Winter, 2009 Date of Issue: January 15, 2009

超電導 Web21
Superconductivity

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Starting a new project: Materials & Power Application of Coated Conductor (M-PACC)

Fundamental Superconducting Application Technologies (Phase II), aimed at developing yttrium-based (Y-based) wire, was completed in March 2008. Major technological advancements included using Fujikura Ltd.'s IBAD-PLD technique for wire fabrication process development to produce a 500 m-300 A/cm-width (@77 K, s.f.), which was the final objective of this project. For the past five years, the development of Y-based wire has rapidly progressed. At the outset, the wires were several tens of meters long and had a critical current I_c of 100 A/cm-width. The wires were lengthened and their I_c was increased through SWCC Showa Cable Systems Co., Ltd.'s MOD technique, Sumitomo Electric Industries, Ltd.'s RABiTS/PLD technique, and Chubu Electric Power Co., Inc.'s MOCVD technique, as well as Fujikura Ltd.'s IBAD-PLD technique. As a result, these companies have achieved a 200-300 A/cm-width at a wire length of approximately 200 m to 500 m, a major breakthrough in wire fabrication technology. In response, the Materials & Power Application of Coated Conductor (M-PACC) Project started in June 2008 under the business-academia collaboration shown in Fig.1. The new project will be carried out for five years from fiscal 2008 through 2012. Contracts between NEDO and the individual companies will be concluded for the first three years of this project.

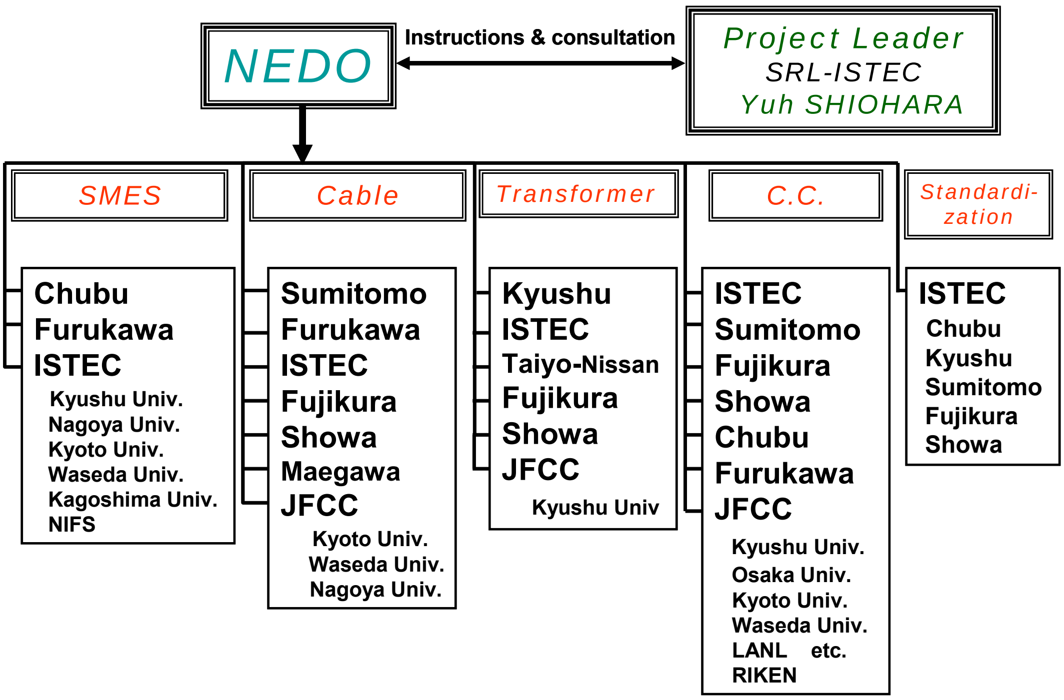

Fig.1 Project implementation system diagram

In this project, three types of power equipment: SMES, power cables and power transformers using Y-based wire, as well as wire required to improve the equipment performance, will be developed for the diffusion and introduction of the equipment around 2020. A conceptual diagram of the introduction of superconducting power equipment is shown in Fig. 2.

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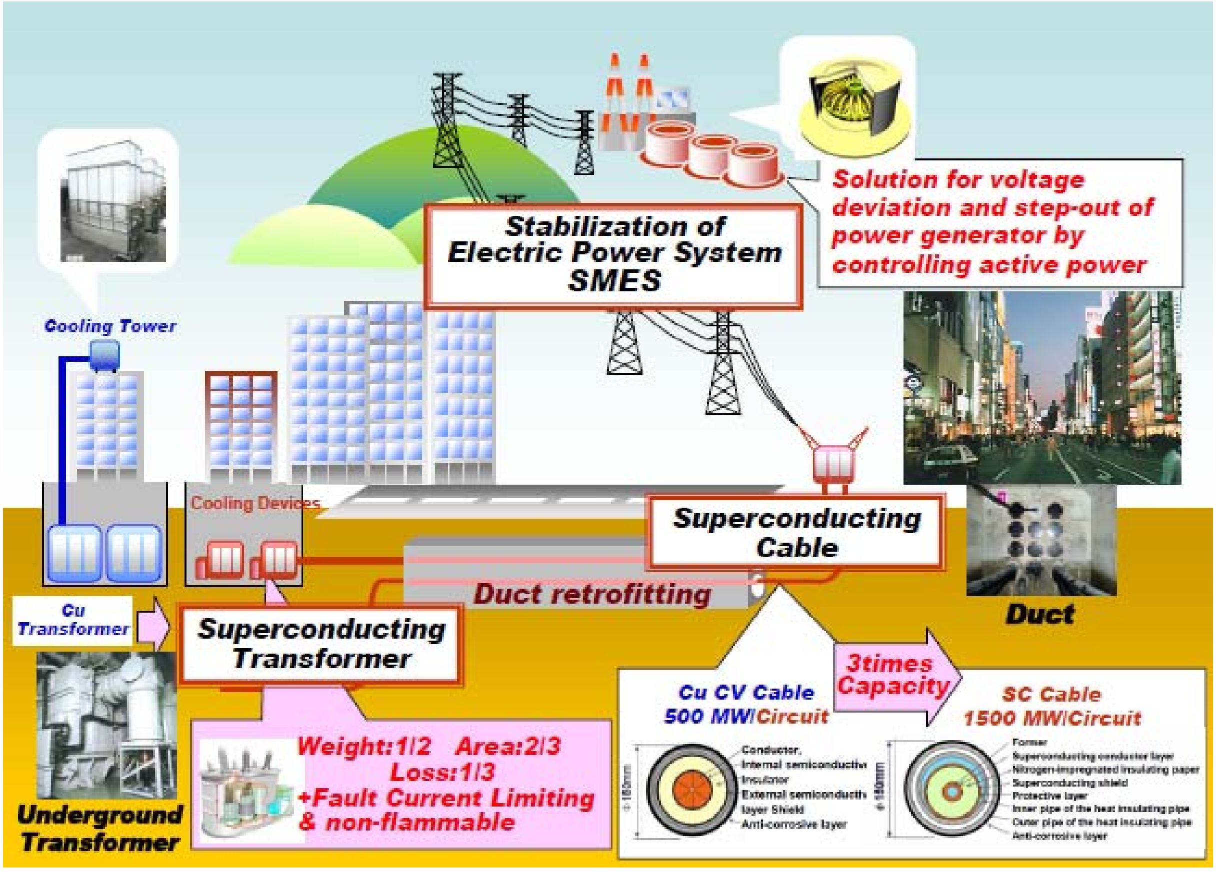

Fig. 2. Large-capacity stable supply of electric power for urban areas from superconducting power equipment

SMES

We will conduct technological development to put 2-GJ-class SMES (Fig. 3) to practical use to control power systems by regulating active power, solving problems such as voltage fluctuations and generator synchronism loss in long-distance power transmission. The companies will further advance the development results obtained in the Development of Superconducting Power Network Control Technology Project conducted until fiscal 2007 to develop 2-GJ-class high-magnetic-field/high-current compact coil composition technology and high-efficiency coil conduction cooling technology.

We will develop an element coil for a 20-MJ-class system required to make a 2-GJ-class coil technologically feasible. We will also develop Y-based superconducting wire with 600-MPa-class hoop stress and conduction characteristics of 2 kA or more that will withstand voltage performance of 2 kV or more to enable conduction cooling in a temperature range of 20 to 40 K. For the last two years of the project, we will conduct a system model verification test using a test model for a high-magnetic-field 2-MJ-class evaluation.

