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Future prospects of high T_c superconductors-coated conductors and their applications

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ABSTRACT

The research and development of high-temperature superconducting wires, especially yttrium-based coated conductors (CCs), and their energy applications have been expected to reduce CO_2 emissions. This article reviews recent progress in this area, mainly focusing on the results obtained by national projects in Japan. The I_c (critical current) × L (wire length) value of CCs has been improved to reach 466,752 A m (572 A/cm-W, 816 m), which exceeds that of Bi-system wires. CCs have also been improved in terms of in-field performance and AC loss reduction to meet market requirements. Power applications such as superconducting magnetic energy storage (SMES) systems, power cables and transformers have been developed using CCs in the current project. Because of fundamental research on high-capacity power cables, a low AC loss of 0.8 W/m-ph at 3 kA and 73.7 K was achieved. System design and fundamental research were performed on a 2GJ-class SMES system and a 20 MVA-class transformer. Based on the technologies developed by the end of the current project (FY2012), the innovation process of those applications will reach the implementation stage, where the long-term reliability tests will be performed. The process is expected to reach the penetration and propagation stage around 2020.

1. Introduction

It has been 100 years since the superconducting phenomenon was discovered in mercury by Heike Kamerlingh Onnes in the Netherlands in 1911 [1]. The year 2011 marks the 25th anniversary of the discovery of high-temperature superconductors (HTSs). In the last 10 years, the focus of research and development has shifted to applied research of HTS wires and tapes, which will have a great impact on industries and our society.

There are high expectations for yttrium-based HTS-coated conductors (CCs) in electric power applications because of their ability to help stabilize and increase the capacity of the electric power supply grid as well as to reduce CO_2 emissions because of their high critical-current characteristics. Many efforts have been made worldwide to improve the superconducting properties of CCs and to develop electric power devices. In this article, research and development results ranging from the exploration of CC to energy applications such as superconducting magnetic energy storage (SMES) systems, power cables, transformers, motors and wind power generators are reviewed, and future prospects are also discussed.

2. Progress of tape/wire developments

Since the discovery of oxide superconductors in 1986 [2], a suite of copper-oxide material systems with high-temperature superconducting properties have emerged, including the yttrium-based system (YBCO) [3], the bismuth-based system (BSCCO) [4], the thallium-based system (TBCCO) [5] and the mercury-based system (HgBCCO) [6], all with superconducting critical temperatures exceeding the boiling point of liquid nitrogen (77 K). Efforts to produce superconductors operating at even higher temperatures reached a state of extreme excitement all over the world. For the fabrication of CCs, research and development has led to progress in the understanding of YBCO characteristics and to the development of processing technologies to realize high in-plane grain alignment, such as IBAD (ion beam assisted deposition), RABiTS (rolling-assisted biaxially textured substrates) and ISD (inclined substrate deposition). The research results demonstrated that the weak inter-grain linkage could be overcome using these high-grain alignment technologies. Using the benchmarking characteristics of critical current (I_c) and length of the conductor (L), Fig. 1 illustrates the progress of development in BSCCO and YBCO superconducting wires/tapes after the discovery of HTS materials. A rapid advance in the development and understanding of BSCCO silver-sheath superconducting wires occurred; however, rapid advances in CCs have recently overtaken those of the BSCCO materials. Fujikura Ltd. in

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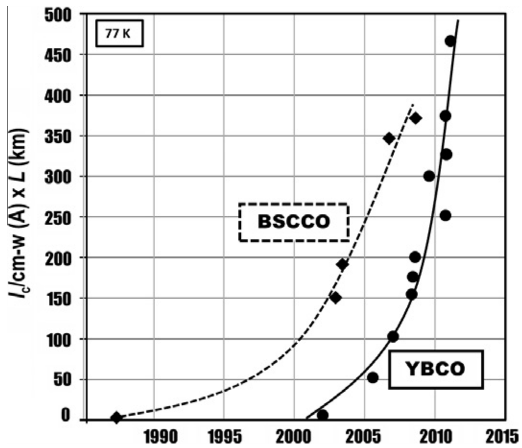

Fig. 1. Progress of development of BSCCO and YBCO superconducting wires/tapes.

