High Temperature Superconductivity: Past, Present and Future

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In 2011, we will celebrate the centennial anniversary of the discovery of superconductivity. The past, present and future perspective based on 24 years' of our activity for high temperature superconductivity (HTS) will be summarized. The superconductivity is deeply related with our social infrastructure, health and everyday life, and it is important to pursue sustained R&D activity.

Keywords: superconductor, superconductivity, cable, motor, magnet, wire

1. Introduction

The superconductivity was discovered in 1911. In the same year, Sumitomo Electric Wire & Cable Works was established (Foundation was in 1897 as Sumitomo Copper Rolling Works), and laid the first Japan-made high-voltage underground cables. In 2011, we will celebrate the centennial anniversary of the discovery of superconductivity, and a high-temperature superconducting (HTS) power cable will be energized at the Asahi Substation of Tokyo Electric Power Company connecting with their power grid for the first time in Japan. The above mentioned HTS cable demonstration project (so called as Yokohama Project) has been supported by Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology Development Organization (NEDO) since 2007. In 1986, high-temperature superconductivity was discovered. The past, present and future perspective based on 24 years' activity of high temperature superconductivity will be summarized.

2. Progress of 24 Years' HTS Wires

We started to develop a bismuth-based HTS wires just after Dr. H. Maeda of National Institute of Materials Science (NIMS) discovered the bismuth-based (Bi-Sr-Ca-Cu-O) HTS material in January 1988. In one year before of Dr. Maeda's discovery, Dr. P. Chu in U.S.A. discovered the yttrium-based (Y-Ba-Cu-O) HTS material and many people started to develop HTS wires using this material.

The bismuth-based HTS wires can be processed using plastic deformation processing technology used in copper wire production and their cross-sectional configurations are same ones during processing. We can call this feature as "Kintarou-ame" (Japanese classical candy) due to their unchanged configuration. In 2004, the industrial materialization of these wires was achieved and then system development stage was pursued.

Contrary to above, the yttrium-based HTS wires can be processed through multi-layers thin film deposition and we can call this feature as "mille-feuille" (French sweets) due to their forms made up of several layers. These HTS wires can be processed using semiconductor fabrication technology of thin film deposition. We should consider "Yield" for every processing step due to a new structure after each step. For industrial materialization of yttrium-based HTS wires, it would be essential to control every step with online monitoring and diagnostics.

The history of the bismuth-based HTS wires can be classified to five period.

(1) Period I (1988 - 1990): the Dawn – seeking concept of wire structure with short sample to several meters length wire
(2) Period II (1991 - 1995): the Growth – processing technology development for 1,000 meters length wire (project of Japan Science and Technology Agency (JST))
(3) Period III (1996 - 1998): the Stagnation – difficult time due to little improvement and yield issue for long length wire
(4) Period IV (1999 - 2003): the Incubation – also difficult time but expect jump through collaboration with academia
(5) Period V (2004 - present): the Advance – breakthrough with newly developed processing technology and collaboration with academia. Time to achieve improved performance, cost reduction and application system development.

2-1 Period I (1988 - 1990): the Dawn

We did repeated many trial & errors with different ideas. Improved critical currents could be achieved with two-step sintering process which was discovered at the early stage of the development. Also, understanding of phase transformation could lead to improve critical currents. Dr. T. Nakahara, the Vice President at that time, taught us that research on materials should pursue to get the ultimate performance of targeted material. It could be considered that it is important to pursue where is Mt. Fuji (what is ultimate performance), not to pursue how to climb it. There are many routes to climb the mountain. It was the big decision for me, manager on the duty at that time, to focus to develop multi-filamentary wires after acknowledging the flexibility performance of these wires, nevertheless single filamentary wire had a better performance in critical currents at that time. That decision turned out to be the right solution due to the fact that we achieved longer length wire and better yield with multi-filamentary wires.

2-2 Period II (1991 - 1995): the Growth

In this period, it was pursued to develop processing technology to obtain 1,000 m long length wire with some 10 M$ loan without interests from JST. It was necessary to develop equipment and components including software with our original ideas. The collaboration program with Tokyo Electric Power Company was started to develop HTS cable conductor in 1991. This collaboration was linked to today's HTS cable demonstration project (Yokohama Project). It was delighted that young researchers we welcomed at these time zone have grown to responsible players today.

