Development of Superconducting Technologies for the Smart grid

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ABSTRACT Superconducting wires that can send large current with low loss have been developed and commercialized since the discovery of superconductivity a century ago. Practical use of superconductors in applications that include an MRI magnet has also been progressing. Furthermore, since high-temperature superconducting materials, which have a critical temperature in the liquid nitrogen range, were discovered 25 years ago, superconductivity could be adopted in a wider range of applications such as electric power devices and industrial equipment.
On the other hand, during this century, the rapidly growing population in the world is creating a higher consumption of fossil fuels. Pervasive issues such as global warming, exhaustion of fossil fuels and others are emerging. Superconducting technologies are not only considered an energy-saving technology, but also new technology that promotes the availability of a larger amount of renewable energy for the smart grid.
Furukawa Electric (FEC) has started to develop superconducting applications that can be used for the smart grid. We are explaining the superconducting devices used for the smart grid and the present status of FEC development in superconducting applications.

1. INTRODUCTION

Superconductivity is that phenomenon where some metals or compounds have no resistivity when it is cooled to extremely-low temperature. The phenomenon was discovered by Heike Kamerlingh Onnes who was a physicist of Leiden University one hundred-two year ago. He found that electrical resistance of mercury became zero at temperature of 4.2 K that was achieved by liquefaction of helium. In the year 1911, when the great physical phenomenon was discovered, the Xinhai [Hsin-hai] Revolution was happening and the Qing dynasty, which controlled China, was imploding in the next year. In Japan, Meiji emperor passed away and Taisyo era started in the following year. From then, the world was heading to a world war. On the other hand, around that time is the predawn of dramatic developments in science field, such as the introduction of Einstein's theory of relativity and the quantum theory.

According to U.N. estimate[1), 2)], the world population of 1911 was about 1.7 billion, and U.N. announced the population went over 7 billion at end of December 2012. (Figure 1) Moreover, because the increasing of population accelerates, the population may increase by 1 billion in the next 20 years. The population increase affects severely the consumption of energy. In Figure 2, the consumption of energy in 1910 was about 1 hundred million ton per year in fuel equivalent. The consumption of energy in 2010 was 1 billion ton per year. It is ten times larger than one of 1911[3)].

Increasing population and consumption of energy will create present issues of shortage of energy, food and water, and future issues of depleted fossil fuel and global warming. Regarding the continuous use of fossil fuels, petroleum and natural gas would run short within 50 years, and coal would run short within 130 years. There are also other problems such as looming abnormal weather, harmful effect of ecology and outbreak of a health infection due to the global warming. Rising sea level is a serious issue for countries that have economical centers and residential area in low altitude place.

To avoid global warming issue, it is necessary that people avoids burning fossil fuel and exhausting huge amount of carbon dioxide, decreases energy consumption by saving energy, and promotes energy supply from renewable sources such as wind-energy and solar energy. In particular, smart grid will be instrumental in the energy saving and in the introduction of the renewable energy. Consequently, FEC expects that superconducting technologies will be one of the key technologies in the smart grid and it will become a future growing business.

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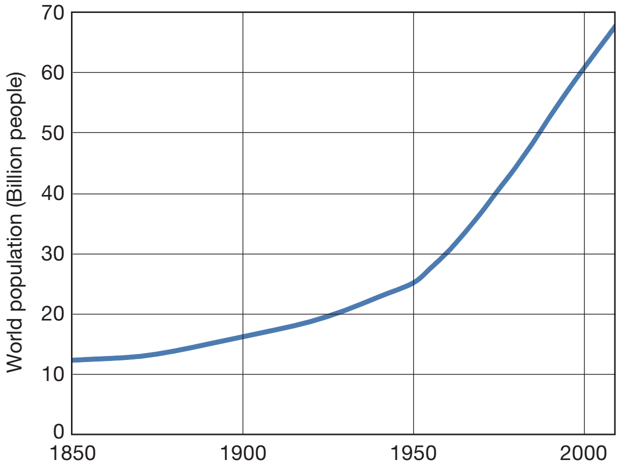


Figure 1　Transition of the population of the world.

