Development of 66 kV and 275 kV class REBCO HTS power cables

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***Abstract*— A Japanese national project called "Materials & Power Applications of Coated Conductors (M-PACC)" started in FY2008. In this project, we are developing 66 kV/5 kA large-current high-temperature superconducting (HTS) cable and 275 kV/3 kA high-voltage HTS cable, using rare-earth barium copper oxide (REBCO) tapes. These HTS cables are expected to offer a compact cable with a large capacity and low power transmission loss. After the cable design has been studied and elemental technologies for each component of the cable system, such as AC loss reduction, protection against over-current, and high-voltage electrical insulation have been developed, two cable systems will be constructed and verified to meet the required specifications in FY2012. This paper described the progress and status of these HTS cable developments in the M-PACC project.**

***Index Terms*— Yttrium barium copper oxide, High temperature superconductors, Transmission lines**

I. Introduction

HIgh-temperature superconducting (HTS) power cables are compact and have a large power carrying capacity. In addition, they make it possible not only to reduce power transmission losses significantly but also alleviate global environmental problems and allow more efficient use of energy resources. In the future, these cables are expected to be installed in the power grid as replacements for existing power cables. A large-current cable (LC cable, 66 kV/5 kA) and a high-voltage cable (HV cable, 275 kV/3 kA) have been developed using rare-earth barium copper oxide (REBCO) tape in the Japanese national project "Materials & Power Applications of Coated Conductors (M-PACC)" which started in FY2008 [1]-[3]. These capacities represent the largest current and highest voltage for HTS cables under development in the world. The structures and targets specifications of both cables are shown in Fig. 1 and Table I, respectively. The elemental technologies for the components of each cable system have been developed and these cable systems were designed utilizing these development results [4]. A 15-m-long LC cable system and 30-m-long HV cable system were constructed for design verification in FY2012. The status of these elemental technology developments and an outline of these cable system verifications are presented in the following sections.

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II. Development of 66 kV/5 kA LC cable

A. REBCO tape (clad-PLD type)

The REBCO tape for the LC cable has been developed by Sumitomo Electric [5], [6]. As shown in Fig. 2 (a), it is composed of a 120-μm-thick textured metal substrate of a new type (clad-type) and a $GdBa_2Cu_3Cu_x$ superconductive layer deposited by pulse laser deposition (PLD). Each tape is coated with 20-μm-thick copper (Cu) by electroplating. 20-m-long REBCO tapes, which were cut from longer tapes, with high critical current (I_c) properties, were obtained to make a 15-m-long LC cable and test samples for system verification.

B. Cable design

The fabrication technologies for the LC cable have been developed by Sumitomo Electric [7], [8]. The design specifications are listed in Table II. Three cable cores are housed in a double corrugated stainless steel cryostat-pipe. Each core consists of a former made of stranded Cu, an HTS conductor, electrical insulation, an HTS shield, and a Cu shield. The HTS conductor and HTS shield consist of 4 layers and 2 layers of REBCO tapes, respectively. In the steady state, the transmitted current flows through the HTS conductor. Current nearly identical to the HTS conductor but opposite in phase flows in the HTS shield. The Cu former and Cu shield work as by-pass circuits for over-current.

C. Development of elemental technologies

1) AC loss characteristic: AC loss in an HTS conductor of the cable can be reduced by making the gaps between the tapes small or restricting the critical current density (J_c) degradation parts near both tape edges [9]. Furthermore, for the multilayer cable, approaching the cross section of the cable to circle by using narrow tapes might efficiently reduce AC loss [10]. This effect is more efficient for the outer layer of a multilayer cable because the entire AC loss is dominated by the AC loss in the outer layers.

The 30-mm-wide REBCO tape was fabricated and cut into 2-mm-wide or 4-mm-wide tapes by a laser or mechanical slitter, which had been improved to restrict J_c degradation near both tape edges at the cutting parts [11]. The outermost layer of the HTS conductor consists of the 2-mm-wide tapes and the other layer consists of the 4-mm-wide tapes.