2-3 Period III (1996 - 1998): the Stagnation & Period IV (1999 - 2003): the Incubation

These two periods were difficult ones that the results could not be combined with our efforts. In 1999, the idea of over-pressure sintering technique was born and it needed 5 years to realize this technology due to many difficulties of world-first technique. The lesson we learned was that our endeavor under right principles could be rewarded.

Our collaboration with academia to achieve improvements of critical currents was pursued. It was very lucky for us to meet with many excellent researchers from younger to elders. Their ideas were different ones from ours, and these were good lessons for us. It is also very much appreciated at present such collaboration with academia.

2-4 Period V (2004 - present): the Advance

The over-pressure sintering technique was adopted satisfactorily. At the beginning, this technique was aimed to produce robust superconducting wires, but results surpassed our expectations. The great improvements of critical currents and mechanical strength were achieved. Also, the properties of long length superconducting wires were improved greatly with systematic results which enabled further improvements at present.

With the collaboration with academia, critical temperature of the bismuth-based superconducting wires were improved up to 117.8K[(1),(2)] which was the highest critical temperature. The systematic results on electromagnetic and mechanical properties were obtained[(3)-(5)] which enabled proper steps for further improvements.

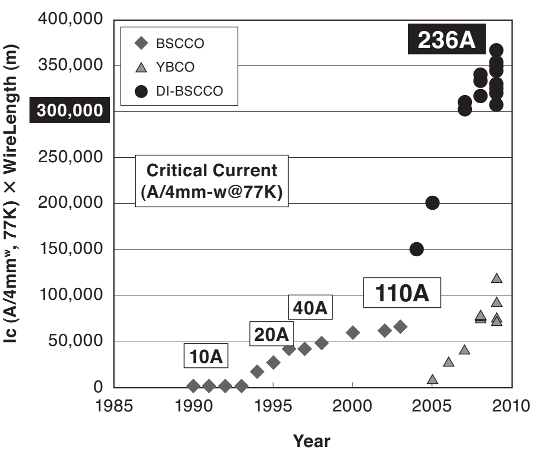

Fig. 1. 24 years progress of HTS wires

Figure 1 shows the 24 years progress of high-temperature superconducting wires. A unit length of DI-BSCCO was over 2,000 m and performance figure (which is product of critical current by wire unit length) was over 300,000Am at mass production result. The figure of 300,000Am is considered to be the industrial requirement. Critical currents were also improved based on fundamental research showing the champion value of 236 A at 77K in November 2009.

2-5 Present status of properties for application

It is important to use critical current value (A), and not critical current density (A/cm^2) when comparing the properties of HTS wires. The critical current is the absolute value of superconducting current, and the critical current density is the relative value per unit area. We use critical currents when designing application. **Figure 2 and 3** show critical currents of the long length HTS wires when we will design cable application and magnet application. It can be seen that DI-BSCCO has excellent magnetic field dependence of critical currents. Furthermore, DI-BSCCO has a critical temperature of 112K, compared with 90K of the yttrium-based wires. DI-BSCCO has stable operation margin when we consider temperature fluctuation of long length cable operation. For example, at 90K DI-BSCCO keeps a half of critical current of 77K, which enables stable operation with local temperature rise.