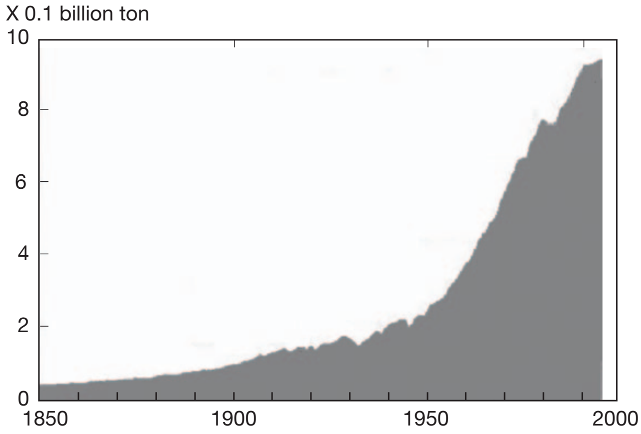


Figure 2　Transition of consumption amount of energy in the world.

2. SUPERCONDUCTING TECHNOLOGIES IN THE SMART GRID

If we talk about the smart grid in terms of superconductivity, the smart grid is an electrical power system that controls energy flow from both the side of the supplier and consumers, it optimizes the combination of various energy sources and delivers the power in a highly effective, reliable and safe way. Especially, the introduction of wind and solar power generation reduces the fuel energy percentage and greenhouse gas emissions, helping the development of human life and the economy. We believe that superconductor technologies will be one of the technologies that promote the introduction of renewable energy.

FEC has developed a superconducting cable (HTS cable), a superconducting fault current limiter (SFCL), and superconducting energy storage. Each of these devices can be included among the superconducting equipment in the Smart grid. An HTS cable is a power transmission cable that can feed large electrical power at a low transmission loss in a conductor of small cross section by using superconducting wires in the conductor. If the renewable energy generator is a new construction, we also construct a new transmission line from the generator to the power network. The HTS cable will be used in the transmission line as a highly efficient transmission line. FEC expects that the SFCL will be one of the power devices that permits a large number of renewable energy generators and avoids the risk of a network accident such as a ground fault and a circuit fault in a complex and huge power network.

As for superconducting energy storage, there is a superconducting magnetic energy storage system (SMES) and a fly-wheel energy storage system (FESS). The electrical power is stored by the SMES as magnetic energy, and by the FESS as kinetic (rotation) energy. We are reporting the status of the development of these devices at FEC.

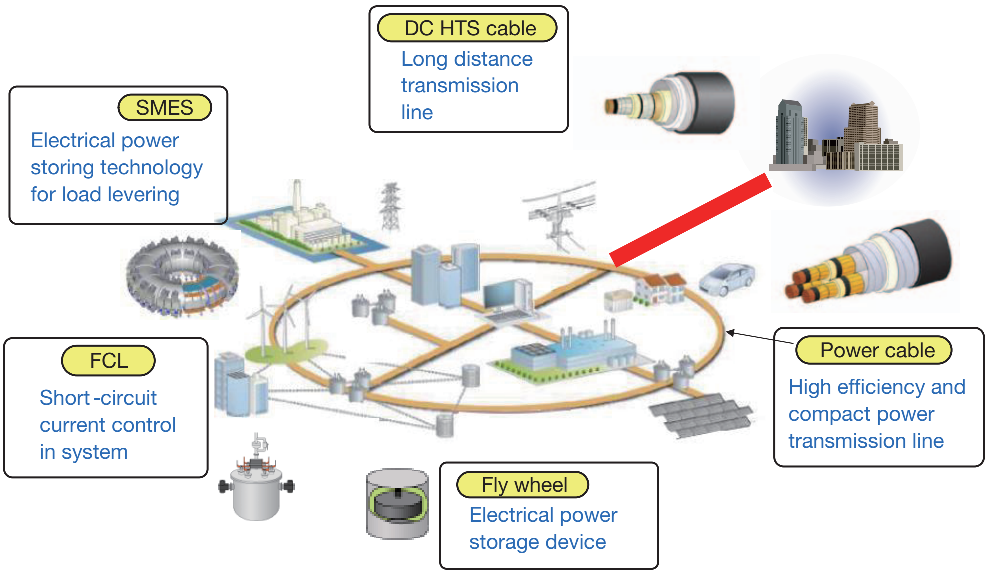


Figure 3　Superconducting devices in Smart grid.