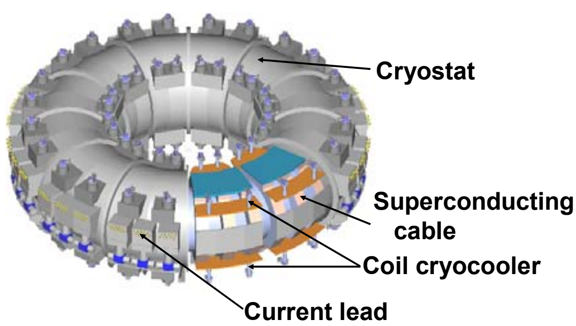

Fig. 3 Diagram of 2-GJ-class SMES

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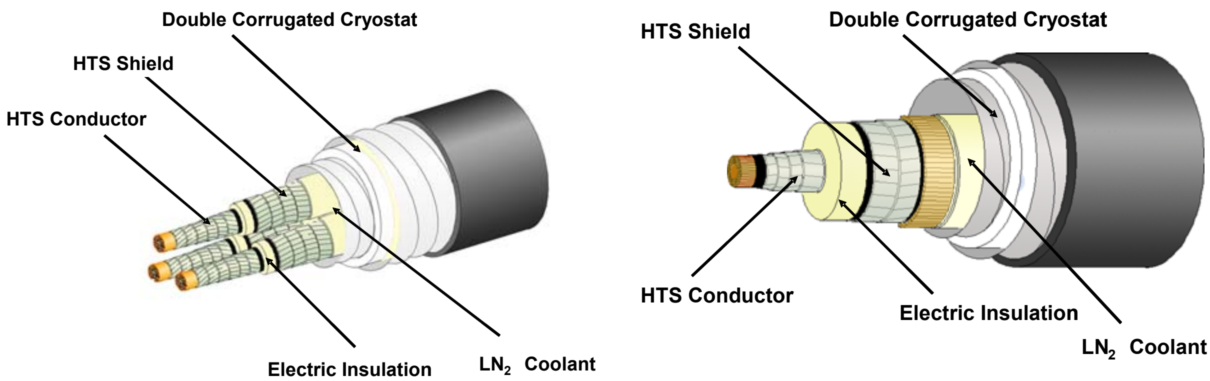
Power cable

We will develop two types of superconducting power cable that are higher in transmission efficiency, lower in transmission loss, and larger in capacity, yet more compact than existing power cable. One is a 66 kV/5 kA three-core high current cable (15 m) and the other is a 275 kV/3 kA single-phase high-voltage cable (with an interconnection at 30 m) (Fig. 4).

We will conduct technological development on high-current/low-AC loss cable, high-voltage insulation/low dielectric loss cable, and power cable heat balance. We will develop a high-efficiency and compact superconducting power cable, while satisfying specifications equivalent to those of existing cables such as the short-time anti-overcurrent test, and will verify the system through a long-term running test for the last two years of the project.



66kV/5 kA 3-core in one pipe 275 kV/3 kA single-core in one pipe

Fig. 4 Diagram of a superconducting cable

Power transformer

We will develop a superconducting power transformer that is lower in loss, more compact, and more fire-resistant than existing normal conducting power transformers. We will implement the technological development required to realize a 66 kV/6.9 kV-20 MVA-class superconducting power transformer (Fig. 5).

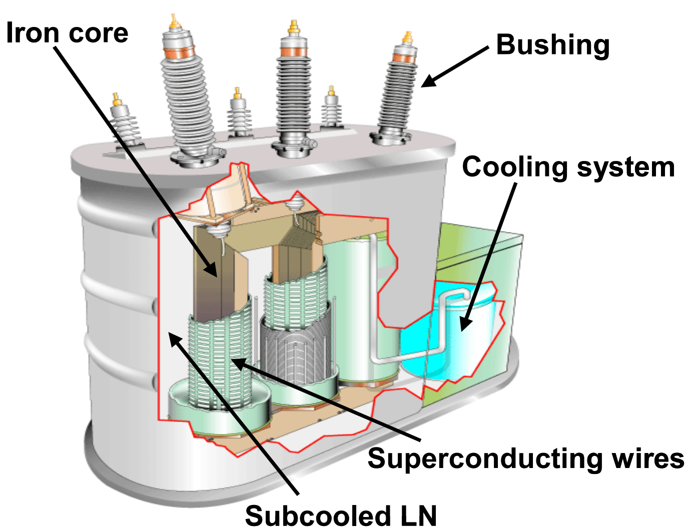


Fig. 5 Diagram of a superconducting power transformer

We will develop power transformer systematization technology, combining 2-kA-class high-current coil technology, anti-short circuit wire coil technology, AC loss reduction technology, and cooling technology including the high-efficiency Turbo Brayton cryocooler. For the last two years of the project, we will conduct system verification of the 66 kV/6.9 kV-2 MVA-class power transformer. We will also implement technological development to add fault current-limiting function to the power transformer to protect it and help to solve problems with short-circuit capacity in electric power system accidents. We will develop a superconducting power transformer provided with several-hundred-kVA-class fault current limiting function for the last two years of the project.

Developing wire

We succeeded in developing 500 m-300 A-class wire fabrication technology using the IBAD-PLD technique (Fig. 6). In this project, however, a wire 20-30 km-long in total is required to develop each piece of equipment as well as the mass fabrication and development of stable manufacturing technology of yttrium-based wire. Also, we need to increase raw material yields, improve wire characteristics, and enhance the reliability of wire for industrial products, while emphasizing stable fabrication.

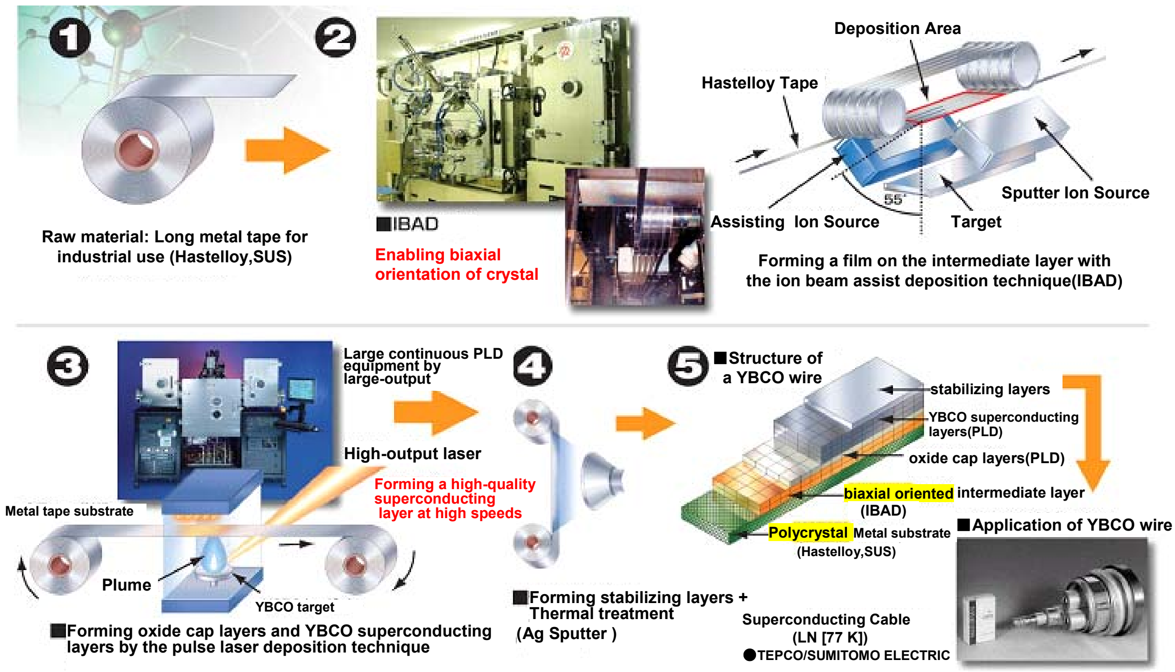


Fig. 6 Integrated wire fabrication process with the IBAD-PLD technique

In view of the above-mentioned, we will work on the following, considering the wire specifications at the time of the diffusion and introduction of superconducting power equipment that is expected around 2020 (Table 1):

1) Determining the wire characteristics
2) Increasing I_c in the magnetic field (critical current)
3) Reducing loss
4) Reinforcing wire and increasing J_e (industrial critical current density)
5) Developing wire fabrication technology to reduce cost and increase yield

In item 1 above, we will study the change in wire characteristics and measures to take given the equipment use environment in high-load operation such as high temperature and stress. We have so far conducted research and development with an eye to wire fabrication, but we will pay more attention to power equipment. Also, we will determine the characteristics of time degradation and age deterioration of wire caused by temperature and humidity, devising preventive measures against deterioration. Item 2

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above is needed for SMES requiring the generation of a magnetic field over ten tesla. Items 3 and 4 are necessary to develop more compact equipment at lower cost and with less AC loss and heat generation. Item 5 is essential to produce wire on a commercial basis. After developing stable fabrication technology of yttrium-based wire in this project, wire companies must reduce the wire cost to 3 yen/Am or less in order to be able to market the wire. In the previous project, we had the prospect of reducing the cost of wire fabricated by PLD technique using pulse laser to 12 yen/Am and that of wire fabricated by the low-cost MOD technique through solution coating and thermal decomposition to 8 yen/Am. We will increase critical current and fabrication speed to make the wire more commercially competitive. Thus, we can achieve cost reduction to 3 yen/Am or less and produce wire on a commercial basis after completing this project.

Table 1. Wire development item

Medium theme	Small theme
(1) Determining wire characteristics	･Age degradation, durability evaluation, etc.
(2) High I_c wire fabrication technology in the magnetic field	･Developing pin introduction technology ･Developing high Birr characteristic materials
(3) Developing low-loss wire fabrication technology	･Developing uniform characteristic wire fabrication technology ･Developing scribing machining and evaluation technologies
(4) Developing high-strength, high J_e wire fabrication technology	･Developing thin wall substrate reinforcing technology ･Developing I_c improvement technology
(5) Developing cost reduction and yield enhancing technologies	･Developing stable wire fabrication technology to put wire to practical use ･Developing high-speed I_c improvement technology at very low cost ･Developing connection and repair technologies

Implementing this project will enable developing major technologies from the fabrication of superconducting power equipment to the production of wire on a commercial basis, and will standardize the application of yttrium-based wire to the equipment. Through implementing the project, we will have the prospect for technological feasibility of superconducting power equipment using new yttrium-based wire. The U.S.A. and Europe are now studying applying yttrium-based cable and wire to superconducting power equipment. Our project is expected to play a leading role in producing yttrium-based wire on a commercial basis and developing superconducting power equipment.