Japan has recently reported the highest ever product value of $I_c \times L$, exceeding 400 kAm (572 A $\times$ 816 m) [7] using the PLD (pulsed laser deposition) and IBAD processes.

With a target of producing CCs that could be used for electric power devices in the future penetration and propagation stage by FY 2012, the research and development of CCs has been performed in the areas of I_c vs. magnetic flux density (I_c–B) improvement, AC loss reduction and cost reduction. Uniformity is also required for many applications. Recently, a long CC with reasonable uniformity (1.35%) was fabricated, indicating that CCs are approaching the level required to fabricate commercial-level power devices.

An effective approach to improve the in-field performance of CCs is the introduction of artificial pinning centers (APCs). $BaHfO_3$ (BHO) was observed to function as a much more effective APC than $BaZrO_3$ (BZO) in PLD-derived CCs [8]. The introduced BHO forms fine nanorods similarly to the BZO and the BHO-doped CCs exhibited less anisotropy in their in-field performance. Moreover, they exhibited a linear thickness dependence of their in-field I_c up to 2.9 μm in thickness, resulting in 85 A/cm-W at 77 K and 3 T as demonstrated in Fig. 2 [8]. The thick film exhibits high characteristics for a variety of temperature and magnetic fields: 300 A/cm-W at 65 K and 3 T, 204 A/cm-W at 65 K and 5 T and 700 A/cm-W at 20 K and 17 T [8]. These results suggest that in-field applications could be possible at liquid nitrogen temperatures.

AC loss reduction is another serious issue for most practical AC applications. Filamentation is an effective approach to reduce AC loss, requiring high uniformity. A 5-mm-wide CC was scribed into five filaments, and the AC loss was confirmed to decrease to approximately one-fifth for both MOD-and PLD-processed CCs, even in coil forms. Another approach to achieve AC loss reduction proposed in 2010, the "Iwakuma effect", was observed in CCs [9]. Fig. 3 plots the observed magnetization loops of the GdBCO tapes with BZO artificial pinning centers at 35 K in a DC bias magnetic field of 2 T (broken lines), 3 T (solid lines) and 4 T (chained lines). The thin and thick lines correspond to the cases of 45° and 15° for the applied magnetic field angle against the tape face. We observe that the magnetization loops for the 15° angle were deformed such that the enclosed areas became small, which corresponded to a drastic decrease of the pinning loss. Note that although the hysteresis loop area was smaller, the measured transport J_c was higher than 3 MA/cm^2 [10]. This new phenomenon is unique to CCs, and the high in-plane grain alignment of REBCO results in this phenomenon.

3. Development of yttrium-based superconducting power devices in Japan

The Materials and Power Applications of Coated Conductors (M-PACC) Project is a 5 year national project in Japan that began in 2008 and that is supported by the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO). The goals of the M-PACC Project are to develop CCs that meet market requirements for next-generation superconducting electric power devices using CCs, including SMES, cables and transformers, and to establish important component technologies for realizing such devices. These technologies are divided into the categories of transmission technology, electric power system control technology, and energy storage technology in the energy field which is one of the four fields promoted in the "Third Science and Technology Basic Plan" made by the Japanese government. These technologies are also listed under the development of equipment in energy and electric power systems in the "Superconductivity Technology Strategy Map 2010" edited and published by METI and NEDO. In this section, the research and development results and future plans of the M-PACC project are reviewed.

3.1. Superconducting cable

Fig. 4 presents the annual progression of the transmission losses of power equipment in Japan [11]. Over the past 30 years,

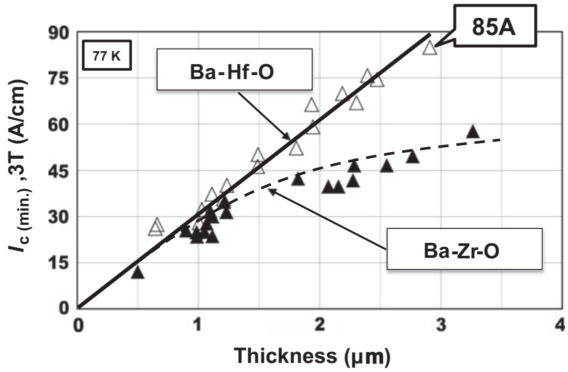

Fig. 2. Critical current (in field) as a function of the thickness of the superconducting layer upon introduction of new artificial pinning centers of $BaHfO_3$ in comparison with those of $BaZrO_3$.

