Development of High-Tc Superconducting Power Cable

by Shin'ichi Mukoyama [*], *Noboru Ishii* [*], *Hiroyuki Iizuka* [*], *Masashi Yagi* [*], *Hironobu Hirano* [*], *Satoru Maruyama* [*], *Yukihiro Yagi* [*], *Masanao Mimura* [*2], *Osamu Sato* [*3] *and Ayafumi Kikuchi* [*4]

ABSTRACT Furukawa Electric is participating in the Super-ACE Project for R&D on fundamental technologies for superconducting AC power equipment that was initiated by METI (The Ministry of Economy, Trade and Industry) in FY2000, and is also carrying out R&D for the High-Tc superconducting electric power cable (HTS cable), which can miniaturize cable size while supplying large electrical power. The introduction of the HTS cable into an electrical network can be expected to produce significant effects because it can meet needs for control of the global emission of CO_2, alleviation of environmental impact, improvement in stability levels and reduction in costs in the network.

Practical use of superconducting cable requires the development of technologies for reducing losses in large capacity cables and cooling long cables. In developing the low loss cable, Furukawa has achieved a technological level of 1 W/m at 3 kA by pitch adjustment and by using twisted filament wires. In terms of cooling long cables, Furukawa has manufactured a 30-m HTS cable model, thereby improving thermal contraction properties, heat loss properties and liquid nitrogen flow. With the success of 30-m cable test, it is planned that field testing of a 500-m, 77-kV single-core HTS cable will be carried out in 2004 at the Yokosuka Laboratory of CRIEPI (Central Research Institute of Electric Power Industry). This field testing will include a construction test, a cooling test, a long term voltage and current load test and so on.

1. INTRODUCTION

Electric power networks connecting power plants to urban areas are composed of overhead lines and underground cables, with the latter used mainly in the urban areas. As the underground cables use copper conductors, current density is about 1 A/mm^2. In contrast, the HTS cable can conduct 50 to 100 A/mm^2 since the HTS wire becomes a superconductor at the temperature of liquid nitrogen (77 K). An underground cable using an HTS wire conductor is therefore considerably more compact. Existing high-voltage cables need a tunnel 3 m in diameter, but an HTS superconducting cable can be installed in a cable duct that is only 150 mm in diameter and can be constructed at a lower cost and in a shorter period. Operating cost is also expected to be reduced because the loss by electric resistance can be minimized, and lower power loss can ultimately reduce CO_2 emissions. The leakage magnetic field from the cable is zero and cable reactance is decreased by a superconducting shield. The resulting increase in the limits on transmission power means that intermediate substations in the power network can be omitted, and construction costs is reduced accordingly [1)]. Thus the HTS power cable is an effective technology to expand the capacity of electrical power networks.

It is said that, from the standpoint of environmental preservation of the earth, energy sources have to shift to electrical power in order to maintain stabilized growth of energy supply. For this reason R&D on superconducting cables is being actively conducted in advanced nations. In Japan, the Super-ACE Project of METI, a developmental project commissioned from NEDO (New Energy and Industrial Technology Development Organization) to Super-GM (Engineering Research Association for

[*] Energy Transmission Research Dept., Ecology and Energy Lab. R & D Div.
[*2] Metal Research Center, R & D Div.
[*3] Power Cable Manufacturing Dept., Power Cables Div.
[*4] Super-GM

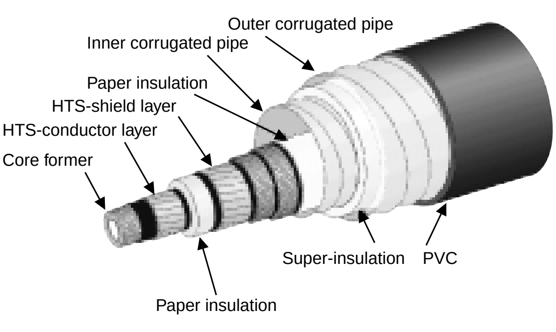

Figure 1 **HTS power cable with single core and cryogenic dielectric.**

Superconductive Generation Equipment and Materials), started in 2000. This project involves R&D on the basic technologies of HTS cables, HTS fault-current-limiters and HTS magnets for reactors and transformers. Furukawa Electric is proceeding with the development of the superconducting cable, and as part of this project is scheduling field testing of a 500-m HTS cable at the Yokosuka Laboratory of CRIEPI in 2003.