(Yuh Shiohara, Dupty Director General concurrent Division Director Superconducting Tapes & Wires, SRL/ISTEC)

(Published in a Japanese version in the September 2008 issue of *Superconductivity Web 21*)

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What's New in the World of Superconductivity (November)

Power

American Superconductor Corporation (November 4, 2008)

American Superconductor Corporation (AMSC) has reported their financial results for their second fiscal quarter ending September 30, 2008. Revenues for the second quarter were a record US $40.4 million, an 87 % increase from the $21.6 million in revenues reported for the same period in the previous fiscal year. The gross margin for the second quarter of fiscal 2008 was 26.5 %, compared with 26.0 % for the same period in fiscal 2007. The company's net loss was $4.1 million, compared with a net loss of $6.7 million for the same period in the previous fiscal year. AMSC generated a positive $0.3 million in cash from operations in the second quarter of 2008. Cash, cash equivalents, marketable securities and restricted cash totaled $128.9 million as of September 30, 2008. Earnings before interest, taxes, other income and expense, depreciation, amortization and stock-based compensation (EBITDAS) were a positive $1.1 million for the second quarter of fiscal 2008, compared with an EBITDAS loss of $2.3 million for the second quarter of fiscal 2007. The company reported a backlog of $597 million at the end of the second quarter, compared with a backlog of $180 million at the end of the same period in the previous fiscal year. Greg Yurek, AMSC's founder and chief executive officer, reported, "We are continuing to execute well on all fronts and expect to achieve profitability on a GAAP basis for the first time in AMSC's history in the fourth fiscal quarter. The strength of AMSC's primary markets, our unique offerings and our significant presence in the Chinese wind market positions us for continued solid growth amidst the global economic downturn." AMSC confirmed its previous forecast of $175 million – $185 million in revenues and a net loss of $13 million to $15 million, with a positive EBITDAS of $7 million to $10 million for full-year fiscal 2008.
Source:
"AMSC Reports Second Quarter Fiscal 2008 Financial Results"
American Superconductor Corporation press release (November 4, 2008)
http://phx.corporate-ir.net/phoenix.zhtml?c=86422&p=irol-newsArticle_Print&ID=1221570&highlight

Zenergy Power plc (November 10, 2008)

Zenergy Power plc has successfully completed the testing of a commercial HTS fault current limiter (FCL), enabling it to qualify for installation in commercial electricity power grids. The FCL is based on a previous development model that was designed, built, and tested last year. The new unit will be delivered to Southern California Edison (SCE) in December of 2008, where it will be installed in SCE's commercial electricity grid. The FCL should be installed in the grid during the first quarter of 2009. Zenergy's HTS FCL utilizes a patented 'saturated core' FCL design that can instantaneously and automatically respond to and absorb multiple surges in electrical power, preventing blackouts and collateral damage while maintaining a continuous, uninterrupted and stable supply of electrical power to downstream users. The FCL is now being made available to additional potential utility customers from whom Zenergy has already received clear expressions of interest.

The global market for FCLs is expected to be worth as much as US $5 billion annually. In the company's press release, the directors of Zenergy Power noted, "...the significant support that the overall FCL market received last year as a result of the United States Department of Energy's commitment to invest over $50 million to accelerate the adoption of HTS based devices into the U.S. electricity power grid. The decision by the Department of Energy to actively promote the use of HTS devices in the United States is

indicative of the central role which they believe HTS devices can play in support of their overall strategy to modernize the aging, overstretched and inefficient U.S. electricity power grid. Further to the commitment from the Department of Energy, the United States Federal Government has also stated its support for the central role that HTS materials and devices can play in securing what it describes as 'a diverse and stable supply of reliable, affordable and environmentally responsible energy' for all U.S. citizens."
Source:
"Key FCL Milestone: Successful testing and Launch of Commercial Grid Stability Device"
Zenergy Power plc (November 10, 2008)
http://www.zenergypower.com/images/press_releases/2008-11-10-fcl.pdf

Zenergy Power plc (November 17, 2008)

Zenergy Power plc has been awarded a €475,000 grant from the European Commission in support of the company's development program for low-cost production techniques for second-generation HTS wires. The grant is part of a €3.55-million project being funded by the European Commission to accelerate the development of a range of ink-jet technologies that can be used to apply layers of ceramic materials onto the surfaces of metals and other materials (the Environmental Friendly Electro-ceramics Coating Technology and Synthesis [EFECTS] project). The grant from the European Commission was made in recognition of Zenergy's ongoing efforts to develop what the company believes will be the industry's lowest-cost manufacturing process for the mass production of second-generation HTS wire. This process will involve the use of ink-jet technologies to 'paint' superconducting ceramic materials onto nickel tape using a roll-to-roll process. The continuous nature of such a roll-to-roll process should make it ideal for the mass-manufacture of second-generation wire in a manner that is both cost effective and high yielding. The 'all-chemical' manufacturing approach being developed by Zenergy is the only such process in the world, and it benefits include the elimination of the time-consuming, labor-intensive batch techniques that are often used with alternative production methods for second-generation HTS wires.
Source:
"European Commission Grant"
Zenergy Power plc (November 17, 2008)
http://www.zenergypower.com/images/press_releases/2008-11-17-european-comission-grant.pdf

American Superconductor Corporation (November 18, 2008)

American Superconductor Corporation (AMSC) has signed an agreement with Shenyang Blower Works (Group) Co., Ltd. (SBW), a leading Chinese industrial equipment manufacturer, for the co-development of a 2-MW doubly fed induction wind turbine that should position SBW to become a leading supplier of wind turbines in the Chinese marketplace. Under the terms of the agreement, AMSC's wholly owned subsidiary AMSC Windtec™ will provide SBW with designs for the wind turbines. AMSC will also help SBW to localize the supply of all core components for the wind turbines, establish its wind turbine manufacturing line, and build and test SBW's first prototype wind turbines. Once certification has been received, SBW plans to manufacture and sell the turbines primarily to the Chinese market. SBW plans to have its first prototype turbines installed and commissioned in 2009 and to begin series production in 2010.
Source:
"AMSC Partners with Shenyang Blower Works for Development of 2 Megawatt Wind Turbines"
American Superconductor Corporation (November 18, 2008)
http://phx.corporate-ir.net/phoenix.zhtml?c=86422&p=irol-newsArticle_Print&ID=1227696&highlight

NMR

Bruker BioSPin (November 19, 2008)

Bruker BioSpin has received an order from King Abdullah University of Science and Technology (KAUST) for ten nuclear magnetic resonance (NMR) spectrometers, including a 950-MHz superconducting NMR magnet. The order is valued at close to $20 million. KAUST is a new graduate-level research university located in Saudi Arabia. BioSpin's 950-MHz superconducting NMR magnet is the world's highest-field superconducting actively shielded high-resolution NMR magnet system; the 22.3-T superconducting magnet is composed of about 160 km of wire, is two stories tall, and weighs 8 tons. The installation of the NMR systems is expected to begin in 2009 and will likely continue into 2010, although some systems will be operational for the planned opening of KAUST in September 2009.

Source:
"Bruker Announces Order for 10 NMR Systems to Enable World-class Scientific Research at King Abdullah University of Science and Technology (KAUST)"
Bruker BioSpin press release (November 19, 2008)
http://www.bruker-biospin.com/pr081119.html

Communication

Superconductor Technologies Inc. (November 12, 2008)

Superconductor Technologies Inc. (STI) has reported its financial results for its third quarter ending September 27, 2008. Net revenues for the third quarter totaled $3.6 million, compared with $4.1 million for the same period in the previous fiscal year. Net commercial product revenues were $2.7 million, compared with $2.3 million for the same period in the previous fiscal year. Government and other contract revenue totaled $854,000, compared with $1.8 million for the same period in the previous fiscal year. Jeff Quiram, STI's president and chief executive officer, commented, "During the third quarter, our wireless operator customers increased their investments in performance enhancement projects. As a result, STI is reporting significantly improved commercial product revenues of $2.7 million, representing a sequential increase of over 100 percent and a 20 percent increase year-over-year. While we cannot predict how the current economic uncertainty may impact operators' investment priorities and capital spending decisions in the future, we are encouraged by our performance in the third quarter. The reduced revenue level from our government projects reflects the completion of Phase I of our Air Force SURF contract during the third quarter of 2008 and we are still awaiting the final approval of Phase II of that contract." Quiram also added, "...we continue to move forward in our collaborative agreement with the Department of Energy's Los Alamos National Laboratory to apply our material sciences expertise to its research initiative to develop HTS coated conductors for next-generation electricity distribution systems." Net loss for the third quarter was $3.2 million compared with $2.0 million for the same period in the previous fiscal year. As of September 27, 2008, the company had $15.7 million in working capital, including $10.7 million in cash and cash equivalents. The company's commercial product backlog was $217,000, compared with $647,000 at the end of the same period in the previous fiscal year.