Fig. 3 shows the measured AC loss characteristic of the model cable core listed in Table II. The I_c values of the HTS conductor and HTS shield were approximately 8100 A and 6200 A, respectively. The measured AC loss of this model cable core was 1.5 W/m/phase at 5 kA_{rms} and the target was achieved. Furthermore, 5 kA_{rms} current loading tests were conducted using this manufactured model cable core. Thermocouples were attached to the HTS conductor. Fig. 4 shows the test result with a loading current of 5 kA_{rms}. During the test, no rapid change was observed in the internal temperatures or in the end-to-end voltages of the model cable core, and the loading test was completed successfully. It was confirmed that the designed cable has enough current capacity for 5 kA_{rms} loading.

2) Mechanical characteristic: A 3-core model cable was experimentally manufactured under the same conditions as those for actual products in order to check the mechanical soundness of the manufacturing process and to conduct bending and tensile tests. The REBCO tape in the model cable had no I_c degradation in these tests. It was confirmed that the model cable met the required specifications [7].

3) Over-current test: The cross sectional area of the Cu former, Cu shield, and Cu stabilizing layer of the REBCO tape were designed to survive fault-current accidents. The designed model cables were prepared and they conducted an over-current (31.5 kA_{rms} for 2 s) in saturated LN_2 at atmospheric pressure. The temperature rises of the HTS conductor layer and HTS shield layer from 77 K (ΔT) under this over-current were 100 K and 120 K, respectively. The I_c characteristics showed no deterioration in the model cables after the tests. It was confirmed that the model cables demonstrated endurance against over-current [12].

D. System verification

Fig. 5 shows the configuration of the LC cable verification system, which have been built at the test site in Osaka. The LC cable is approximately 15 m long and has terminations at both ends. The cable system is cooled by sub-cooled liquid nitrogen (LN_2). In this system, current flows through the HTS conductors of two cable cores and the shielding current is induced in the HTS shield of two cable cores. On the other hand, voltage is applied to all cores. As shown in Table III, various tests were planned using with the 15 m LC cable system to confirm nominal current and voltage performance and no degradation by heat cycling between room temperature and LN_2 temperature.

III. Development of 275 kV/3 kA HV cable

A. REBCO tape (IBAD-TFA-MOD)

The structure of REBCO tape for the HV cable is shown in Fig. 2 (b). An ion-beam-assisted deposition (IBAD) substrate was supplied by Fujikura and ISTEC-SRL and an yttrium barium copper oxide (YBCO) superconductive layer was deposited on the IBAD substrate by metal-organic deposition including trifluoroacetates by SWCC Showa Cable Systems and ISTEC-SRL, respectively. The REBCO tape was covered with Cu by electroplating in Furukawa [13]-[15]. 50-m-long REBCO tapes, which were cut from longer tapes with I_c properties, were obtained to make a 30-m-long HV cable and test samples for system verification.

B. Cable design

The cable fabrication technologies for the HV cable have been developed by Furukawa Electric [16]-[18]. The design cable specifications are listed in Table IV. This cable structure is different from the LC cable in the following points. A single cable core is housed in a double corrugated stainless steel cryostat-pipe. The Cu former is hollow, allowing LN_2 to flow through it. The HTS conductor and HTS shield consist of 2 layers and 1 layer of REBCO tapes, respectively.

C. Development of elemental technologies

1) Electrical insulation system for 275 kV: Polypropylene laminated paper (PPL-paper) was used for the electrical insulation material of the HV cable [16]. Model cables using PPL-paper were fabricated to measure the partial discharge inception electric field strength (PDIE) and a design stress of the 22 kV_{rms}/mm value was obtained from PDIE of 0.1% partial discharge (PD) probability of this model cable [18]. The 275-kV-class model cable was designed and fabricated using 22 kV_{rms}/mm of design stress, and the required test, which was determined on the basis of IEC and JEC Japanese cable standards, was carried out. The cable properties were found to be sufficient for electric insulation. A 275 kV termination and joint were developed and also passed the required voltage test. The n-value of the model cable using PPL-paper impregnated with liquid nitrogen was obtained as 50 from a *V-t* characteristics test concerning breakdown stress. From this n-value, the voltage value in the long-term operation test, which is equivalent to 30 years, was determined.

2) Cable loss characteristic: 5-mm-wide REBCO tape was fabricated and cut into 3 mm widths by a laser to remove the J_c degradation parts near both tape edges for AC loss reduction, as described Section II-C-1. The HTS conductor of the cable was fabricated using 3-mm-wide tapes, and the measured AC loss at 3 kA_{rms} was 0.124 W/m/phase. The dielectric loss of the designed 275 kV cable was derived from measured values of permittivity ε and dielectric dissipation factor tanδ. The dielectric loss was 0.60 W/m/phase. The total loss, comprising the dielectric loss and the AC loss of the HTS conductor at 3 kA_{rms} loading, was less than 0.8 W/m/phase, which meets our development target [18].