3. HTS CABLE

Figure 4 shows the structure of the HTS cable that was made from high-Tc superconducting tapes (HTS wire). HTS cable consists of a cable core and a cryostat pipe. The cable core consists of a copper stranded cylindrical conductor that is called former, a conductor layer that is a wound HTS tapes around the former, an electrical insulation layer (dielectric layer) that is a wound dielectric papers around the conductor layer, an HTS shield layer that is a wound HTS tapes around the insulation and a protective layer. The cryostat pipe is utilized for flowing liquid nitrogen (LN_2) that cools the cable core at about -200 degree C. The cryostat pipe needs a thermal insulation layer between the pipes. Moreover a vacuum between the two corrugated pipes is maintained in the cryostat pipe in order to obtain a high thermal insulation property. We call the HTS cable that has one cable core in the cryostat pipe as a 'single core cable', the HTS cable that has three cable cores in the cryostat pipe as a 'three core cable', The single core cable is used in high voltage cables such as 275 kV cable, which has thick dielectric, and the three core cable is used in medium voltage cables as 66/77 kV cable, whose cable cores has a small diameter.

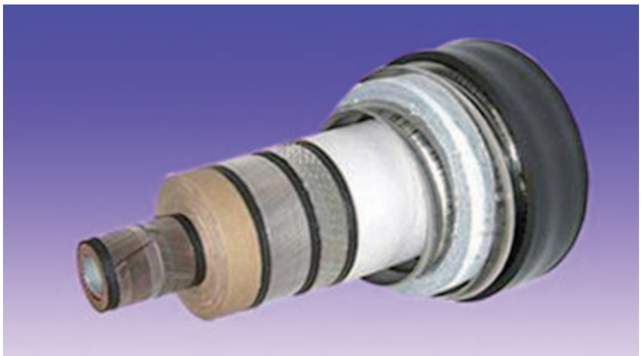


Figure 4 Single core HTS cable (275 kV 3 kA).

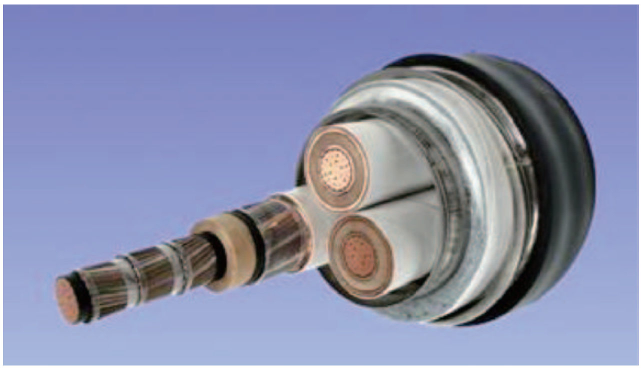


Figure 5 Three core HTS cable (66/77 kV 3 kA).

3.1 Development of Bi Based HTS Cable

FEC started HTS cable development by using HTS conductor from the time when HTS material was discovered. FEC presented a demonstration of a prototype cable that consisted of a cable core of 5-m length, a 66 kV-2 kAp, a cryostat pipe and terminations in collaboration with Tokyo Electric Power Company (TEPCO)[4)]. In 2000, FEC fabricated 66 kV three core cable of 20 m length and tested it [5)].

We have participated in the New Energy and Industrial Technology Development Organization (NEDO) projects since 2000, such as Super-ACE project, M-PACC project, … etc., We have implemented the innovations of HTS cable technologies and the basic cable technologies such as AC loss, insulation, electrical and mechanical properties and the accessories such as a termination, a cable joint and a cryogenic system, … etc. [6)].

In the Super-ACE project (2000-2005), in order to investigate the practical development of a long length HTS cable, we demonstrated a 500 m HTS cable, which was the longest cable at that time in the world, and FEC installed it at Yokosuka Lab. in Central Research Institute of Electric Power Industry (CRIEPI) as shown in Figure 6. The cable was a single core cable of 77 kV and 1 kA in a cable, with 143 mm diameter installed in a cable conduit. The cable manufacture and the cable installation contractor were FEC. Long term voltage current loading tests were conducted by CRIEPI and FEC. The test started from March 2004, and for one year we conducted various tests to get cooling properties, thermal mechanical properties, electrical properties, and superconductive properties of the cable and the system as necessary experiences for the practical installation[7)].