2. HTS CABLE

The HTS cable is a power transmission cable that takes advantage of superconductivity by which electrical resistance is zero. A large amount of electric power can thus be transmitted by a compact HTS cable that can be installed in a duct of 150 mm diameter. Figure 1 shows the structure of an HTS cable with a single core and cryogenic dielectric. The core of the HTS cable, consisting of an HTS-conductor layer, an electric insulation layer and an HTS-shield layer around a flexible core former, enclosed in a cryogenic pipe comprising double stainless steel pipes that provide vacuum insulation using super-insulation (SI).

The HTS conductor layer, in which the current flows, consists of a large amount of Bi2223 silver alloy sheath tape wound spirally around the core former. The insulation layer is a laminated structure of semi-synthetic paper. In operation, the insulation layer is infused with the pressurized liquid nitrogen to maintain high insulation performance. The HTS shield layer, in which the shielding current flows, consists of a large amount of Bi2223 silver alloy sheath tape wound spirally, as in the conductor layer. By connecting the ends of three shield layers constituting three-phase AC supply, a shielding current of equal magnitude but opposite phase is induced by the conductor current. As a result, magnetic field leakage to the outside is shielded and becomes zero. The current on the cryogenic pipe sheath is suppressed negligibly small, and the sheath loss is decreased effectively.

3. REDUCING AC LOSSES IN THE HTS CABLE

The advantage of the HTS cable is the possibility of large power transmission despite of its compact size because of low losses. The losses of the HTS cable comprise AC losses (hysteresis loss, coupling loss, etc.) and heat invasion loss in the cryogenic pipe. Unless these losses are effectively reduced, the advantage of using a superconducting cable is lost. Therefore, techniques for reducing heat invasion and AC losses are very important in applying the HTS cable in a practical power network. Furukawa Electric is developing these aspects of the Super-ACE Project.

In an HTS cable with identical spiral pitch in the outer and inner layers, current is concentrated in the outer layer because its inductance is smaller than that of the inner layer. This state is known as a non-uniform distribution current state. AC current flows in the conductor with non-uniform distribution, the magnetization remaining in the tape is large and the hysteresis loss also becomes large. The authors found this phenomenon in the current test of the 50-m long HTS conductor [2].

We assumed that adjusting the spiral pitch would equalize the inductance. A method of adjusting spiral pitch was developed to equalize current distribution in the conductor and reduce AC losses [3]. The principle of this method is described below [4), 5)].

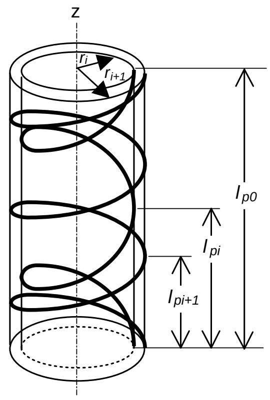

Figure 2 Closed circuit enclosed with an i layer tape and an i+1 layer.

Figure 2 shows the closed circuit made with each tape in the i layer and the i+1 layer of the multilayer conductor with adjusted spiral pitch. Flux (ϕ_i) in the superconducting closed circuit cannot change with time because of zero resistance as shown in Equation (1). This phenomenon is characteristic of superconductivity.

$$\frac{d\phi_i}{dt}=0 \quad (1)$$

The permanent current mode of the superconducting magnet makes use of the fact that the magnetic field of the magnet does not change with time. Magnetic flux (ϕ_i) enclosed with the closed circuit of the i layer and i+1 layer divides into circumferential flux($\phi_{i\theta}$) and axial flux(ϕ_{iz}). The circumferential flux($\phi_{i\theta}$) is shown by Equation (2), where the radius and the current of the i layer are r_i and I_i, the radius and the current of i+1 layer are r_{i+1} and I_{i+1} and the lowest common multiple of the pitch of the i layer and i+1 layer is l_{p0}.

$$\phi_{i\theta}=\frac{\mu_0 l_{p0}}{2\pi}\, ln\, \frac{r_{i+1}}{r_i}\sum_{k=1}^{i} I_k \quad (2)$$

The axial flux(ϕ_{iz}) is shown by Equation (3).

$$\phi_{i\theta}=\mu_0 l_{p0}\left(\frac{a_{i+1}}{l_{p(i+1)}}-\frac{a_i}{l_{pi}}\right)\sum_{k=1}^{i}\pi r^2{}_k\left(a_k\frac{I_k}{l_{pk}}\right)$$
$$+\mu_0 l_{p0}\left(\frac{a_{i+1}}{l_{p(i+1)}}\pi r^2{}_{(i+1)}-\frac{a_i}{l_{pi}}\pi r^2{}_i\right)\sum_{k=i+1}^{n}\left(a_k\frac{a_k}{l_{pk}}\right) \quad (3)$$