3) Over-current characteristics of the cable with joint: an HTS model cable with a joint, whose specifications are listed in Table V, was manufactured to confirm the protection against over-current (63 kA_{rms} for 0.6 s). The over-current test was conducted in saturated LN_2 at atmospheric pressure. The ΔT, which is temperature rise from 77 K, versus duration at 63 kA_{rms} is shown in Fig. 6. The highest ΔT of the HTS conductor was about 17 K. This value was less than the ΔT reported in [17] because of an increase in the cross sectional area of the Cu former. ΔT after the application of over-current is shown in Fig. 7. Immediately after the over-current application, the ΔT of the HTS shield began fall as a result of cooling by the LN_2 in existed between the cable core and double corrugated stainless pipe. ΔT reached zero about 500 s after over-current application. This time was shorter than without the hollow former design given in [17]. This result indicates that LN_2 in the hollow of Cu former is efficient at cooling the HTS conductor after over-current application because the electrical insulation layer, whose thermal resistance is high, interrupts the cooling from LN_2 existed between the cable core and double corrugated steel pipe. After the over-current test, the I_c values in the HTS conductor and HTS shield showed no degradation. It was confirmed that the over-current test at 63 kA_{rms} for 0.6 s on the HTS model cable with a joint was conducted successfully.

D. System verification

Fig. 8 shows the configuration of the HV cable verification system. The HV cable is approximately 30 m long. It has terminations at both ends and a cable-to-cable joint in between. The cable system is cooled by sub-cooled LN_2. The cable system is being built at Shenyang Furukawa Cable Co., Ltd. in Shenyang City, China. In this system, current flows through the HTS conductors of the cable core, and a shielding current is induced in the HTS shield. As shown in Table VI, various tests were planned using the 30 m HTS cable system to confirm nominal current and voltage performance. Details of the test plan and the status of the 275 kV cable system verifications were presented in [20].

IV. Conclusion

Elemental technologies for the LC cable and HV cable have been developed and both cable systems are being manufactured using these developed technologies. After cable system construction, various verification tests, such as long-term operation under the rated current and voltage, equivalent to a 30-year evaluation, will be completed in FY2012.

Acknowledgment

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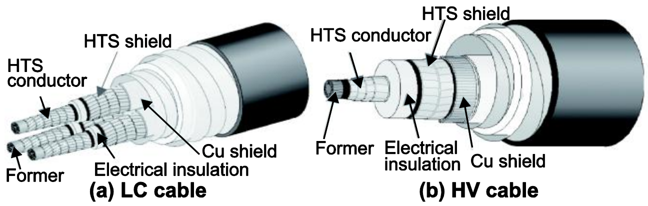

Fig. 1. Structures of the LC and HV cables

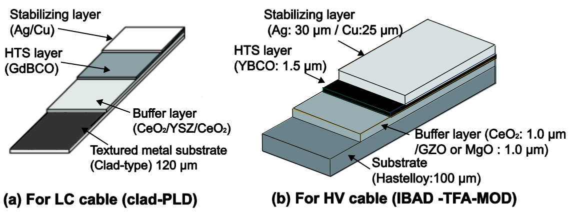

Fig. 2. Structures of the REBCO tape

TABLE I
TARGET SPECIFICATIONS OF LC AND HV CABLES

	LC cable	HV cable
Voltage/ current	66 kV/5 kA (570 MVA)	275 kV/3 kA (1420 MVA)
Structure	Three cores in one pipe, 15 m in length with terminal	Single core in one pipe, 30 m in length with terminal and joint
Cable loss	2.1 W/m/phase @ 5 kA_{rms}	0.8 W/m/phase @ 3 kA_{rms}
Cable outer diameter	Designed cable can be installed in 150 mm conduits	< 150 mm ϕ
Over-current withstood	31.5 kA for 2 s	63 kA for 0.6 s

TABLE II
66 KV CABLE DESIGN SPECIFICATIONS

	Construction	Diameter (mm)
Former	Cu stranded 140 mm^2	21
HTS conductor	4 layers Layers 1–3 (inner): 4-mm-wide tape 45 Layer 4 (outer): 2-mm-wide tape 27	23
Insulation	PPLP 6-mm-thick	37
HTS shield	2 layers 4-mm-wide tape 50	38
Cu shield	Cu tape 100 m^2	42
Protective	Craft paper	44
Sheath	PVC	140