Source:
"Superconductor Technologies Inc Reports Third Quarter 2008 Results"
Superconductor Technologies Inc. press release (November 12, 2008)
http://phx.corporate-ir.net/phoenix.zhtml?c=70847&p=irol-newsArticle&ID=1225504&highlight

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Hypres Inc. (November 17, 2008)

Hypres Inc. has demonstrated a newly patented Digital-RF™ switch matrix technology that enables RF distribution and routing functionality completely within the digital domain of radio architecture. The demonstration represents the achievement of a major milestone for Hypres and is also an industrial first. The Digital-RF switch matrix technology is essential for realizing the full potential of high-performance, reconfigurable multi-band and multi-channel radio systems, such as Software Defined Radio. Dr. Deepnarayan Gupta, Vice President of Research and Development at Hypres, explains, "Analog-based RF switch matrices present significant deficiencies in terms of signal loss, isolation and crosstalk. In addition, they also suffer from a lack of scalability and reconfigurability. Our Digital-RF switch matrix technology solves these issues by moving the boundary between analog and digital domains to directly after the antenna, allowing the switch layer to be incorporated in the transceiver digital domain." Richard Hitt, CEO of Hypres, added, "Given the extremely high switching speeds needed for multi-band, multi-channel radio applications—in the tens of GHz—Digital-RF™ distribution and routing is only possible in high performance superconducting integrated circuits. With switching times measured in picoseconds, these chips are unmatched in the industry."

Source:
"Hypres Demonstrates Digital-RF™ Distribution and Routing, a New Milestone in Software Radio Technology"
Hypres Inc. press release (November 17, 2008)
http://www.hypres.com/pages/new/bnew_files/digitalswitchmatrix.pdf

Basic

Brookhaven National Laboratory (November 5, 2008)

Researchers at the U.S. Department of Energy's Brookhaven National Laboratory have discovered new imaging methods that have enabled them to sharpen images of the energy spectra produced by high-temperature superconductors. These imaging methods enabled the researchers to confirm that the electron pairing required to carry current through a superconducting material occurs at temperatures above the transition temperature, but only in a particular direction. The Brookhaven team bombarded a copper-oxide material (maintained at temperatures above and below the transition temperature) with beams of light from the National Synchrotron Light Source and then analyzed the energy spectra of the electrons emitted from the sample. This imaging method, which is known as angle-resolved photoemission spectroscopy (ARPES), typically allows only the energy levels of electrons below the so-called Fermi level to be visualized. To visualize the energy levels of electrons above the Fermi level, the researchers utilized analysis methods similar to those used by astronomers to increase the resolution of celestial images. As a result, they were able to observe a symmetrical energy gap extending above and below the Fermi level, indicating electron pairing, at the pseudogap above the transition temperature. This finding strongly suggests that electron pairing can occur at temperatures above the transition temperature. Interestingly, the pairing only occurred along certain directions in the crystalline lattice comprising the superconducting material. The observation of these preformed electron pairs and their directional dependence should advance our understanding of high-temperature superconductivity, as the discovery rules out certain explanations for the development of high-temperature superconductivity (i.e., "spin density wave"- and "charge density wave"-derived theories) and provides support to other competing theories (involving "Mott insulators" and "charge stripes"). The group's findings were published in the November 6, 2008, issue of *Nature*.

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Source:
"Electron pairs precede high-temperature superconductivity"
Brookhaven National Laboratory press release (November 5, 2008)
http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=853

National Institute of Standards and Technology (November 13, 2008)

Researchers at the National Institute of Standards and Technology and their colleagues at several institutions recently published two new papers (in *Nature Materials* and *Physical Review*) on the topic of iron-based high-temperature superconductors; in these papers, the researchers report that either the relation between magnetism and superconductivity is even more complex than previously thought or a whole new mechanism may be responsible for some types of superconductivity. The group used neutron beams to examine the atomic structure of iron-based superconductors and found that the materials were similar to copper-oxide superconductors with regard to how doping influences their magnetic properties and superconductivity. When un-doped iron-based materials were examined, however, the volume of the material's crystal structure was compressed by an unusually high percentage when the materials were subjected to a moderate pressure. Furthermore, the materials became superconductive without any evidence of magnetism. This unusual behavior under pressure suggests that an entirely different mechanism may be responsible for the superconductivity in iron-based materials. Alternatively, magnetism may be an ancillary component of high-temperature superconductivity in general, with a deeper mechanism underlying high-temperature superconductivity in both types of materials.
Source:
"Iron-based materials may unlock superconductivity's secrets"
National Institute of Standards and Technology press release (November 13, 2008)
http://www.lanl.gov/news/index.php/fuseaction/home.story/story_id/15126

Los Alamos National Laboratory (November 24, 2008)

Researchers at the Los Alamos National Laboratory have posited a new explanation for superconductivity in non-traditional materials that describes a potentially new state of matter in which the superconducting material simultaneously behaves like a nonmagnetic material and a magnetic material. The researchers cooled a cerium-rhodium-indium compound until it became superconducting at a point just above absolute zero; they then subjected the crystal to pressure changes and a magnetic field to perturb the alignment of the electrons within the material. Based on the material's behavior under different pressures and temperatures, the researchers believe that the material reaches a quantum critical point near absolute zero. At this point, the material retained the properties of a metal—a state of matter that has never before been described. The researchers believe that this quantum critical point provides a mechanism for electron pairing into a quantum state that gives rise to superconducting behavior. In other words, the research suggests a possible mechanism for superconductivity that does not involve phonons. The group's research and ideas were presented in a letter published in the November 20, 2008, issue of *Nature*.
Source:
"Los Alamos Scientists See New Mechanism for Superconductivity"
Los Alamos National Laboratory press release (November 24, 2008)
http://www.nist.gov/public_affairs/techbeat/tb2008_1112.htm#htc

(Akihiko Tsutai, Director, International Affairs Division, ISTEC)

(Published in a Japanese version in the January 2009 issue of *Superconductivity Web 21*)

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Feature Articles: Superconducting Digital Device Technology - Prospects for the Application of Superconducting Digital Devices by JJ Size -

Superconducting circuit using the fewest Josephson junctions (JJ) is RF-SQUID which has only one junction, followed by DC-SQUID, which has two junctions. RF-SQUID and DC-SQUID are the ultimate magnetic sensors with a wide range of applications, but they are not digital circuits. Although determining whether they are in the category of digital circuits is complex, a sampler that measures electric signal waveforms can be composed of at least five JJs by using a JJ switch to put single flux quantum (SFQ) in and out of a superconducting loop. A sampler with additional functions consists of 15 JJs.[1]. Arround 30 JJs are used in a random number generation circuit used for creating a code.[2]. A Time to Digital Converter (TDC), which measures the time difference between two inputs at an accuracy of 10 picoseconds or less, can be composed of approximately 600 JJs.[3]. A flash-type Analog to Digital Converter (ADC), a key component of a real-time oscilloscope that can measure high-speed waveforms in real time, can be fabricated with 5,000 JJs including 4-bit error correction and high-speed output circuits.[4]. HYPRES, Inc. in the U.S.A. has already delivered digital RF receivers to the US army. A high-accuracy ADC, including peripheral circuits, used for the digital RF receiver has 12,000 JJs. [5] These circuits, excluding the random number generation circuit, are the head of a measuring instrument. Superconducting circuits are used only for units requiring high-speed, high-sensitivity performance that cannot be achieved by semiconductors.

A Digital Signal Processor (DSP), which performs digital signal processing at high speeds, is one of the attractive applications of an SFQ circuit. Performance far beyond the limits of semiconductors is expected from the DSPs. A Fast Fourier Transfer (FFT) circuit is a typical DSP and a 64-bit FFT can be composed of 80,000 JJs. [5]

A superconducting detector represented by a Transition Edge Sensor (TES) is a high-sensitivity detector that outclasses others, but the TES detection area is small. Arraying is performed to compensate for this disadvantage. It is, however, quite difficult to have signal lines running from each of numerous arrayed superconducting detectors to room temperature, given the thermal inflow. For this reason, multiplexing signals in a cryogenic environment and substantially reducing the number of lines is necessary. SFQ circuits, which operate at very low temperatures like superconducting detectors and have very low power consumption, are promising as a circuit for multiplexing signals. Although development of the SFQ circuits for multiplexing signals is just started, an SFQ circuit is estimated to be composed of 200 JJs/ch[6]. The estimate shows that a 100 x 100 array can be composed of 2,000,000 JJs. As the number of detector arrays increases, ease-of-use will be improved accordingly. Even multiplexed circuits for a 10 x 10 array, a medium-level array composed of 20,000 JJs, will greatly help users.

Using semiconductor circuits to fabricate a digital device with the same performance as that of superconducting circuits is possible, but the power consumption of semiconductor circuits exceeds the permissible limits. Network routers and supercomputers are such type of devices. For example, the power consumption of a 100-Tbits/s-class router switch in a superconducting circuit including a cryocooler is estimated at 10 kW, while power consumption of 330 kW is required for a semiconductor circuit. In such an application, a large scale is required to differentiate superconducting circuits from semiconductor ones. A 2 x 2 switch is a basic unit for a router switch. The scale can be expanded by the basic unit. The Superconductivity Research Laboratory has worked to make SFQ 2 x 2 switches more compact and succeeded in developing a switch composed of 74 JJs. A 10-Tbits/s-class router switch using semiconductor circuits cannot currently be fabricated with one rack owing to heat generation. The number of JJs required for this router switch is estimated at 330,000 JJs for each I/O of 80 Gb/s[7]. Since scheduler circuits for collision control and I/O circuits are also needed, about 1,000,000 JJs in total seems to be required. Since a 100-Tbits/s-class router switch requires elements 100 times (n^2) more than a 10-Tbits/s-class router switch, about 100,000,000 JJs is needed if the same magnification applies. If this is reduced to 30 times (nlogn) by devising a new method, 30,000,000 JJs will be required. An SFQ Reconfigurable Data Path (RDP) has been proposed as an accelerator that can raise the performance to that of a supercomputer by adding the 100-Tbits/s-class router switch to a normal computer. SFQRDP is new architecture that can solve the problem of insufficient memory in a supercomputer, but this architecture is difficult to develop with a semiconductor circuit owing to heat generation. Development using an SFQ circuit is expected[8]. A Floating Processor Unit (FPU), a basic component of an RDP, requires 50,000 JJs. In a 32 x 32 composition that enables a 10-TFLOPS disk side supercomputer, 50,000,000 JJs are required. Since a network switch that variably connects between FPUs also requires the same number of JJs, the total number of JJs required is estimated at 100,000,000.