When Equations (2) and (3) are substituted into Equation (1), we obtain Equation (4) which gives the current distribution in the i layer and i+1 layer.

$$\frac{d\phi}{dt} = 0 = \frac{1}{2\pi}\ln\frac{r_{i+1}}{r_i}\sum_{k=1}^{i}\left(\frac{dI_k}{dt}\right)$$
$$+\left(\frac{a_{i+1}}{l_{p(i+1)}} - \frac{a_i}{l_{pi}}\right)\sum_{k=1}^{i}\pi r^2{}_k\left(a_k\frac{\left(\frac{dI_k}{dt}\right)}{l_{pk}}\right)$$
$$+\left(\frac{a_{i+1}}{l_{p(i+1)}}\pi r^2{}_{i+1} - \frac{a_i}{l_{pi}}\pi r^2{}_i\right)\sum_{k=i+1}^{i}\left(a_k\frac{\left(\frac{dI_k}{dt}\right)}{l_{pk}}\right) \qquad (4)$$

N-th simultaneous equations can be made using the above equations for all layers, such that each pitch l_{pi} at which the current of each layer is equal can be obtained by solving the simultaneous equations.

At present, the superconducting wire that is the most advanced for the superconducting cable is a Bi2223 Ag alloy sheath tape, the only tape that has high critical current density (J_e) and a length in the 1-km class. Bi filaments are generally formed into tape by rolling and pressing in order to obtain a high critical current density. Bi2223 filaments of less than 10-µm thickness are molded in an Ag alloy matrix with a tape shape of 3.5 mm in width 0.2 mm in thickness.

When AC current flows in the HTS wire, AC losses are generated within the wire because of the irreversibility of magnetic fluxes against the external magnetic field. AC losses reduce the efficiency of superconducting devices, and their reduction is therefore important for the HTS wire. An effective method for reducing AC losses is the use of twisted superconducting filaments (Figure 3), but this twisting causes damage to the HTS filaments and degradation of its I_c. Furukawa Electric has established a technology for manufacturing twisted filamentary wire that has almost the same I_c as the non-twisted wire [6)]. Moreover, the AC losses of the manufactured twisted filamentary wire could be reduced to 1/5 compared with the non-twisted HTS wire.

An HTS conductor was produced using the filament twisting technology and pitch adjustment technology, and its AC losses were measured [7)]. Table 1 shows the specifications of the HTS conductor.

AC currents up to 3 kA were applied to this HTS conductor, and the AC losses were measured. Figure 4 shows the results. The AC losses of the conductor were smaller than the values calculated for a uniform current distribution (UCD) model [3)] or a monoblock model. AC losses of the pitch adjusted conductor without twisted filaments, and the monoblock model well accords with those for a conductor without adjusted pitch or twisted filaments. From the test result, we were able to achieve AC losses of 1 W/m at 3 kA.

In studies on reducing AC losses, developments in technologies for accurate measurement of AC losses become as important as reducing the AC losses themselves. AC losses are represented as $I\times V\times\cos\theta$, where I is current, V is voltage and θ is phase shift between current and voltage in the HTS conductor measured electrically by a lock-in-amplifier. In this electrical method, however, the method of forming terminals for measuring the voltage and errors in measuring electrical values have not been well established. We are concerned about the accuracy with which AC losses are measured by the electrical method, and have therefore developed a calorimetric method for measuring AC losses [7), 8)]. AC losses can be measured directly from the calories into which all AC losses in the HTS conductor are converted in a calorimetric device. Figure 5 shows the calorimetric device that has been developed. AC losses can be measured accurately by reducing heat flows, such as heat conduction and heat invasion from the outside.

Table 1 Specifications of the HTS conductor.

Item	Specification
HTS wire	Bi2223-Ag alloy tape
Dimensions	0.21 mm × 3.3 mm
Filament pitch	15 mm
I_c (77.3 K, 0 T)	45 A
Core former	Outer diameter 35.0 mm
Conductor layer	4-layer structure
Pitch	1st layer 180 mm
	2nd layer 480 mm
	3rd layer -510 mm
	4th layer -160 mm
Number of tapes	118
Length of sample	2 m

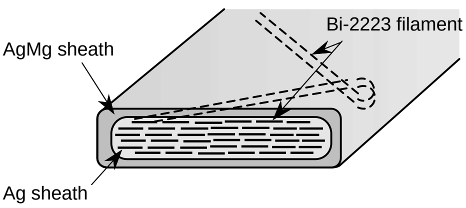

Figure 3 Structure of twisted filament tape.