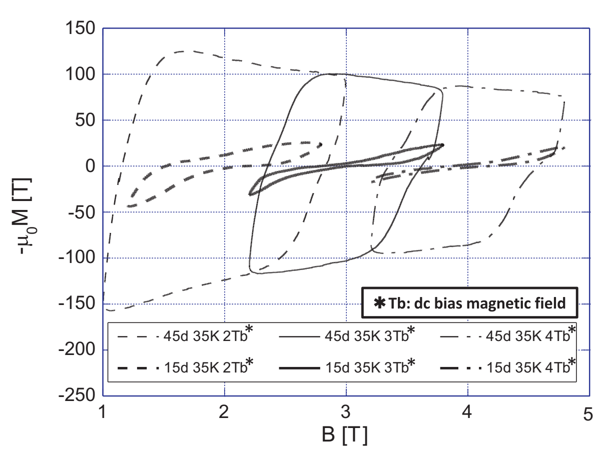

Fig. 3. Magnetization loops of the GdBCO tapes with BZO artificial pinning centers at 35 K in DC bias magnetic field of 2 T (broken lines), 3 T (solid lines) and 4 T (chained lines). The thin and thick lines correspond to the cases of 45° and 15°, respectively, in an applied magnetic field angle against the tape face.

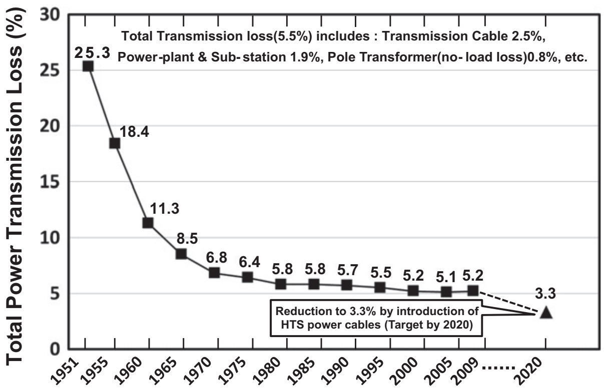

Fig. 4. Annual progression of the transmission losses encountered by power equipment in Japan.

approximately 5% of the total annual volume of electricity generated has been lost due to transmission and distribution losses in Japan, which is considered to be at a saturation point. The losses can be categorized as follows: 2.5% stems from the transmission lines, 1.9% stems from the power plants and the transformer substations, and 0.8% originates from no-load losses (iron losses) in pole transformers [11]. The saturated transmission losses would be expected to be reduced using innovative superconducting technologies because superconducting conductors have no Joule-losses caused by electrical resistance. The lower AC loss significantly reduces transmission losses and evades any cryocooling penalties.

A yttrium-based superconducting cable could reduce conventional underground transmission cable losses to 1/3 and contribute to energy savings and a significant reduction in CO_2 emissions. Additionally, compact power transmission cables would make use of the large current-carrying capabilities of superconducting power to prevent overloading local power grids, as well as possibly simplifying power grids by replacing the existing 154 kV circuit with a 66-kV high-current transmission circuit.