At present, a niobium SFQ circuit has 10,000 JJs. The Superconductivity Research Laboratory is preparing a new process called advanced process (ADP) and is planning to realize a circuit of 100,000 JJs within three years by using the ADP. The minimum diameter of a JJ in the ADP is 1 µm. The pattern size is more than 10 times larger than that of the semiconductor advanced process. For this reason, improving the scale of integration by miniaturizing an SFQ circuit by semiconductor advanced process equipment is possible. Enlarging a chip from the present 5-mm square to an 11-mm square and using a 0.25 µm minimum JJ diameter process will allow 10,000,000 JJs to be packed on one chip, although there are some problems with enlargement described in the following report[9]. Also, an SFQ circuit can use superconducting wiring to transmit data of 100-Gb/s/ch between chips.[10] A multi chip module (MCM) with two or more chips arranged on a substrate provided with superconducting wiring can be operated as a one chip. For this reason, even a circuit composed of 100,000,000 JJs may be realized with an MCM of a 5-cm square.

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(Mutsuo Hidaka, Director, Low Temperature Superconducting Device Division, SRL/ISTEC)

(Published in a Japanese version in the October 2008 issue of *Superconductivity Web 21*)

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Winter, 2009 Date of Issue: January 15, 2009

Superconductivity Web21

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Feature Articles: Superconducting Digital Device Technology
- Technical Challenges for Putting Large-scale Superconducting Digital Circuits to Practical Use -

The Superconductivity Research Laboratory fabricated a 4 x 4 switch prototype system, using a single flux quantum (SFQ) circuit with niobium as a superconductive material and succeeded in an experiment transferring motion pictures between four PCs via this system. The system throughput was 320 Gbps, which is equivalent to transmitting 4,800,000 pages of A4 paper in a second. The SFQ circuit power consumption was less than 1 mW. The bit error rate (BER) was less than 10^{-12}, which is required for communication applications. This system has proven satisfactory reliability. Some problems still remain to be solved to increase the SFQ switch system throughput to 10 Tbps or more, a throughput as attractive as that of a semiconductor switch.

An SFQ circuit using niobium is cooled down to around 4 K, its operating temperature, with a cryocooler. Inputting and outputting signals to and from the SFQ circuit with broad-band signal lines is essential in order to produce the high-speed performance of the SFQ circuit. In the above-mentioned SFQ switch system, 32 broad-band electric signal lines are used to input and output signals to and from the SFQ circuit. Heat flow into the cryocooler through the lines is about 800 mW, but almost all of the cooling capacity of the cryocooler being consumed by the heat flow is problematic. Since a large-scale circuit with a high throughput has more I/O lines, taking advantage of the low-power consumption characteristics of the SFQ circuit is impossible without solving this problem. I/O using optical fiber has been proposed as a solution. Optical fiber is very low in thermal conductivity and has a band far broader than an electric signal line so that a large throughput per signal line can be expected. The Superconductivity Research Laboratory are developing I/O technology to and from the SFQ circuit using optical fiber and has successfully operated the SFQ circuit with optical input of 40 Gbps.

As an SFQ circuit becomes larger, the bias current supplied to the circuit increases. Although the SFQ circuit is designed so the bias current flow is dispersed, the current inevitably concentrates in some places. The SFQ circuit consists of superconducting loops containing Josephson junctions. The SFQ circuit is very sensitive to magnetic fields because the circuit has the same structure as SQUID, which is a high-sensitivity magnetic sensor. For this reason, the magnetic field induced by the bias current causes a decrease in the circuit operation margin, resulting in difficulty in operating a large-scale circuit. The current solution to this problem is surrounding the bias current line with a superconductor providing good magnetic shielding. This structure is effective for a circuit up to 10,000 junctions, but not sufficient for larger-scale circuits. The Superconductivity Research Laboratory uses a niobium multilayer structure to arrange two or more superconducting layers between the bias line and the active layers containing Josephson junctions, further enhancing the magnetic shielding effect.

Another problem with a large-scale circuit is that the absolute value of the supplied bias current increases. Even if the magnetic field generated in the chip can be reduced by two or more niobium films as mentioned above, the magnetic field generated by the bias current flowing in from the outside through the lead line may block the circuit operation. Since the bias current is DC, the bias current once used can be used many times. In order to realize this, separating grounds and signal line coupling using inductance or capacitance is required. This technique is called current recycling. If current recycling is applicable, the bias current supplied to the cryogenic environment can be drastically reduced.

Improvements of process and design technology also need to be sophisticated to realize large-scale superconducting digital circuits. From the research conducted so far, we have the prospect of developing the current recycling technology. The question seems to be the amount of resources we will have in the future to pursue this project.

Among the technologies discussed in this report, we are researching optical I/O and current recycling technologies in NEDO's Development of Next-Generation High-Efficiency Network Device Project. Also, we research magnetic shielding using the niobium multilayer structure in JST's Reconfigurable Data Path processor using the single flux quantum circuit project.

(Mutsuo Hidaka, Director, Low Temperature Superconducting Device Division, SRL/ISTEC)

(Published in a Japanese version in the October 2008 issue of *Superconductivity Web 21*)

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Winter, 2009 Date of Issue: January 15, 2009

Superconductivity Web21

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Feature Articles: Superconducting Digital Device Technology - Technical Challenges to Superconducting A/D Converters for Measuring High-speed Signals to Exceed Semiconductors -

The superconducting A/D converter (ADC) can be roughly divided into two types: the oversampling type, which is characterized as high resolution (high bit rate), and the flash type, which is notable for high speed. The latter is important for high-speed signal measuring instruments such as high-end digital oscilloscopes and digitizers. In this report, reviewing the historical development of the flash type, I will describe the technical challenges for developing the flash type ADC in ISTEC.

The development of the flash type superconducting ADC, which has a long history, dates back to 1975 when Zappe from IBM proposed it. [1] The principle of operation is using the periodicity of the circulating current accompanied by quantizing the magnetic flux entering the Superconducting Quantum Interference Device (SQUID) to analog input signals. The current flash type superconducting ADC is also based on the same concept. If semiconductors are used, 2^n-1 comparators will be required to compose an n-bit ADC, while only n comparators will be needed if superconductors are used as shown in Fig. 1. When an analog signal is applied to a superconducting loop containing one Josephson junction, flux quanta (Φ_0) enter the loop (flux is quantized) one by one as the amplitude increases, and the circulating current passing through the superconducting loop periodically varies as the trace in Fig. 1. When a threshold is set to a proper current level, the output alternates between "1" and "0" and is converted into digital data called gray code. As shown in Fig. 2, an N-bit ADC can be fconstructed with a current distribution circuit by an R-2R resistance network and N comparators. The reduction in the number of comparators by using the quantization phenomenon is a major benefit that cannot be obtained from the semiconductor.

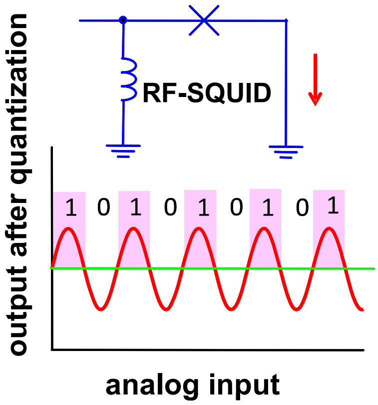

Fig. 1 Diagram of the basic principle of a superconducting ADC

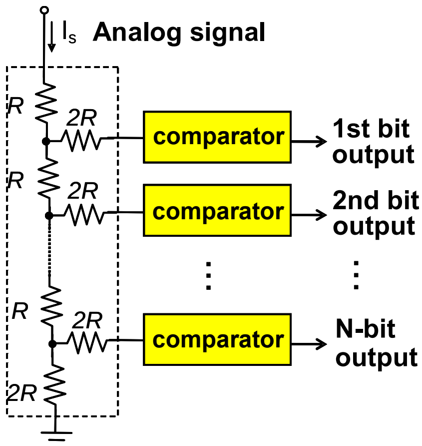

Fig. 2 Block diagram of an N-bit superconducting ADC

Comparator circuits in the early years had problems with high speed and accuracy because they used a multi-junction SQUID with hysteresis to perform quantization and sampling at the same time. In order to compensate for this shortcoming , Ko from UC Berkeley proposed a Quasi-one junction SQUID (QOS) comparator in which quantization is separated from sampling by using the characteristic without hysteresis.[2] Afterward, he was employed by Hewlett Packard Laboratories to continue the research and development, aiming to apply QOS to measuring instruments such as digital oscilloscopes. Since the zero voltage state of the Josephson junction called a latching logic was used at that time, the QOS comparator did not reach the commercial stage because of problems such as the operation speed limit due to the AC bias drive and the

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comparator threshold level fluctuation due to heat generation on the chip. These problems were solved or remarkably improved by the proposal for the ADC to use an SFQ circuit.[3] HYPRES, a superconducting venture company, conducted research and development aimed at performance exceeding a bandwidth of 10 GHz at an effective bit rate of 6. The company demonstrated basic operation up to 6 bits in a bandwidth of 1 GHz and up to 3 bits in a bandwidth of 20 GHz.[4] A digital correction circuit to avoid serious errors caused by the fluctuation of threshold values owing to thermal noise and a technique called interleave (an increase in resolution of about 2 bits becomes possible) to increase the number of bits of the ADC were proposed. At that time, only the function test for the operation of some circuits was conducted. The basic technology required for flash ADC was established by the research mentioned above.