3.2 Development of the Yttrium Based HTS Cable

FEC started the development of the Yttrium based HTS cable (YBCO HTS cable) that uses YBCO wires from 2006 in the NEDO project. The wire has a property of a high critical current and a potential of low cost. FEC evaluated the applicability of YBCO wire to the cable, and conducted a short circuit test of 31.5 kA, 2 sec by using 20 m long cable during cooling the cable at 77.3 K[8)]. Full blown YBCO HTS cable development was installed in the M-PACC project of NEDO from 2008 to 2013. Previous HTS cable development has aimed medium voltage cable with 10 kV to 77 kV because it can be replaced with a conventional underground cable in the urban area. The HTS cable needs compact and large transmission capacity compared to the conventional cable. On the other hand, recent high voltage cables have been developed for the backbone network in many countries. The backbone network in Japan consists of overhead lines of 275 kV to 500 kV and the underground cables of 275 kV. FEC has advanced a 275 kV 3 kA HTS cable development that is the highest voltage and the largest power in the world as a part of the M-PACC project[9)].The electrical insulation is the most important technology in the 275 kV HTS cable

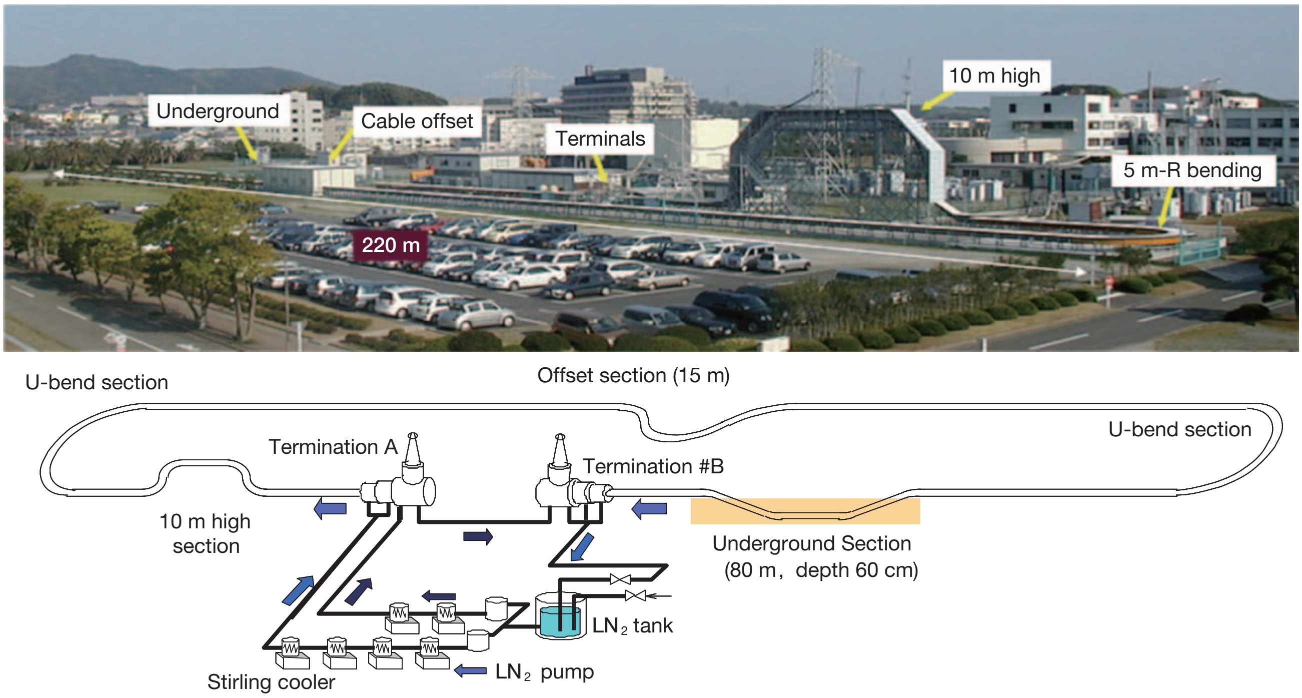
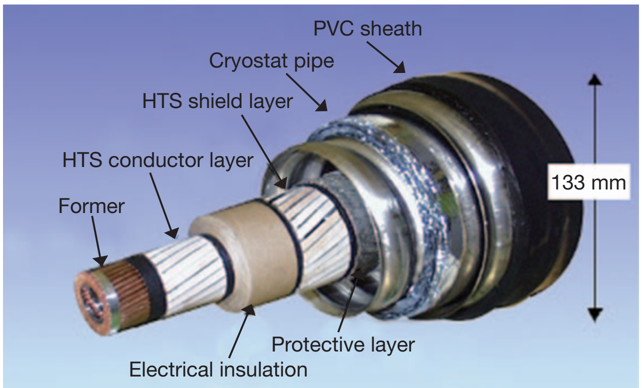


Figure 6 Layout of 500 m HTS cable demonstration in the Super-ACE project.