In Japan, cable technology development has aimed at larger current capabilities and low AC losses. The reduction of AC losses has involved the structural design of "four-layer superconducting tapes and two-layer superconducting shield tapes," which are tested using short current tests and joint tests. These designs have resulted in a total cable loss of 1.8 W/m/phase at 5 kA and 63.8 K for the four-layer conductors and shield layers, as demonstrated in Fig. 5 [12]. The development of high-voltage and low-dielectric-loss cable technology has yielded positive results in successfully reducing cable loss down to 0.8 W/m-phase at 3 kA and 73.7 K (AC loss = 0.2 W, dielectric loss = 0.6 W) [12]. This result is a significantly reduced AC loss compared with the BSCCO cables being investigated to achieve 1 W/m-phase at 2 kA in a 66 kV system [13]. A CC carries current in a smaller region compared with BSCCO, therefore enabling drastic reductions in AC loss. The aforementioned tests also confirmed that the joints made between strands at the midpoint of the superconducting cable have yielded a low electrical resistance of several nΩ. The voltage impression tests indicated that no abnormalities were present in the cables or the joints.

3.2. Superconducting transformer

Several advantages are present in developing transformers with CCs: an efficiency improvement compared with conventional type oil-filled transformers, compactness, lightweightness, the requirement of less installation space and non-flammability. Because CCs have superior critical current densities at high temperatures and in magnetic fields, maintaining their insulating characteristics is possible by using liquid nitrogen as a coolant. In cables, measures to reduce AC loss are different from the transformer case, where the AC loss is attributed to fluctuations in magnetic fluxes. These losses result from the coil shape and mainly from the loss caused by the fluctuations in the magnetic fluxes applied perpendicular to the surface of the tapes. Thus, a filament with no electrical coupling is an effective measure to reduce the fluctuation-width (moving distance), which has been recently accomplished as described in Section 2.

In Japan, current developments for a superconducting transformer utilizing CCs involve a prototype 400 kVA transformer, which is undergoing short-circuit evaluation trials. The trials confirmed the superior characteristics of the transformer at six times the rated value and its positive current carrying characteristics at 2 kA, revealing no deterioration in the tape windings and no abnormalities before or after the short circuit tests. The investigations were performed by designing a 66 kV/6.9 kV-2 MVA-class model and a cooling system study, resulting in the system design of a 66 kV/6.9 kV-20 MVA-class transformer utilized for a distribution system. Fig. 6 presents the result of a fault current limiting test in which a small-type tape-winding model coil successfully

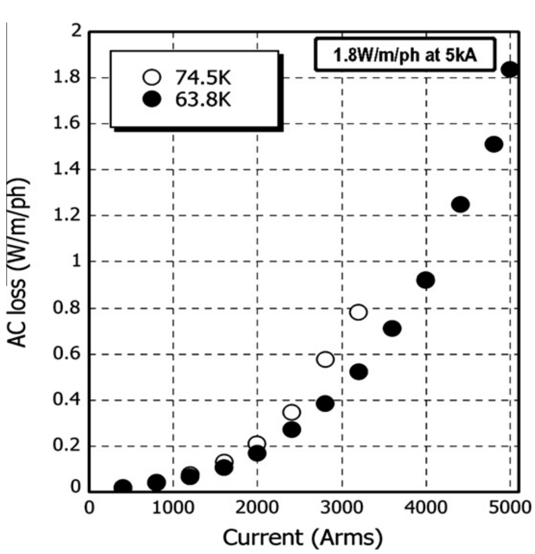

Fig. 5. AC loss in cable conductor (66 kV–5 kA) measured at 74.5 K and 63.8 K.

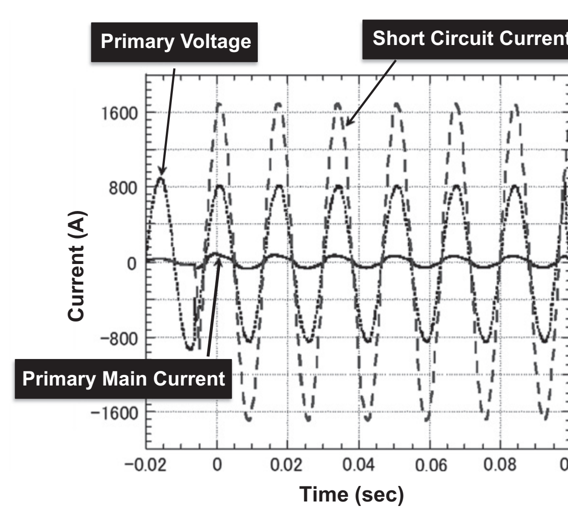

Fig. 6. The results of fault current limiting test in the superconducting transformer. A short-circuit current of 1200 A was reduced to 43 A in the small-type tape-winding model coil.