The essential factors that restrict the performance - the bandwidth and bit rate - of a high-speed flash type ADC are as follows; 1) restriction upon the frequency range by the through rate and 2) restriction upon bit accuracy owing to fluctuation in threshold current attributable to thermal noise. The former is the problem of how much flux quantum enters the superconducting SQUID loop and whether SQUID can follow the analog signal when high-speed analog signal is input. The problem restricts the effective bit rates. The latter affects uncertainty in converting an analog signal into digital “1” and “0”. Fluctuation in the SQUID threshold value accompanied by a change of the critical current of the Josephson junction due to thermal noise created this uncertainty. Increasing the critical current density of the Josephson junction and enhancing the switching speed by miniaturization are effective for solving these problems. Improvement of the performance can also be expected by developing suitable circuit to enhance the through rate.

A comparator circuit currently under development by the Superconductivity Research Laboratory as NEDO’s next-generation high-efficiency network device technology development research project is expected to operate at higher speed than conventional comparator circuits. The comparator circuit (1-bit ADC) is shown in Fig. 3. We have simulated the maximum sampling frequency f_s(max) in a 4-bit ADC as a function of the critical current density J_c. The simulation results are shown in Fig. 4. Basically, f_s(max) increases in proportion to

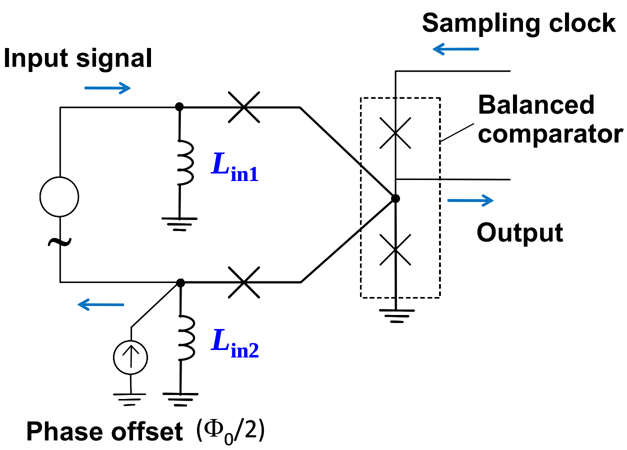

Fig. 3 Equivalent circuit of a complementary superconducting comparator

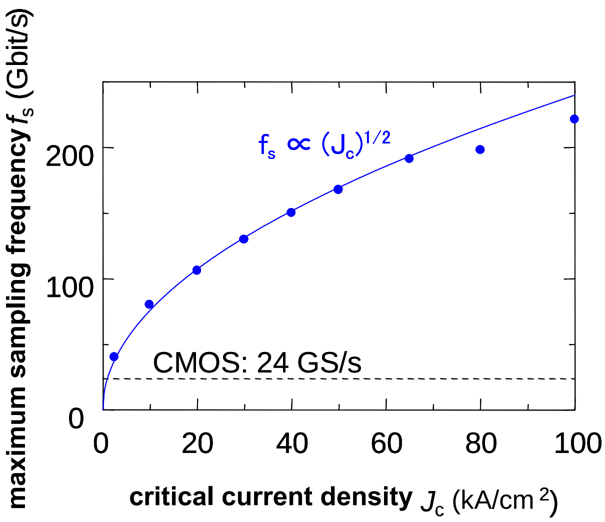

Fig. 4 Correlation between maximum sampling frequency and critical current density (results of a simulation using a complementary superconducting comparator)

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the square root of J_c. Where, half the sampling frequency, a Nyquist frequency, is given as an analog signal. The 6-bit (4 or 5 bits as an effective bit rate) ADC using the CMOS operating at a sampling frequency of 23 GHz has been reported recently. In SRL's Nb standard process, the critical density J_c is 2.5 kA/cm^2. Fabricating an ADC with a sampling frequency of more than 100 GHz with semiconductors would be difficult. However, If J_c of 40 kA/cm^2 Nb process is established, fabricating such an ADC will become possible by the superconducting technology. When converting high-speed analog signals to digital form with two or more comparators, we have problems with circuit technology, as well as the problem of high-J_c junction fabrication technology. The resistor circuit network shown in Fig. 2 has a physical length as heat is generated. As a superconducting comparator has an inductance component, the development of analog input circuits containing superconducting comparators for high-frequency operation is vitally important. Although SFQ circuits are better-suited in high speed digital circuits, they have difficulty in performing high-frequency operations in a mixed signal of analog and digital. This is the good challenge of a superconducting device come into play. We are working on research and development, aiming to fabricate high-performance superconducting ADCs, which is difficult with semiconductor technology.

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(Published in a Japanese version in the October 2008 issue of *Superconductivity Web 21*)

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Winter, 2009 Date of Issue: January 15, 2009

Superconductivity Web21

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Feature Articles: Superconducting Digital Device Technology - Superconducting Single Photon Detector (SSPD) Essential to the Quantum Key Distribution System -

Shigehito Miki
Kobe Advanced ICT Research Center
National Institute of Information and Communication Technology

The cryptographic system in the present information telecommunications network is based on computational security. This conventional system will be exposed to decoding as science and technology progress, but the Quantum Key Distribution (QKD) system is a new form of technology that assures unconditional information security based on the uncertainty principle. Since the performance of a single photon detector directly limits QKD performance, the semiconductor photon detector currently used is a major bottleneck to improving QKD performance. The National Institute of Information and Communication Technology (NICT) of Japan and National Institute of Standards and Technology of the USA (NIST) developed a high-performance, portable superconducting single photon detector (SSPD) system and applied the system to a QKD experiment. As these institutes have showed the way to open up the bottleneck, the effectiveness of the SSPD system has been recognized.

Fig.1 Picture of an SSPD system

For application to the Quantum Key Distribution System, the SSPD system must have a multichannel I/O configuration and a small, simple cooling system that can be operated continuously. Both NICT and NIST have successfully developed general-purpose SSPD systems using a small and portable coolant-free Gifford-McMahon (GM) cryocooler that operates with a 100 V AC power supply (Fig. 1). Since either system can be provided with up to 6 to 8 light-sensitive superconducting devices, only one system can cover the number of channels (for example, 4 channels for BB84 system) required for a Quantum Key Distribution test. Since the current SSPD system has reached a dark count rate of 100 Hz, system

Winter, 2009 Date of Issue: January 15, 2009

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detection efficiency of 1 to 3 %, and operation speed of about 30 to 50 MHz (See Table 1), the system has the advantage over the semiconductor devices. [1] Furthermore, the application to the test on the Quantum Key Distribution System using the practical SSPD system has already begun. For example, a joint NEC Corporation-NICT-NIST team conducted a field test using the BB84 protocol at a fiber-optic cable distance of 97 km. The team successfully achieved a key generation rate 100 times higher in a conventional field test range of 100 km and 10 times higher in a laboratory test. [2]

Table 1 Specifications and performance of an SSPD system

Number of channels	6 – 8 channels
System detection efficiency	1～3 %
Dark counting rate	<100 Hz
Response speed	50 MHz
Jitter	50 ps
Bias current	10 - 50 υA
Power supply	AC 100 V, 15 A
Operating temperature	2.9 K

Although the practical SSPD system shown above performs unsatisfactorily compared to the potential of the SSPD system, the system has been steadily improving at the basic research level. For example, in the ASC2008 International Conference held in Chicago, U.S.A., the system detection efficiency was reported to have been increased by about 40 % owing to improvement in the absorption efficiency of light-sensitive superconducting devices and increased operation speed owing to multielements or parallel stripping. Reflecting these results in the practical SSPD system will be the future focus.

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(Published in a Japanese version in the October 2008 issue of *Superconductivity Web 21*)

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Feature Articles: Technical Trends in Superconducting Power Equipment - From Topics of ASC 2008 -

Chicago, where ASC 2008 was held

ASC 2008 (2008 Applied Superconductivity Conference), an international conference on applied superconductivity, was held from August 17 to 22, 2008 in Chicago, Illinois.

Approximately 1,600 people from 40 countries around the world attended the conference where advanced applied technologies on superconducting materials, superconducting electronics, and superconducting power equipment and their trends were presented.

The presentations concerning superconducting power equipment accounted for one third of the approximately 1,350 presentations. Technological prospects for SMES, superconducting power cable, superconducting fault current limiters, and superconducting power transformers based on significant oxide superconducting wire technology advancement were presented. Information useful to Japan's Materials & Power Application of Coated Conductor project that started around the same time was also released.

We reported on ASC 2008 in the October issue of Superconductivity Web 21. Experts who participated in this conference will report in detail on topics in each field for SMES, superconducting power cables, superconducting power transformers, and superconducting fault current limiters.