development. The thickness of the cable insulation is increased in proportion to the operation voltage. If the dielectric loss and the AC loss are high, the temperature of the conductor rises and the superconductivity is not maintained because most electrical insulation materials have bad thermal conductivity. Therefore, the high voltage HTS cable requires low cable losses such as AC loss and dielectric loss. These technologies are explained in detail in the next paper. We need to study the reliability of the electrical insulation for a power cable. First we selected a dielectric material that doesn't electrically breakdown for long period, and we made cable samples and tested them under AC breakdown test and impulse breakdown test to get their permissive stresses for the design. Under a low voltage at which the sample doesn't break down, it is thought that a partial discharge in the insulation deteriorates dielectric property. We have measured Partial Discharge Inception Volt (PDIV) and a degradation factor of the long-term life, by obtaining the initiation time under supplying less than PDIV for long time. The insulation thickness of 275 kV HTS cable insulation was determined by using the design stress that was estimated from these data of the breakdown and the longtime stability.

With respect to the hysteresis loss in the superconducting layer, we have reduced it by using the 3 mm width tape for the layer, and by winding the tapes with a small gap between tapes. From the method, the AC loss achieved was 0.12 W/m at 3 kA, which is 50 % less than a previous HTS conductor. This AC loss value leads to that the transmission loss of the 275 kV HTS cable becomes about one forth compared to conventional Cross-linked polyethylene (XLPE) cable of the same capacity. In general the energy save effect of superconducting devices is more important in large capacity devices than in small capacity devices. It is expected the use of the 275 kV HTS cable into real power networks will reduce emission of carbon dioxide. [10), 11)]



Specification	
Voltage	77 kV
Current	1 kA
Thermal invasion	1 W/m
Wire	BSCCO

Figure 7 Structure of 500 m HTS cable.

Figure 8 **Short-circuit current test of the 66 kV-3 kA YBCO HTS cable (A cable joint, and a 10 m cable that was set in the back from the joint were fabricated by FEC).**

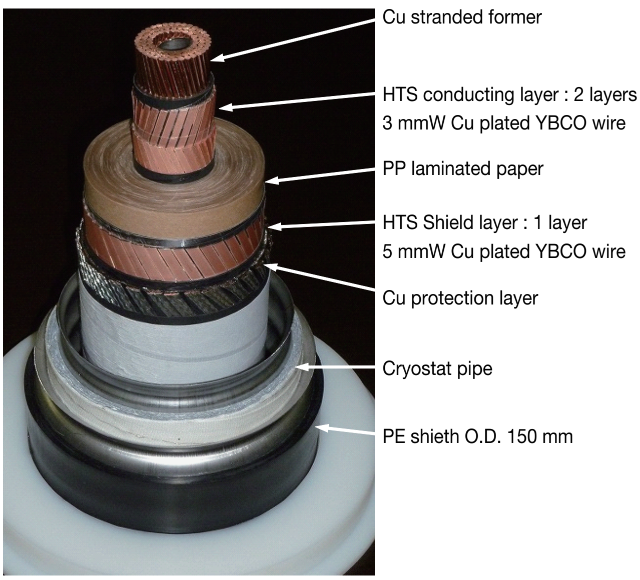


Figure 9 **Structure of the 275 kV 3 kA HTS cable.**

4. FAULT CURRENT LIMITTER

Short-circuit accidents often happen on a transmission line because the line comes into contact with other things such as a tree, an animal or a crane, the line is hit by lightning, the line is cut by the load of the snow or the electrical breakdown of a transformer because of aging. If the accident of earth fault and short-circuit fault happens, large current flows in the line to the fault point because of the reduced impedance at the point. The fault sometimes forces a blackout in the network. In Japan, the blackout rate is very low because the power utilities check the power equipment periodically to avoid faults. In case of a fault, the fault line is instantaneously shut off by a protection relay. The protection relay has been improved as breaking speed of the current relay is less than 0.1 sec, which is about 1/10 compared to old relays. However fault current is increased by enhanced and complex power networks and by the introduction of renewable energy generators. If the fault current magnitude surpasses the capacity of a protection relay system, the relay cannot break the circuit. And, if all relays were to be replaced, it would be at a large cost. It is proposed to introduce the fault current limiter to the networks in order to suppress fault current.

SFCL presents low impedance when operating at a low current at its superconducting state during steady state condition, but its impedance rises quickly when operating at normal conductivity during fault condition.

Conventional relay has a certain delay time from the detection to the operation. SFCL can suppress the first wave of the fault current and can reduce maximum current. FEC has developed the SFCL, called resistive superconducting fault current limiter, by making use of the transition between superconductivity and normal-conductivity.