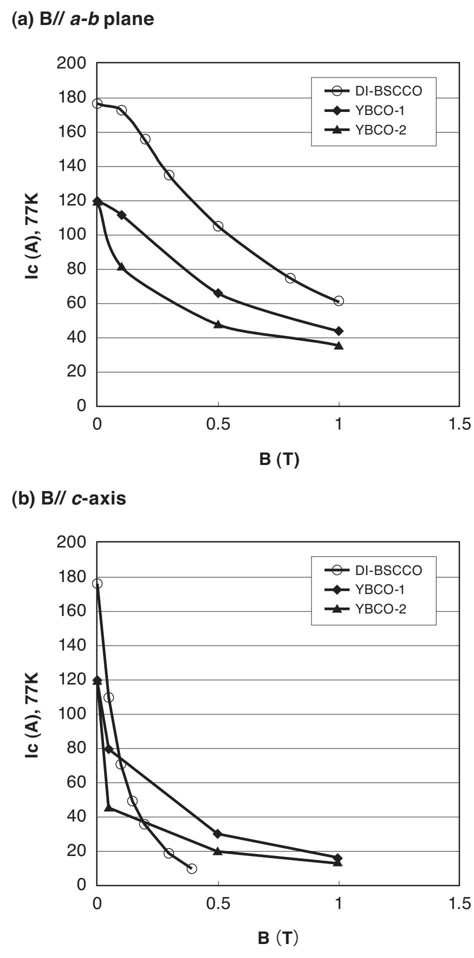

Fig. 2. Magnetic field dependence of critical currents of long length HTS wires (77K) (a: B// *a-b* plane, b: B// *c*-axis)

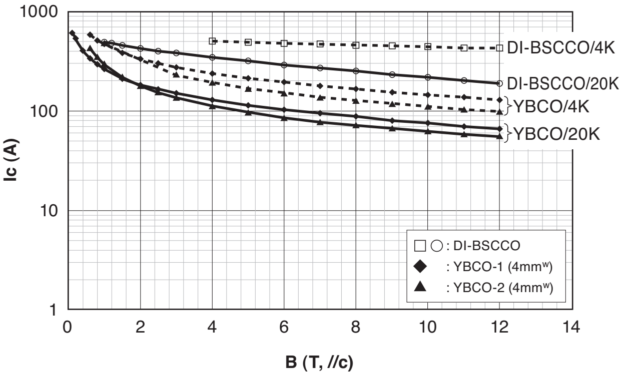

Fig. 3. Magnetic field dependence of critical currents of long length HTS wires (4K, 20K, B//*c*-axis)

It is wrongly understood that the bismuth-based HTS wires are vulnerable to magnetic fields of critical currents, which is generally shown using critical current densities (A/cm^2). The superconducting areas of the bismuth-based HTS wires (0.4 mm^2) and the yttrium-based HTS wires (0.004 mm^2) differ by two orders of magnitude. Thus, it is properly needed to compare with critical currents (A). When we design application, we use critical current not critical current density. It is needed to improve the critical current of DI-BSCCO against parallel magnetic field to *c*-axis of 0.5 Tesla or more at around 77K.

3. 24 Years Progress of Application

The HTS wires are based on oxide ceramics, and at the beginning of development the critical current was below 1 A, and no one was confident that long length wires could be available with these brittle oxide materials.

Figure 4 shows application "toys" made at around 1990, when multi-filamentary HTS wires could be tolerable against repeated bending. All these three "toys" were handy-sized ones, showing future usable application.

At present, real-sized prototypes, such as several MW ship propulsion motors, HTS electric cars, power cables connected with existing power grid, Maglev trains, MRI magnets and NMR magnets, are now developed and under evaluation.

Figure 5 shows one example of progress of application, i.e. cable development. The collaboration with Tokyo Electric Power Company started in 1991 for cable development. The initial cable conductor development was followed by 7 m cable model, long length cable, electrical insulation, terminations, and world-first HTS cable verification program of 66 kV, 1 kA and 100 m length after 10 years development.

The target of HTS cable development was to replace underground copper cable of main transmission lines. The underground transmission cable was already laid up to 21,000 km-circuit in Japan as shown in **Table 1**, and 50 % of these underground transmission cables in Tokyo area.

The Japanese gross electricity demand is about 10^{12} kWh per year and loss in transmission and distribution is