(Editorial office)

(Published in a Japanese version in the November 2008 issue of *Superconductivity Web 21*)

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Feature Articles: Technical Trends in Superconducting Power Equipment - Report on SMES -

Naoki Hirano, Manager
Superconductivity Group, Electric Power Research & Development Center
Chubu Electric Power Co., Inc.

There was one oral presentation session and three poster presentation sessions on SMES. There seemed to be more presentations this year than usual.

In the oral presentation, Professor Tanzo Nitta from Meisei University introduced the power system interconnection test results of the 20-MJ/10-MVA-class SMES using NbTi coils. The SMES was conducted as a NEDO project. It was demonstrated that power fluctuations were successfully controlled by installing SMES in the system located in Nikko, and electricity was charged and discharged from SMES to handle load fluctuations in the factory. The system operated stably even after over 50,000 repetitive charging and discharging operations when only 20,000 charging and discharging operations were planned. A high-speed charging and discharging operation that is difficult to perform with other power storage equipment was also verified. Mr. Kim from South Korea introduced a 2.5-MJ-class SMES plan using oxide-superconducting wire, which started in fiscal 2008. The purpose was to control fluctuations of a small-scale power system installed on a small island that was interconnected with a wind power generator and to verify the power system stabilization. He explained that choosing Y-based or Bi-based wire was under consideration and he was carefully studying how handle this matter, carefully watching the trends in wire development. He stated that the project safely started. The Materials & Power Application of Coated Conductor Project started in fiscal 2008 in Japan. South Korea seemed to have this Japanese project in mind. I am looking forward to seeing the competition between Japan and Korea in this field.

Professor Mito from the National Institute for Fusion Science introduced the results of the voltage sag compensation system test using conduction cooling 1-MJ-class NbTi coils. Professor Nomura from the Tokyo Institute of Technology proposed an SMES coil shaped considering the reduction in electromagnetism. Italy proposed SMES using liquid hydrogen as a cooling medium to apply SMES to hybrid transportation devices. A cooling medium has an advantage that it can be used as fuel as it is. A patent appears to have already been issued for this idea, simulation of this system completed, and SMES using liquid hydrogen will move from the theoretical stage to system trial production and evaluation.

South Korea, which gave many poster presentations, presented cooling systems aimed at developing a 2.5-MJ-class SMES, as well as system design results. South Korea and Poland each presented research and development on oxide SMES using Bi2223 wire. Japan presented the test results of a small-scale coil fabricated on an experimental basis for SMES using yttrium and 2-GJ-class system trial design results as the achievements of two national projects: Fundamental Superconducting Application Technologies and Development of Superconducting Power Network Control Technology. Japan explained that YBCO coils have outstanding mechanical strength and show exceptional temperature stability even if over twice the critical current is passed through it. Also, Japan presented a design result that the volume of a YBCO coil can be reduced to one third or less because a higher magnetic field design is possible for YBCO coils than for NbTi coils. Applied research and development on SMES and its related technologies using YBCO coils will probably increase both in Japan and abroad in the future.

(Published in a Japanese version in the November 2008 issue of *Superconductivity Web 21*)

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Feature Articles: Technical Trends of Superconducting Power Equipment - Technical Trends of Superconducting Power Cables -

The projects for power cable implemented or planned are shown in Table 1. I will report on technologies that were presented at ASC 2008 including covering form, loss, and cable cooling.

Table 1. Superconducting power cable development projects

Project	Country	Voltage kV rms	Current A rms	Capacity MVA	Length m	Form	tapes	Grid	year
Albany (DOE)	USA	34.5	800	48	330	3 in 1	1G+2G	○	2006
AEP (DOE)	USA	13.2	3000	69	200	tri-axial	1G	○	2006
LIPA (DOE)	USA	138	2400	574	600	1 core ×3	1G	○	2008
LIPA2 (DOE) *	**USA**	**138**	**?**	**?**	**600**	**1 core ×?**	**2G**	○	**?**
Hydra (DHS) *	**USA**	**13.8**	**4000**	**96**	**300**	**1 core ×3**	**2G**	○	**2010**
Entergy (DOE)	**USA**	**13**	**2500**	**60**	**1760**	**tri-axial**	**2G?**	○	**2013**
DAPAS2	Korea	22.9	1250	50	100	3 in 1	1G		2007
DAPAS3	**Korea**	**154**	**3750**	**1000**	**?**	**1 core ×?**	**?**		**2010**
Fundamental Superconducting Application Tech.	Japan	66	1000	-	10+10	3 in 1	2G		2007
YOKOHAMA	**Japan**	**66**	**1750**	**200**	**200-300**	**3 in 1**	**1G**	○	**2011**
Y-based wire project	**Japan**	**66**	**5000**	**570**	**15**	**3 in 1**	**2G**		**2012**
		275	**3000**	**1430**	**30**	**1 core**	**2G**		**2012**

Legend: Red characters denote the highest values in the projects. Blue characters denote planned values. The superconducting power cables in projects marked with an asterisk (*) have a fault current limiting function.

Form

The cable form varies from project to project. Three-core cable is used in Albany and Fundamental Superconducting Application Technologies, while three-core coaxial cable is used in the AEP and single-core cable in LIPA and DAPAS3. AEP former is hollow. Single-core cable former is solid-core, but hollow-core cables may be planned.

AC-Loss

It was reported in Albany that the AC loss measured by using a 2.5-m single phase cable (Y-based wire) was 0.34 W/m@800 A. Fundamental Superconducting Application Technologies reported that an AC loss of 0.1 W/m-phase @ 1 kA had been achieved. In Japanese projects such as YOKOHAMA and Y-based wire project, loss reduction is emphasized.

Cooling cable

For how to cool cable, we will introduce AEP. A three-phase coaxial, 13.2 kV, 3 kA, 200-m cable has a hollow core conductor, which is a flow path for liquid nitrogen. Also, there is another flow path on the outside of the three-phase superconducting layer. When liquid nitrogen goes out, it can cool the inside of the cable. When liquid nitrogen returns, it can cool the outside. The temperature distribution in the longitudinal direction of the superconductor can be reduced by changing the liquid nitrogen flow rate.

Short-time overcurrent

It was reported in YOKOHAMA that a short-circuit test condition of 31.5 kA, 2 seconds had been set, with allowances made for the overcurrent values and passing time assumed based on the substation conducting the cable demonstration. In the 154 kV, 1,000 MVA DAPAS3 cable plan, a short-time overcurrent was reported at 50 kA, 1.7 seconds, which appears problematic. There was no I_c deterioration even if a current of 31.5 kA, 2 seconds was passed through a conductor layer composed of 2G wire of one out of three cores (two cores are dummies).

Long-term operation

In Albany, a 30-m long 2G cable has been connected to the system for over 12 months after Phase-II to operate the system. The set target will be achieved in 2008 and the cable will be disconnected from the system in 2009 for evaluation. Economic efficiency and reliability will be studied.

Others

LIPA started system operation in April 2008. The effect of noise from the cooling system of a superconducting cable upon neighboring residential areas was reported.

LIPA2 and HYDRA, a project of the U.S. Department of Homeland Security (DOHS), are characterized by the fault current limiting function provided to a cable. HYDRA will be continued until the cable length reaches 300 m while the project was being verified with 3-meter- and 25-meter-long test cables. For Entergy, which is notable for a length of 1,760 m, no detailed reports were available to the best of the author's knowledge.

(Noboru Fujiwara, Director of the Electric Power Equipment Division, SRL/ISTEC)

(Published in a Japanese version in the November 2008 issue of *Superconductivity Web 21*)

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Winter, 2009 Date of Issue: January 15, 2009

Superconductivity Web21

Published by International Superconductivity Technology Center
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Feature Articles: Technical Trends of Superconducting Power Equipment - Development of Superconducting Power Transformer -

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Almost all the reports on trends on the development of superconducting power transformers presented at ASC held in Chicago this past August concern the conceptual design of superconducting power transformers, or the experimental fabrication or test results of ultra-compact power transformers. Among these power transformers, only the 100-kVA transformer using YBCO wires developed by a group from Nagoya University was considered to be at an adequate research and development level of superconducting power transformers for power equipment. In this ASC, the mainstay of the research and development of superconducting power transformers was a transformer-type fault current limiter. There were only a few R&D focused on the transformer function. Also, for even those focused on the transformer function, there were no presentations that clarified the requirements for a power transformer as mentioned below or that discussed how those requirements were satisfied. There was no movement toward a breakthrough in the suspension of the research and development of superconducting power transformers in Europe and the United States. Amid growing calls in the United States for the research and development of superconducting cables provided with a fault current limiting function, the development of superconducting fault current limiters of transformer type means, to look at it from a different angle, the development of superconducting power transformers provided with a fault current limiting function. In NEDO's Materials & Power Application of Coated Conductor (M-PACC) project, which started in Japan this past June, the addition of a fault current limiting function to a superconducting power transformer is planned. This plan is based on the same idea as above. However, we found the biggest difference between equipment focused on a fault current limiter and that focused on a power transformer. Researchers aim to develop a non-inductive coil for the fault current limiter and the magnetic field applied to the coil is extremely low. While the coil's empirical magnetic field is so high that AC loss reduction technology must be developed on a full-scale basis because the power transformer transmits voltage from the primary coil to the secondary coil. In either case, the superconducting fault current limiter of the transformer type is still within the bounds of imagination, and research and development has just begun. The report on fault current limiters will be made separately. I would like to discuss technical trends on superconducting power transformers, what problems Japan faces to develop a superconducting power transformer, and how Japan is handling these problems.