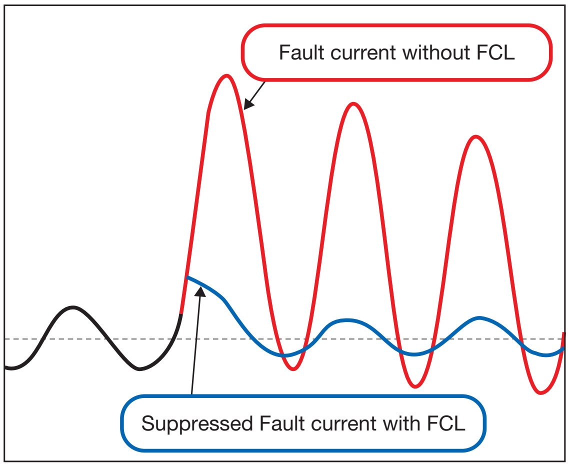
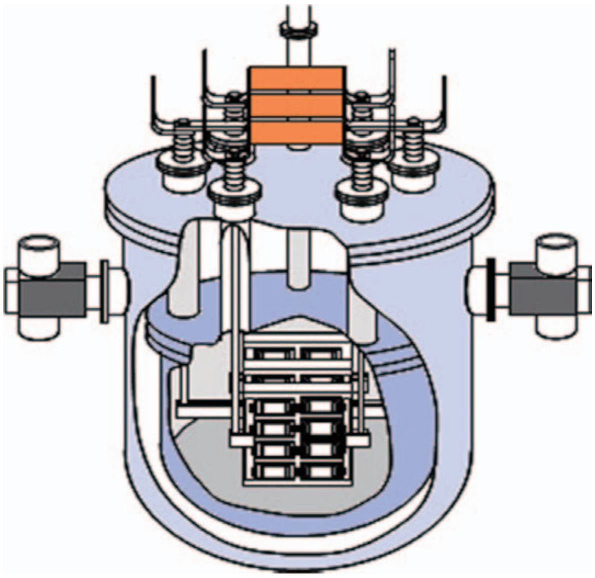


Figure 10 **Principle of resistive SFCL (Suppressing Fault Current).**

FEC group has developed two types of SFCL. One is an SFCL that uses YBCO thin film superconducting plate, and the other is the SFCL that uses 2G HTS wires by SuperPower Inc. (SP) which is Furukawa's subsidiary company in U.S. Both SFCLs utilize superconducting/normal state transition on the YBCO thin film plates and the 2G wires, respectively. SFCL utilizing the YCBO elements which has a state named superconducting/normal state transition (S/N state transition). This element presents a zero electrical resistance in its normal operation state and a high electrical resistance when an over current exceeds a specific threshold, thus limiting this over current. The SFCL houses multiple YBCO elements in a cryostat which is a sealed container kept at low temperature by liquid nitrogen. Figure 11 shows thin-film superconducting plate (thin film) and conceptual diagram of SFCL. The thin film has been developed by FEC by introducing the process of metal organic deposition (MOD) technology developed by Agency of Industrial Science and Technology (AIST)[12]. The structure of the thin film consists of an intermediate layer, a superconducting layer and a metallic protective layer on the sapphire substrate (plate). In the SFCL using the thin film, a SFCL unit joints the 32 thin film plates per one phase films in 4 parallel and 8 serial, and the thin film is connected to current leads that feed current to the SFCL units. We have designed the SFCL with 6.6 kV 400 A as a protection device for distribution networks and for renewable generation system.

SuperPower Inc., a subsidiary of the FEC group has developed a 138 kV proof-of-concept SFCL, as depicted in Figure 12, and has further developed and tested FCL modules using SuperPower 2G HTS wires. The SFCLs are intended to be used in the protection equipment of a high voltage transmission network.