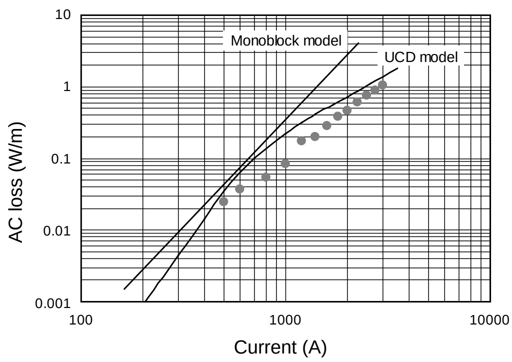

Figure 4 Results of measurement of AC losses in HTS conductor.

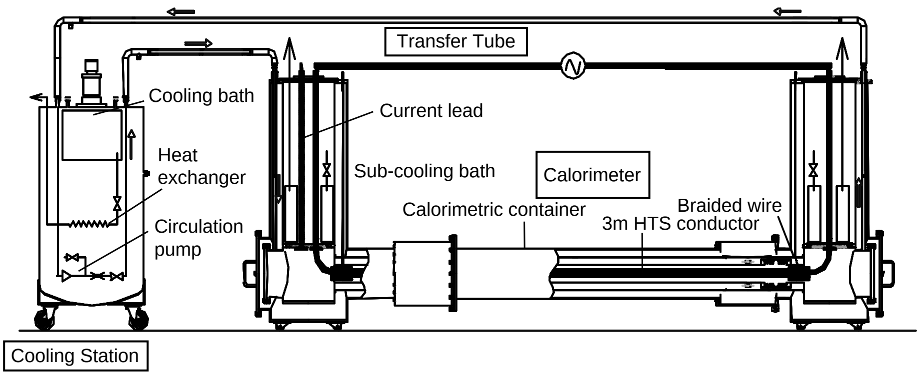

Figure 5 Calorimetric device for measuring AC losses in HTS conductor.

4. TEST OF 30-M MODEL CABLE

An HTS cable model with a length of 30 m was produced and tested to investigate the influence of the mechanical history in the manufacturing, an installation and cooling processes [9]. Table 2 shows the specifications of the 30-m model cable. The cable core was made using a corrugated aluminum pipe, conductor layer and electrical insulation layer. The conductor layer consisted of two HTS wires and 18 Cu wires, wound spirally around the corrugated pipe. Photo 1 shows a cutaway view of the model cable, and Photo 2 shows the 30-m cable installed in an oxbow shape.

4.1 Test of Thermal Contraction

In most metals, it is known that the thermal contraction from room temperature to 77 K is about 0.3 %. The outer pipe of the cryogenic pipe does not contract differently from the inner pipe or the cable core. Moreover, the HTS cable is not allowed to contract in practical use because the cable is fixed when installed. In the 30-m cable test, the heat stress and the heat contraction were measured in straight and oxbow configuration respectively. As a result, in the straight configuration the heat contraction length corresponded to 0.3 % of the cable length (9 cm) and the heat stress was 8.8 kN. In the oxbow configuration, the heat contraction lengths as evaluated from the moving lengths of both ends were 3.4 cm, and 4.5 cm respectively. The contraction length in the oxbow was approximately 1 cm shorter than that in the straight configuration, because the cable core and inside cryogenic pipe were pulled to the inside of the curvature in part of the oxbow. Consequently, the heat stress in the oxbow cable configuration was decreased to 2.9 kN.

4.2 Test of Critical Current (I_c)

Figure 6 shows the critical currents (I_c) of a sample cutoff after cable manufacture and for the 30-m cable in the straight and oxbow configuration and under thermal stress or free of stress. Each I_c is normalized to the I_c of the wire before cable manufacture. I_c degradation due to cable manufacture was held within 5 %, and no I_c degradation was caused by the cable or thermal contraction. The test results thus indicated that the cable would withstand manufacture, installation and thermal contraction.

Table 2 Specifications of 30-m HTS model cable.

Item	Specification
Core former	Corrugated aluminum pipe
Outer diameter	30 mm
Conductor layer	
Number of wires	HTS wires 2 Cu dummy wires 18
Outer diameter	35 mm
Insulation layer	LN_2 impregnated multilayer paper
Thickness	8 mm
Cryogenic pipe	
Inner diameter	82 mm
Outer diameter	123 mm
PVC sheath	
Outer diameter	133 mm

Photo 1 Sample of 30m-model cable.