The advantage of a superconducting power transformer is small size, lightweight, and improved efficiency. This is based on the guideline that after setting one-turn voltage, which is a parameter for designing a power transformer, lower than that of a normal conductor and decreasing the cross section of the iron core, if we take advantage of low loss and high current density, which are characteristics of a superconducting wire, we can make the coil smaller and lighter even if the number of windings increases.Critics will ask what the point is of converting a power transformer with efficiency of over 99 % into a superconducting power transformer. For a power transformer installed in an underground substation in an urban area, the initial equipment costs to take a 1 % heating value from underground to outside and cool it down account for 40 % or 50 % of the power transformer cost because the transmitted power is enormous, even with only a 1 % transmission loss. This fact is little known. If the loss, in other words, the heating value, is decreased to one third or one

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fifth by developing a superconducting power transformer, the initial equipment costs will be substantially reduced.

Making a power transformer more compact and lightweight by only taking advantage of the characteristic of a superconducting wire, that is, high current density, is possible. However, unless the superconducting wire has a low AC loss, an improvement in efficiency will not be achieved. Since a cryocooler commensurate with the amount of loss is required, neither weight nor size reduction will be achieved as a power transformer system.

An experimental fabrication of a superconducting power transformer by the sub-cool liquid nitrogen cooling method using Bi2223 wires has already been performed four times in Japan: (1) a 6.6/3.3 kV-800 kVA power transformer in 1996 (Kyushu University and Fuji Electric Holdings Co., Ltd.), (2) a 22/6.9 kV-1 MVA power transformer in 1998 (NEDO: Fukuoka Prefecture Local Consortium Research and Development Project, Kyushu Electric Power Co., Inc.), (3) a 66/6.9 kV-2 MVA power transformer in 2003 (NEDO: National project), (4) a 25/1.2/0.4 kV-4 MVA power transformer for a Shinkansen train in 2005 (Railway Technical Research Institute). All of them were single-phase power transformers. For characteristics other than short-circuit strength, the operation up to design rating has been verified. In particular, Japan's first power system interconnection test with a 22/6.9 kV-1 MVA power transformer in item 2 was carried out at the Imajuku substation of Kyushu Electric Power Co., Inc. Also, for item 2, a 22/6.9 kV-1 MVA power transformer, a 100-kV impulse withstand voltage test was conducted on the actual unit. For item 3, a 66/6.9 kV-2 MVA power transformer, a 350-kV impulse withstand voltage test and a 140-kV AC overvoltage test were carried out on the actual unit. The insulation strength was verified, too. Although the Bi2223 wires demonstrated high current density, they did not achieve low AC loss so that the superconducting power transformer by the sub-cool liquid nitrogen cooling method using Bi2223 wire was not appealing as a true superconducting power transformer system.

In NEDO's Fundamental Superconducting Application Technology Research and Development Project, the development of a superconducting power transformer was begun to solve the above-mentioned problem, i.e. reducing the AC loss of wire. The main theme of the project is to develop a YBCO thin-film superconducting tape, but development aimed at reducing AC loss was started, according to the above-mentioned logic, to set a goal that a superconducting power transformer should also have characteristics enabling application to general equipment. However, the guidelines for reducing the AC coil loss of conventional superconducting multi-core wires, that is, the techniques for reducing the hysteresis loss by making filaments thinner and reducing the coupling loss by making the resistance of matrix materials higher and making twist pitches shorter, cannot be applied to thin-film tape wires.

Therefore, in the project, we proposed a new concept to reduce the AC losses in superconducting thin films ahead of other countries. In order to achieve this goal, we are developing wires and conducting a verification experiment at coil levels. Although the details have not been disclosed yet because of international patent pending, the new concept is a combination of scribing processing of thin film tape wires into multifilament wires by laser or etching and special winding technology. Since the buffer layer is made of insulators, filaments are electrically insulated from each other though they are on the same substrate. In the project, a three-filament wire was obtained by scribing a 10-mm-wide YBCO wire by laser and the wire was wound into a 16-layer coil. The coil was compared with a coil made of an unprocessed wire. It was verified that the AC loss was reduced to one third. Furthermore, a 5-filament wire was obtained by scribing a 5-mm-wide wire by laser and the wire was wound into a 19-layer coil. It was also verified that the AC loss was reduced to one fifth, compared with the coil made of an unprocessed wire. According to the person in charge, as the wire fabrication technology improves, the AC loss will be further reduced in proportion to the filament width.

Unfortunately, as mentioned above, research and development of the superconducting power

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transformer is not being carried on in Europe and the United States. European and American researchers woke up to the fact that the low AC loss of superconducting wires is the key not only to power transformers, but to all superconducting power equipment. The necessity of reducing AC loss has already been understood qualitatively. The product of research and development enabled the quantitative determination of the low AC loss. Under the auspices of DOE in the United States, a research group consisting of Waukesha Electric Systems, SuperPower, Energy East, and ORNL tried to fabricate a three-phase 24.9 kV/4.2 kV-5/10 MVA power transformer on an experimental basis through 2003 and into 2004, aiming to develop a 138 kV/13.8 kV-30 MVA power transformer, and tried to test its characteristics. Bi2223 wires were used. As helium gas was used as a cooling medium, the power transformer produced a dielectric breakdown. As a result, the trial fabrication ended in failure. Subsequently, the United States decided to suspend the development because there is little hope of reducing the AC superconducting wire loss. In Europe and the United State, the research and development of superconducting rotary machines continues because a superconducting rotating field winding has basically a DC specification.

In NEDO's Fundamental Superconducting Application Technology Research and Development Project, in addition to reducing the AC wire loss, the project team succeeded in both AC and DC conduction tests of a kA-class large current capacity conductor with REBCO wires used for a transposed parallel conductor. Also, in order to meet JEC standards, the project team has repeated a dielectric breakdown test, using a partial simulation test coil, and has been trying to determine the required insulation distance.

A successor project, Materials & Power Application of Coated Conductor, to the Fundamental Superconducting Application Technology Research and Development Project began in fiscal 2008. The fabrication of a 2 MVA-6 MVA power transformer of 66/6.9 kV on an experimental basis in four years has been planned. Superconducting windings and cables of high-current density are provided with a fault current limiting function by taking advantage of S/N transition. From this perspective, in this project, the development of an original technology to add a fault current limiting function to a superconducting power transformer, without imitating Western technologies, has been planned from the very beginning.

(Published in a Japanese version in the November 2008 issue of *Superconductivity Web 21*)

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Feature Articles: Technical Trends of Superconducting Power Equipment - Technical Trends of Superconducting Fault Current Limiter (SFCL) -

There are more presentations on SFCL than on other power equipment.

The fault current limiting function is characteristic of superconductivity. The fault current limiting function based on MgB_2 wires, as well as 1G and 2G wires, has been researched. Also, a variety of reports were made on the technological clarification of the fault current limiting phenomenon, the structure to develop and produce a fault current limiting function, the concept of fault current limiting taking advantage of temperature dependency, the interlocking with a high-speed switch, and more. I will report the progress of major projects country-by-country.

The United States

2G wires are used in the 115 kV fault current limiter project implemented by Southern California Edison (SCE), SIEMENS, AMSC, Nexans, and other institutions. A prototype fault current limiter that reduces a fault current (short-circuit current) of 63 kA to 40 kA at a rated current of 1,200 A is under development. In this fault current limiter, the superconducting wires can be shortened and the current can be maintained at proper levels by connecting an SFCL and a high-speed switch in a series circuit and connecting inductance in parallel circuit. The fault current limiter will be introduced into the secondary Bus Tie of the 500-kV/115-kV substation.

2G wires are used in the 138-kV fault current limiter project implemented by SuperPower, AEP, EPRI, Oak Ridge National Laboratory, Sumitomo Electric Industries, Ltd., and other institutions. This limiter operates a fault current of 13.8 kA (a design value of 37 kA) at a rated current of 1,200 A. At present, these companies are fabricating a prototype to verify the reliability by passing the fault current while passing the load current through the limiter.

Japan

Toshiba Corporation reported the development of a 6.6 kV fault current limiter as an achievement of Fundamental Superconducting Application Technologies Project. A factory test showed that an S/N transition type fault current limiter using 2G wires reduced a fault current of 1,600 A to 800 A. Now that the fault current limiter has achieved the desired results, Toshiba Corporation is conducting a test in the field where a house power generator has been installed. The purpose of this fault current limiter is to hold down the current passing from the house power generator into the electric power system in the event of an accident in the system. Toshiba reported that the company would develop a fault current limiter of a higher voltage.

Korea

Korea is developing a 22.9 kV, 3 kA fault current limiter to prevent a fault current caused on the secondary side of the 154 kV/22.9 kV substation. At present, a 22.9 kV, 630 A fault current limiter is under development at an intermediate stage. This fault current limiter is a hybrid between the S/N transition type and saturated iron core type. As Korea sees a steadily growing demand for power and short-circuit capacity is increasing, the country has great expectations for superconducting fault current limiters as economical and reliable measures against fault currents.

China

China has already developed a fault current limiter of saturated iron core type using three-phase 35 kV/90

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MVA Bi-based wires, introduced it into an actual system, and conducted a test. Furthermore, China reported a new project in which a 220 kV/1,200 A fault current limiter is under development to introduce it into the system in 2009.

(Noboru Fujiwara, Director of the Electric Power Equipment Division, SRL/ISTEC)

(Published in a Japanese version in the November 2008 issue of *Superconductivity Web 21*)

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