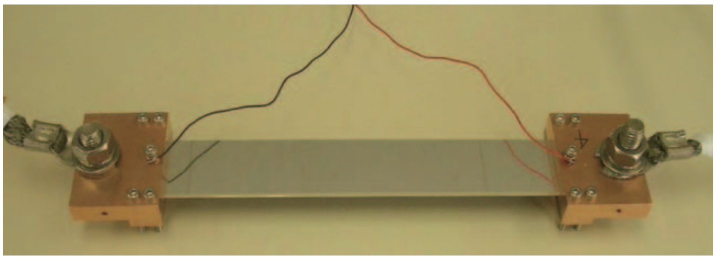
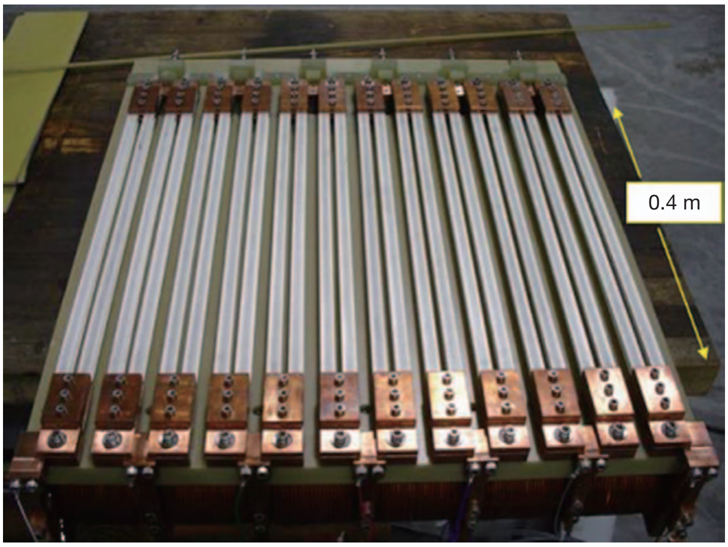


Figure 11 Conceptual design of SFCL and thin film YBCO superconducting plate. These were designed and fabricated by FEC.



FCL unit combined 2G HTS wires

Figure 12 SFCL with 2G HTS wires developed by SuperPower Inc.

Table 1 Specifications of the SFCL developed by SuperPower Inc.

	Transmission SFCL
Line Voltage	138 kV
Load Current (rms)	1,200 A
Power	165.6 MVA
Prospective Fault	40 kA
Limited Fault	10 kA
Limiting Capability	65-75 %
Type of Superconductor	2G HTS wire
Working Temperature	68 K – 77 K
Recovery Under Load	RUL Capable
Repetitive Fault Freq.	Any
Fault Duration	Any
System Dependence	100% Passive
Ground Footprint 3 Phase	6 m^2
MVA/Footprint	27.6 MVA/m^2

5. SUPERCONDUCTING ENERGY STORAGE SYSTEM

Renewable energy such as a wind generation and a solar panel that are expected to have a higher share of generated power depending the condition of wind and sunlight. To utilize the natural energies effectively, it is necessary and important to prevent fluctuation of the output. The energy storage system is one of the candidate solutions to absorb the fluctuation and to make output flat. The storage system required has to have the main features of a quick response, and repetitiveness of charge and discharge. Therefore, a battery based on chemical reaction doesn't provide a quick response and we have to consider a lifetime under repetitive charge and discharge. The superconducting energy storage system (SESS) such as SMES and FESS has semi-permanent lifetime.

5.1 SMES

Chubu Electric Power company (Chuden) and Toshiba developed the SMES for stabilization of power networks in Superconducting power network technology project supported by NEDO and METI from 2004 and they conducted a field test of 20 MJ class SMES in 2007. The SMES was connected to a real network in Hosoo water generation of Furukawa Nikko Power generation Inc.[13] The system used NbTi wires manufactured by Nikko factory of FEC and the system was cooled with liquid helium. (Figure 13)

Regarding HTS SMES used HTS wires, Chuden and FEC have developed the HTS SMES in the M-PACC project. The HTS SMES is expected to be low cost and small size compared to the LTS SMES[14]. Chuden has addressed test of 20 MJ elementary coil and design high field and compact coil of 2 GJ class. Chuden also addressed a refrigerator cooling technology for easy maintenance. FEC has developed a 2G wire by Metal Organic Chemical Vapor Deposition (MOCVD) to supply the wire to SMES development.

Capacity : 10,000 kW
Storage Energy : 19 MJ
Operation Temp. : 4.2 K
Operation Current : 1350 A
Operation Voltage : 1.1 kV
Maximum magnetic field : 4.4 T

Figure 13 LTS SMES that set in Hosoo water power plant of Furukawa Nikko Power generation Inc.. (2007~2008).

5.2 Flywheel Energy Storage system (FESS)

Railway technology research institute (RTRI), Kubotech, Mirapuro, Yamanashi Prefecture, and FEC started a next-generation flywheel electrical storage system development, in collaboration, in Development of Safe and low cost large scale electrical storage system technologies supported by NEDO.