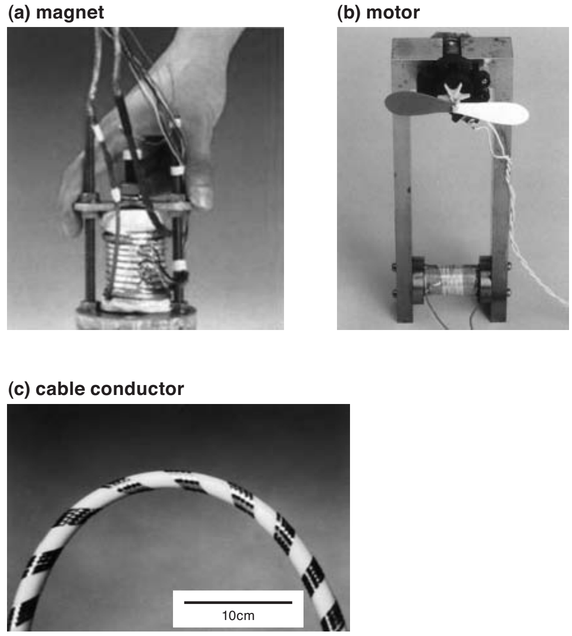

Fig. 4. Handy-sized HTS "toys" in 1990

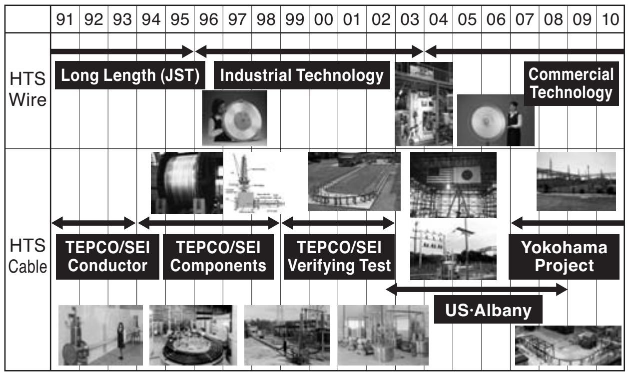

Fig. 5. Progress of cable development

Table 1. Transmission and distribution cables in Japan

Distribution	Overhead	3,948,159 km
	Underground	67,683 km
Transmission	Overhead	146,241 km
	Underground	21,011 km

about 5 % as shown in **Fig. 6**, resulting 5×10^{10} kWh losses per year due to ohmic losses by copper and aluminum conductors. Also, **Fig. 6** shows the technical limit exists in traditional conductors. HTS cables can reduce ohmic losses and total construction costs with reduced cable size laying HTS cable into existing standard compact ducts (15 cm diameter), and not into large size tunnels (3 m diameter).

It took about 10 years to conduct applied basic research, components technology development and prototype test in the case of HTS cable. Recently, "Strategic Promotion of Innovative Research and Development" (SPIRE) program in Japan Science and Technology Agency launched. In this program, the Japanese Government could fund for 10 years seamlessly to applied basic research, components technology development and application model. It will be greatly useful for researchers to settle down their R&D and not be twisted around a short time target.

It sounds natural to spotlight superconducting components in superconducting related projects. Nevertheless, non-superconducting components often become keys to actual implementation. We should consider developing a series of technology collectively including peripherals and software.

For an example, let us consider the efficiency of refrigerators for HTS equipment operated around 77K. **Figure 7** shows the actual efficiency (%Carnot). At present, the actual efficiency is about 30 % at the most. This means the COP (coefficient of performance) is about 0.1. It will need 10 times energy at room temperature than cooling energy at 77K, showing the subject to achieve economic advantages. Further important issues are longer time interval before maintenance and cost down of refrigerator. It will need sustained R&D efforts.

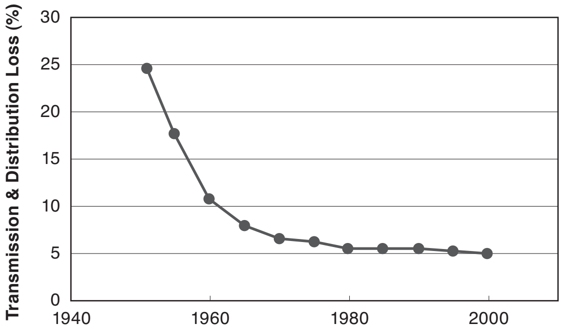

Fig. 6. Transmission and distribution loss
(Data from The Federation of Electric Power Companies of Japan)

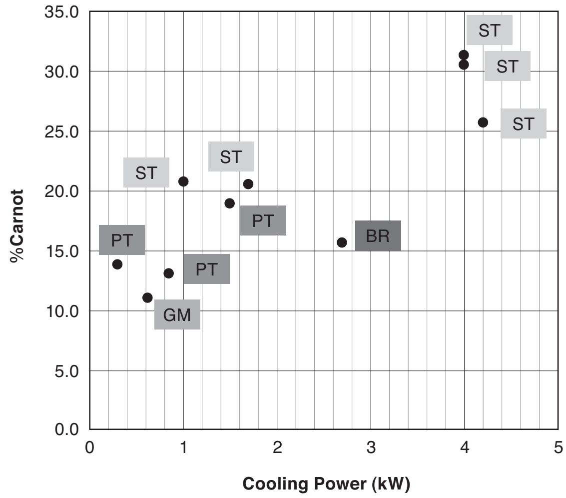

Fig. 7. Efficiency of refrigerators for HTS equipment
(ST: Stirling, PT: Pulse Tube, BR: Brayton, GM: Gifford-McMahon)