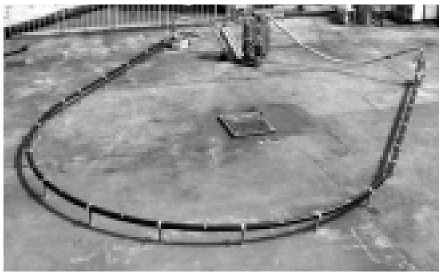

Photo 2 30-m HTS cable installed in oxbow shape in Furukawa Electric's laboratory for tests.

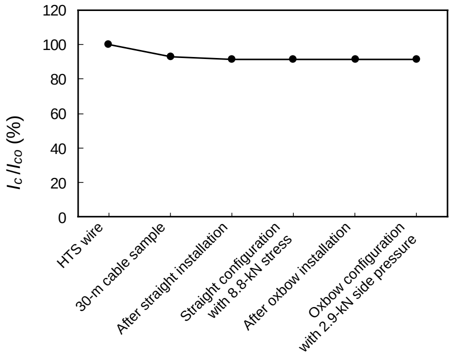

Figure 6 Critical currents of a cut-off sample after cable manufacture and installation.

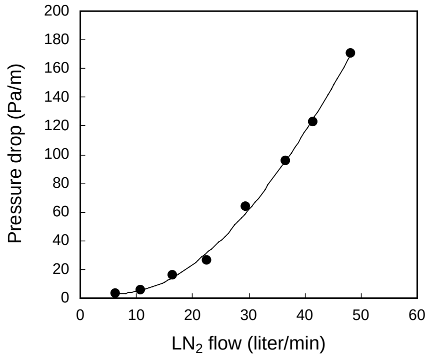

Figure 7 Pressure drop of single-phase LN_2 flowing into 30-m long HTS cable.

4.3 Test of Heat Invasion

Heat invasion to the cable was measured by the evaporation of liquid nitrogen from the cable. The cryogenic pipe had super-insulation (SI) in the multiple layers between the double corrugated pipe made of stainless steel, and had high thermal insulation performance by maintaining a vacuum by SI. Heat invasion to the superconducting cable was held to 1 W/m, half of that of previous HTS cables, by optimizing this insulated structure. Moreover, even when the side pressure was joined by the heat contraction in the oxbow of the cable, heat invasion was restricted to the low value of 2 W/m.

4.4 Test of Pressure Drop in the Cable

In designing a cooling system and determining the installation interval for the cooling system for a practical HTS cable, it is important to investigate the pressure drop of the liquid nitrogen that flows to the cable. Subcooled liquid nitrogen was circulated at 50 l/min in the 30-m cable, and the pressure drop was measured. Figure 7 shows results of measuring the pressure drop per meter.

5. FIELD TEST OF 500-M LONG HTS CABLE

Field testing of a 500-m long HTS cable for the Super-ACE Project will be carried out at the Yokosuka Laboratory of CRIEPI from March to December of 2004. Various techniques for cooling the cable to extremely low temperature will be examined with the aim of achieving practical use of a 5-km class HTS cable. The test items scheduled are:

- Fundamental test: to investigate properties of initial cooling and endurance of the conductor against cable installation, and to measure AC losses.
- Operation test: to investigate the stability of long-term voltage and current loading, and the influence of thermo cycles.
- Load change test: to investigating the influence of load change and overcurrent.
- Extreme conditions test: to investigate the limits of current, voltage and overload in case of interruption of liquid nitrogen circulation.

It has been decided that Furukawa Electric will take charge of manufacturing the cable and ancillary equipment, and of installing the cable. CRIEPI, Chubu Electric Power, Tokyo Electric Power and Kansai Electric Power will be in charge of the testing and evaluation of this project. The cable line emulates the configuration of a cable that is installed in an actual cable duct with a 10-m vertical rise, 10-degree slopes and 5-m radius curves. The 500-m cable will have the functions of electrical insulation, and the cable installation and short circuit characteristics required in an actual transmission cable.

6. CONCLUSION

It is necessary to understand the cooling characteristics of long-length superconducting cables and the circulation of liquid nitrogen to realize the HTS cable. Therefore, field testing of the 500-m HTS cable longest in the world is planned in the Super-ACE Project [10]. The 30-m HTS cable model was tested to obtain design data and improve the production technologies for the manufacture and installation of the 500-m cable, and this was accomplished successfully. Based on this success with the 30-m cable tests we have started preparing substantive tests and manufacture of the 500-m long cable.

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