A FESS stores electrical power that solar panels generate by rotating a heavy wheel in the equipment[15]. If electricity generated is decreased due to cloudy weather, flywheel outputs electricity to refill the decreased generation of electricity. The system that we are developing aims strong property in repetitive operation and good efficiency in the operation by using a superconducting technology to float the rotating wheel. FEC developed a HTS coil that is an element of the superconducting magnetic bearing. In the FESS project, design and fabrication of the FESS will be carried out from 2014 to 2016, and a prototype of the FESS will be tested at Mt. Yonekura in Yamanashi prefecture with solar panels constructed in 2017.

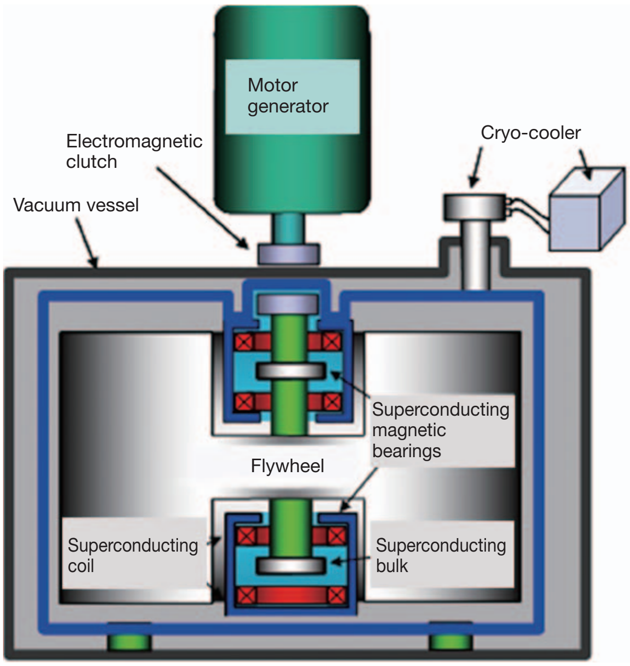


Figure 14 Conceptual design of Flywheel Energy Storage System (FESS).

6. FUTURE DEVELOPMENT

It is thought that one of the solutions for achieving responsibility in reduction of the CO_2 emission in future is to introduce a lot of new power sources that do not use fossil fuel. Due to the high degree expectation of renewable energy, the quantity and the schedule of the introduction may be large and fast. However, if a lot of the distributed power sources are connected into the network, many kinds of problems would be occur. Especially, since the renewable energy source of the distributed power source leads to power fluctuation, there is the issue that introduction of the renewable power source will receive limit quantitatively not to accept lager quantity than the permitted capacity of the network. The HTS cable, SFCL and FESS that are mentioned above seem to have possibility solved these problems. If the superconducting devices are listed as components of a smart grid, we think, that could make the design flexibility and the economical efficiency higher. Moreover we could design smart grid system that earns large profit. Therefore, the HTS devices should be developed considering cost and early development by the time of its practical implementation in 2020. If an HTS device is used as infrastructure equipment, it is required to provide reliability, stability and safety. To confirm the reliability and so on, field test of the real network is important. FEC expects to participate in the field demonstration with power utilities or power producers.

7. SUMMARY

The superconducting phenomenon was discovered a century ago, a High-Tc superconducting material was also discovered one fourth century ago, and Tokyo Central Laboratories of FEC started a development of superconducting wires half century ago and started producing and selling NbTi wires in 1968. FEC has commercialized many kinds of material of superconducting wire since then, and FEC has supplied these wires in the applications of MRI magnet, accelerator, nuclear fusion, and other advanced applications. However, the business scale is smaller than main business fields of FEC such as power cable, telecommunication cable and non-ferrous materials, and the scale of the quantity keeps for long time as almost same. The major causes are that superconducting materials are expensive and these need to be cooled at cryogenic temperature. The applications that outweigh these negative points are the devices and the feature that can't be realized by conventional material such as aluminum and copper. However, it appears that the HTS material might expand its applications in energy saving devices and economical devices, because the cooling penalty is improved by changing liquid nitrogen from liquid helium as coolant, and cost of the wires will be expected to be good cost performance. This year, FEC acquired HTS wire maker of SuperPower Inc. in U.S. , which sell 2G wires around the world.

The smart grid seems to be a useful technology for not only developed countries like Japan but also, especially, for the improvement of the infrastructure of developing countries. Modern society has been depending on the large consumption of energy consumption, in particular by burning fossil fuel. The introduction of the smart grid will allow the development of a smart society and of an efficient social environment. We are confident that superconducting technologies would continuously contribute to the improvement of societies and technologies, from a smart grid and environment view point.

Acknowledgment

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