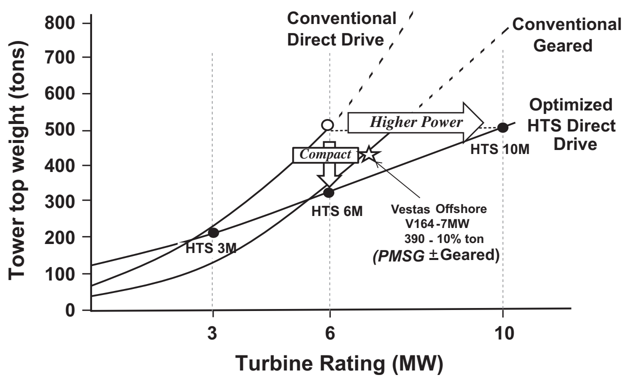

Fig. 7. Effect of HTS wind power generator.

reduced a 1200-A fault current to 43 A of the primary main current, corresponding to 1/30 of the fault-current-limiting efficiency [14]. A short circuit event results in the flow of a large current, and by taking advantage of the phase transition phenomenon of a superconductor in transitioning from the superconducting state to the normal conducting state, the small-type wire-winding model successfully managed such an event by limiting the current supplied to the coils. Since conventional transformers do not limit the inrush current, the fault current limiting function is another advantage of the superconducting transformers.

3.3. Superconducting magnetic energy storage (SMES)

SMES system developments must be adapted to power grid control technology. In Japan, research has led to technological development in the fabrication of a high-magnetic field and a compact coil; in addition, with coil conduction cooling technology offering easier maintenance, the development of highly reliable components with excellent tolerances has followed, which is essential for the coils of SMES systems. The current aims are focused on the development of 2 GJ-class SMES.

To date, the largest-scale SMES system was rated at 20 MJ and employed NbTi-based wires. Although the US (3.4 MJ) and Korea (2.5 MJ) have also started to develop SMES systems utilizing CCs, the scale of Japan's development of a 2 GJ-class SMES outshines them. Several component coils for the 2 GJ-class SMES have already been fabricated; in addition, tolerance tests that carry the large current were performed, and hoop stresses (BJR calculated from the magnetic field B, current density J, and radius R) were evaluated during operations. The results revealed hoop stresses exceeding 600 MPa for a multilayered coil, with a current capacity large enough to exceed 2.6 kA for a 4-bundle conducting coil [15].

4. Applications for rotating machinery (motors and wind power generators)

CCs have strong critical current characteristics at high magnetic fields. Therefore, further developments for devices for various applications are greatly anticipated. Europe and the US have both witnessed substantial development activity for electric motors employing high-temperature oxide-based superconducting wires/tapes. In Japan, this activity has primarily focused on the development of ship-propulsion motors that utilize BSCCO wires. Additionally, activities to replace permanent magnet (PM) rotors in synchronous electric motors with CC-derived electromagnets are ongoing and are largely aimed at reducing the consumption volume of rare-earth elements used in PM, such as Nd and Dy. The

Table 1
Roadmap for the realization of electric power applications.

