layers of HTS tapes, of which one layer is fabricated with HTS tapes from InnoST, and four layers are fabricated with HTS tapes supplied by Sumitomo. The HTS DC cable was installed at Henan Zhongfu Industrial Park. In order to test the bending performance of the cable, the HTS DC cable was designed to be bent at nine separate locations, and three of them are in the vertical direction and six of them are in the horizontal direction, and the minimum bending radius is 3m. After installation, the cable was tested at 77K. Tests show that the critical current of the cable by 1m/cm was more than 12.5kA. Then, the cable was used to connect the substation and the bus-bar of an aluminum electrolyzing workshop of the Industrial Park. A view of the installed cable is shown in Figure 2. The operation of the cable shows that the operation voltage of the cable waves between 1.0kV and 1.3kV, the operation current waves between 6.0kA and 13.0kA, and the cable can work stably. Tests also show that the cable can save

Fig. 2. 360m/10kA high-temperature superconducting DC cable [2].

more than 65% of transmission losses compared with the conventional one.

3.2 The 10kV superconducting power substation

The superconducting power substation consisted of the following superconducting power equipments: a 3-phase, 10kV/1.5kA high Tc superconducting (HTS) power cable which is 75m in length; a 3-phase 10kV/1.5kA SFCL; a 3-phase 10kV/0.4kV HTS transformer whose capacity is 630kVA, and a 1MJ/500kVA SMES which can be operated at 10kV distribution network. This project was sponsored by Institute of Electrical Engineering, CAS, and supported by MOST, CAS, CPCC and Baiyi City Government. For this superconducting power substation, all of the superconducting equipments were demonstrated at substations or distribution systems from 2004-2008 before they are combined at Baiyin Industrial Park. The substation was integrated during 2010-2011, and has been operated since February 2011. A view of this superconducting power substation is shown in Figure 3.

The HTS power cable used in the substation consists of a three-phase warm-dielectric type, of which each cable is used for each phase. The conductor for the cable was made of Bi-2223 tapes manufactured by AMSC. The cable was designed and manufactured between 2001-2004, and was operated in the distribution network of the Changtong Power Cable Company (CPCC), serving for 5 factories of the company's headquarters during December 2004 and October 2005. After operating for more than 7,000 hours, no damage was found in the cable's conductor and insulation. Before it was moved to the substation, the termination and refrigeration system was then improved in order to reduce the heat losses.

The SFCL which is used in the substation employs 3

Fig. 3. 10kV superconducting power substation at Baiyin Industrial Park [3].

HTS coils in which each coil is used for a phase. The HTS coils consist of double pancakes made of Bi-2223 tapes supplied by AMSC, and the inductance of each coil is about 6.24 mH, the critical current of the coils are about 600A at 77K. The SFCL was developed from 2001 to 2005, and installed at Gaoxi Substation at the Loudi City of Hunan Province. A 3-phase-to-ground short-circuit test at the live grid shows that the potential fault current of 3.5 kA was reduced to 635A on the first peak. After that, the FCL operated in the live distribution grid for more than 11,000 hours during August 2005 and November 2006. During operation, single phase-to-ground fault occurred on three occasions, but the fault current was so low that the SFCL did not need to take any action. Before it was installed at the substation, a new cryostat was fabricated for the SFCL in order to reduce heat losses.

The superconducting transformer used in the substation comprises HTS windings and amorphous alloys, which in comparison with conventional transformers can reduce both the copper winding losses and iron core losses. After routine tests to comply with state standards, it was connected to the live distribution grid of the headquarters of the TBEA Group at Changji City. During November 2005 and January 2006, it served for the new energy factory of TBEA for more than 2 months without fault.

The SMES of this substation was designed and fabricated during December 2003 and December 2006. The superconducting coil for the SMES was fabricated with BSSCO tape (supplied by AMSC) and operated at 4.2K. The inductance of the coil is 6.28H, and the critical current of the coil is 564A. The coil is cooled by liquid helium and a zero-boiling-off system in which 4 G-M cryo-coolers with cooling power of 1.5W at 4.2K for each was used. The power conversion system of the SMES is voltage source type in which carrier phase shifting technology is used. The SMES was tested at Beijing Mentougou Substation during July 2007 and June 2008 before it was moved to the superconducting substation.

3.3. Superconducting fault current limiters (SFCLs)

During 2006-2012, saturated iron-core type FCLs have been developed by Innopower Company, and supported by MOST, Yunan Electric Power Company and Tianjin Electric Power Company. A 35kV/1.5kA FCL and a 220kV/0.8kA FCL have been developed and installed at the Puji Substation and Shigezhuang substation respectively [4, 5].

The 35kV/1.5kA FCL was installed at the Puji substation of Yunan Electric Power Company. Once installed, a series of field tests were carried out (in July 2009). In order to fully examine its performance, current-limiting tests were conducted under an artificially imposed three-phase to ground short-circuit. The live-grid experimental results show that it can reach the design expectations well. After installation and tests, it was then connected to the grid for live operation.

The 220kV/0.8kA FCL was installed at the Shigezhuang substation of Tianjing Electric Power Company. Installation of the device was completed in the first quarter of 2012. Acceptance tests on this device were then carried out by Tianjing Electric Power Company. The results showed that the SFCL was successfully restored to its functional capabilities. Live-grid operation of this FCL was then started since 2012 in order to test its performance and reliability.

3.4. Superconducting magnetic energy storage (SMES)

Since 2005, HTS SMES equipment with capacities of 1MJ/500kVA and of 35kJ/7kVA, and low temperature superconducting (LTS) SMES equipment made of NbTi with capacities of 500kJ/150KVA and of 100kJ/25kVA were successfully developed in China. These projects were supported by MOST, CAS and Beijing Electric Power Company [6-7].

For the 1MJ/500kVA SMES operated at the superconducting power substation, it has been descript above. For the 500kJ/150kVA low temperature superconducting (LTS) SMES, it consists of an NbTi magnet of 500kJ, an IGBT current source converter of 150 KVA and three phase-shift inductors. A pair of double-spiral current leads of Bi-2223 tapes was designed for the magnet. Experiments were carried out to test the compensation performances for both balanced and unbalanced voltage sags with a 110 kW load of resistance. The results demonstrate that the load voltage recovers in less than one cycle (20 ms) whenever a three-phase or single-phase voltage sag occurs.

For the 35kJ/7kVA HTS SMES, it was developed for dynamic simulation research at Huazhong University of Science and Technology in 2005. In the dynamic simulation experiment, a three-phase short-circuit of 350ms was simulated on the transmission line near the generator. During the test, the SMES automatically detects the fault and compensates for the imbalance of power by reducing the oscillation in the simulated power system. The tests show that the SMES can dampen the power oscillation effectively. The SMES also can supply a fast power support to the AC power system during the fault, which enhances the dynamic stability of the AC power system. After the dynamic simulation experiments, a field test was also conducted on the SMES. The field test was carried out at Laohukou Hydropower Plant in Zigui City. The results show that the mobile SMES system can operate on the power network at different locations and effectively suppress the power fluctuation of the generator terminal.

4. SUMMARY

In last decade, the R&D for HTS tapes, superconducting cables, superconducting power transformer, SFCL and SMES have been achieved significant progresses, and all the superconducting equipments for power grid have been successfully operated at live grid for demonstration. Besides, the world's first superconducting power substation has been successfully integrated and operated for demonstration. In the future, with the development of renewable energy, the HTS for power would be further developed in China.

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