4. Future Perspective of HTS Wires and Application

The past and present status of HTS wires and their application were reviewed in the previous chapter. The HTS real-sized system developments were started after HTS wire industrialization in 2004. Hereafter, it will need to promote the practical use of these real-sized systems and enhance the variety of application products. Also, it is indispensable to pioneer the frontier of HTS application toward green energy and save energy technology.

4-1 Future perspective of HTS wire

The HTS wire is the basis for enlargement and acceleration of implementation of a variety of HTS application, and it is essential for HTS wires to show their potential performance. The material researchers should pursue the ultimate performance of their targeted material. At present, the critical current of the bismuth-based HTS wire is 200 A reaching 20 times or more than those at 20 years ago, but still there is a large room for improvements because their potential critical current is in the range of 1,000 A to 2,000 A.

The present bismuth-based HTS wires were studied with the hall probe scanning microscope, and the critical current density of the center area (80,000～90,000 A/cm^2) was nearly twice than that of the average of whole wire area[7]. So, it can be anticipated that a large improvement of critical current could be achieved with precise micro-structure control.

The HTS wire is evaluated with the value of Yen/Am (cost to carry 1 A over 1 m) from the point of cost performance. A part of Yen/m can be improved with mass production effect and production technique, and a part of Yen/A can be improved with critical current improvement. These two multiplier effects can improve cost performance jointly. The improvement of critical current is greatly correlated with complex solid chemical reaction control of this material which is composed of five cations and one anion. The other correlated factors are alignment of crystals, critical temperature and grain boundary analysis and their control. The grain boundary analysis is very hard to do, and the recent advanced analytical equipment, such as SPring-8, a strong synchrotron radiation source, and J-PARC, a strong neutron source, is a key for difficult analysis.

4-2 Future perspective of HTS application

The HTS application is now on going in the following five areas;

(1) world-wide energy and ecology technology (power cables, generators, transformers and fault current limiters)
(2) transportation technology (ship propulsion motor, superconducting electric cars, Maglev)
(3) IT technology (DC current distribution in data center)
(4) production technology (single crystal pulling, magnetic separation and induction billet heaters)

(5) medical and bio-technology (MRI and NMR)

These five areas are deeply related with our social infrastructure, health and everyday life. The HTS wires can bring the features of save energy, compact, light weight, high performance and save resources, and could play a trump on forthcoming low-carbon society. One of the application areas is DC transmission and distribution. In AC current operated superconductor, there is a small hysteresis loss, but there is no such loss in DC current operation. Transmission and distribution system with almost no voltage drop could be realized with HTS DC system. At present, DC transmission and distribution system is used such as high voltage long length overhead transmission line, submarine cable, Back-to-back connection, frequency change station, trains and subways.

In 1880, Thomas Edison developed generator and initiated DC electricity distribution business. At that time, he used copper conductor to distribute electricity and he had a large voltage drop due to ohmic loss of RI^2, resulting that only 2 km was a limit of electricity distribution. This situation was a same in Kyoto, Japan at the Keage hydro generation site, which was a first commercial electricity generation in Japan. The HTS DC transmission and distribution power system can give us a low voltage and large current system which is not possible with traditional technology.

For example, electricity from a solar cell system (PV), a low voltage DC current, could be transmitted with low loss and long length HTS cables. Thus, we could share solar cell energy in world wide, resolving short-comings of non-uniformity (space and time) of renewable energy.

Figure 8 shows an image of new power grid with renewable energy and HTS cable. A controlled electricity distribution could be possible using batteries effectively. Batteries could be placed in electricity heavily demand area.

Table 2 shows the issues and countermeasures when renewable energy and HTS cable are combined.