Device	2008 - 2010	2011 - 2012	2013 - 2020	2020~
	M-PACC Project		*Implementation stage*	
SMES	•SMES coil construction technology Hoop stress≧600MPa, Current≧2kA •Effective conduction cooling technology 20∼40 K area, Electrical Insulation≧2 kV •Optimization of the base system for 2GJ class SMES coil	◎High reliability and durability SMES coil technology Same performance as 20,000 times repetitive charging/discharging@20K (conduction cooling)	Total evaluation of the performance and cost etc. Comparison with other technology ↓ Discussion of target grid and field test site	**Penetration & Propagation Stage**
Cable	○Large current (LC cable) •AC loss reduction <2W/m@5kA •Fault current test : 31.5kA-2sec •5kA transport test ○High voltage (HV cable) •Loss(AC•dielectric)<0.8W/m@3kA •Fault current test：63kA-0.6sec •275kV voltage test •Selection of insulation materials: (polypropylene laminated paper)	◎Fabrication and verification tests ○LC cable •System：66kV/5kA,15m •Loss：2.1W/m@5kA •Diameter <150mmf ○HV cable •System：275kV/3kA,30m •Loss：0.8W/m@3kA •Diameter：150mmf	Field tests of 150-500m long cable at a substation etc. (Long term reliability verification test)	
Trans-former	•Withstanding short circuit current 20MVA class Tr.(%Z=15%) •Verification of FCL function •High efficiency & compact cooling system (Brayton cycle) turbo-compressor & expansion turbine efficiency ≧65% •2MVA Tr.-model design	◎Fabrication and verification tests 2MVA class Tr. • Loss reduction ≦1/3 • Current limiting function (≦rated current ✕3) • Refrigeration power : 2kW@65K COP≧0.06@80K	Field tests of 20MVA Tr. at hydroelectric power Plant etc. (Long term reliability verification test)	

development of industrial electric motors exceeding 1000 rpm and ship propulsion motors capable of 100–300 rpm are likely to contribute energy savings effects in the future, and further development is anticipated. Moreover, the development of wind turbine generators (several 10's of rpm) for sources of renewable energy and the reduction of CO_2 emissions are currently being advanced in Europe and the US. The use of CCs is expected to result in more compact, lightweight and high-capacity generators, as demonstrated in Fig. 7. In particular, further weight reduction of the wind turbine nacelle has been instrumental in the realization of a large-scale wind turbine generator (>3 GW) and in promoting the introduction of offshore wind turbine generators into the mainstream. Therefore, development efforts have focused on at least replacing the field winding coils with Y-based superconducting electromagnets to improve efficiencies and reduce weight.

5. Future prospects of CC applications

Three years have passed since the M-PACC Project began. In this section, we review the prospects of the M-PACC Project for the next 2 years as well as after the M-PACC Project in terms of the development of superconducting power systems and superconducting CCs. For the next 2 years, we will not only reach the final targets as early as possible but will also prepare for future tasks. These tasks include the development of superconducting power systems and superconducting CCs at the implementation stage after the M-PACC Project to demonstrate the long-term reliability and the penetration and propagation stage after approximately 2020, as presented in Table 1. The production capacity of CCs that satisfy the requirements in specifications and cost must be sufficient. The production capacity of superconducting CCs has to be scaled up according to the demands at each stage described above.

In the first 3 years of the M-PACC Project, in FY 2008–2010, CC technologies necessary for the implementation stage were developed. Stable mass production of CCs will be established in the next 2 years, in FY 2011–2012, mainly by CC manufacturers. CCs of higher specifications will simultaneously be developed for the penetration and propagation stage, including ultra-high $I_c(-B)$ (e.g., >2000 A/cm-W at 77 K, s.f., 500 A/cm-W at 65 K, 5 T) and ultra-low AC loss specifications due to a low lord factor and the Iwakuma effect. Several breakthroughs are desired to realize such high specifications. Stable production technologies and the expansion of the production capacity of high-performance CCs will be established at the implementation stage by CC manufacturers, which will lead to the commercial production of practical superconducting power systems and CCs.

6. Conclusions

Superconductor technology holds the key to realizing the benefits of greater device efficiencies and system compactness, which will result in technologies that remarkably lead the way to solving environmental issues such as the reduction of CO_2 emissions and energy savings.

The research and development results of the 5 year M-PACC Project and of rotating machinery, including motors and wind power generators, were reviewed and their future prospects were discussed. The M-PACC project, which focuses on CCs, transmission cables, transformers, and SMES systems, together with preliminary work on rotating machinery were explained in terms of their necessity and their current status. The M-PACC Project should achieve its final targets by the end of FY 2012 with effective collaboration with other national projects and/or institutions. These efforts will lead to the establishment of stable mass production of Y-based superconducting CCs and the widespread implementation of superconducting electric power systems in the near future.

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