Figure 9 shows the loss study in long distance PV power delivery with HV/DC overhead line and HTS/DC cable. The rate of operation of PV is small number, but recently 30% of rate of operation is reported. The maximum capacity of PV site in operation at present is 60 MW in Spain. Higher power PV sites from 80 MW to 600 MW are planned.

It is considered that HTS/DC cable transports PV power more efficiently for several tens MW level which is planned at present with improved better cable thermal insulation and more efficient refrigerators.

Similar application of HTS/DC cable is the power supply network for DC electric railways[(8)-(10)]. It was shown that introduction of HTS cable for the DC electric railway could reduce feeder losses, reduce number of substations and reduce invalidness rate of regeneration.

Other expecting applications are electric ship propulsion systems and electric vehicles equipped with HTS motors. These applications together with Maglev could make energy saving transportation systems and new modal shift.

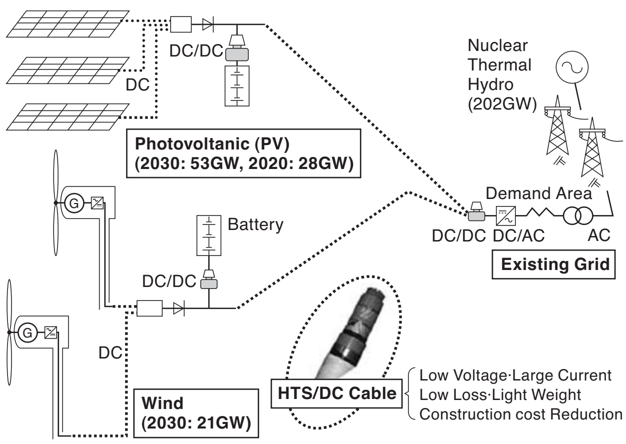

Fig. 8. New power grid with renewable energy and HTS cable

Table 2. Issues and countermeasures for new power grid

Issue	Countermeasure
• Weather dependence and low rate of operation	• Timely balance by joint use of plural energy source and batteries • Spatial and timely balance by connecting local size, country size and global size grid
• Necessity of cooling	• Improvement of refrigerator efficiency (%Carnot: present; 20-30%→future; 45%) • Improvement of cable thermal insulation (Reduction of thermal load to cryostat)
• New system concept	• System study for renewable energy and HTS cable combination • Technical study for DC current power grid system

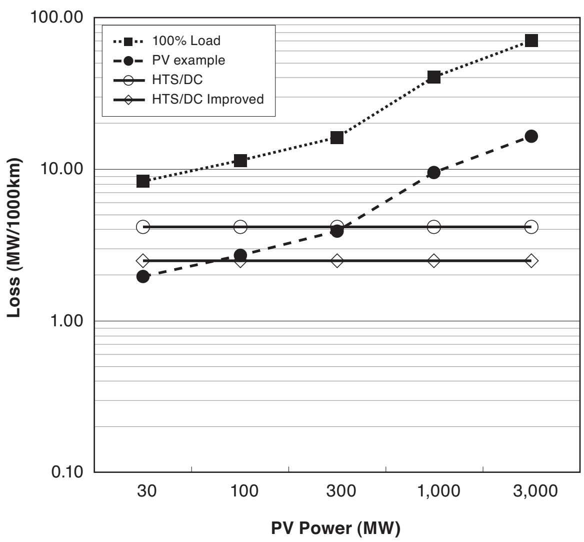

Fig. 9. Loss study of long distance PV power delivery with HV/DC overhead line and HTS cable
(100% load: HV/DC overhead line loss under 100% load,
PV example: HV/DC overhead line loss under 30% rate of operation of PV, HTS/DC: HTS/DC cable loss at present technology, HTS/DC improved: HTS/DC cable loss with near future technology)

5. Conclusion

It has passed 24 years since the discovery of high-temperature superconductivity and 99 years since the discovery of superconductivity. High-temperature superconducting technology has proceeded to demonstrate real-sized prototype systems. We need tenacious and sustained R&D efforts toward actual implementation. The author yells to young researchers who are challenging to these efforts and would also like to express hearty thanks to all who have involved.

* "DI-BSCCO" is a trademarks or registered trademarks of Sumitomo Electric Industries, Ltd.

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