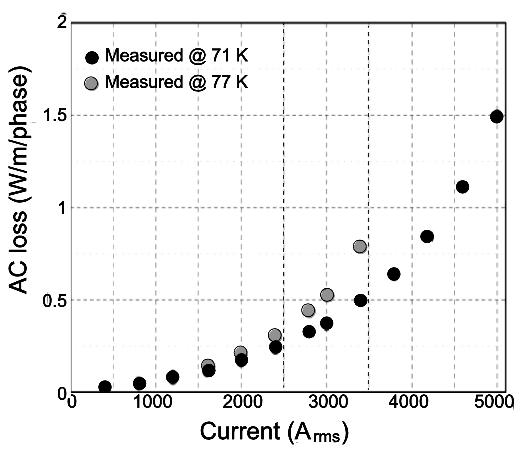

Fig. 3. Measured AC loss of the HTS cable core using clad-PLD tape

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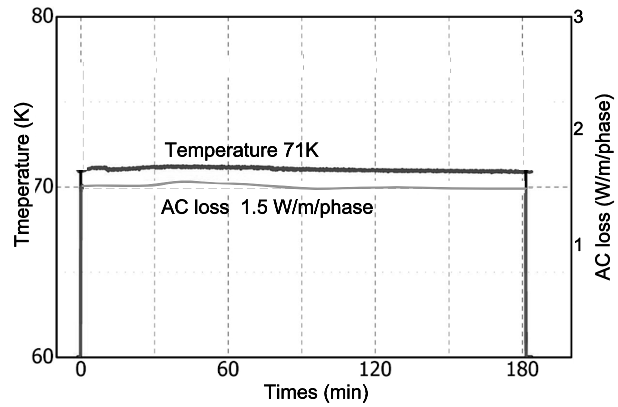

Fig. 4. Results of 5 kA_{rms} loading test on the HTS cable core

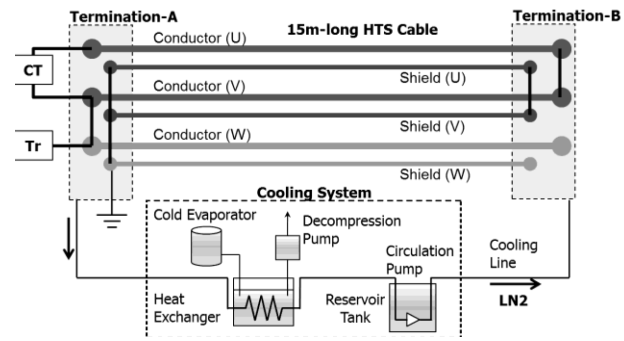

Fig. 5 . System configuration of 15-m-long LC cable system

TABLE III
TEST SPECIFICATIONS OF 15-M-LONG LC CABLE SYSTEM

	Test items
Electrical test (including sample test)	• I_c measurement • Power frequency withstanding voltage test: 110 kV_{rms} for 10 min • Impulse test: ±385 kV for 3 shots, etc.
Thermal tests	• AC loss measurement at 5 kA_{rms} loading by calorimetric method, etc.
Long-term operation test	• 51 kV_{rms} (to ground) • 5 kA_{rms}; 8 hours on, 16 hours off
Cooling capacity	• 3.5 kW@65 K

TABLE IV
275 KV CABLE DESIGN SPECIFICATIONS

	Construction	Diameter (mm)
Former	Cu stranded hollow 400 mm^2	30.6
HTS conductor	2 layers 3-mm-wide tape 60	35.4
Insulation	PPLP 22 –mm-thick	79.4
HTS shield	1 layer 5-mm-wide tape 43	80
Cu shield	Cu tape 2 layers 240 mm^2	83
Protection	Craft paper	86.5
Sheath	PVC	150

TABLE V
275 kV CABLE JOINT DESIGN SPECIFICATIONS

	Diameter (mm)	
	Normal	Joint
Former	30.6	30.6
HTS conductor	35.4	35.4
Insulation	79.4	179.4
HTS shield 1 layer	80	181.0
Cu shield	83	186.8
Protection	86.5	188.0

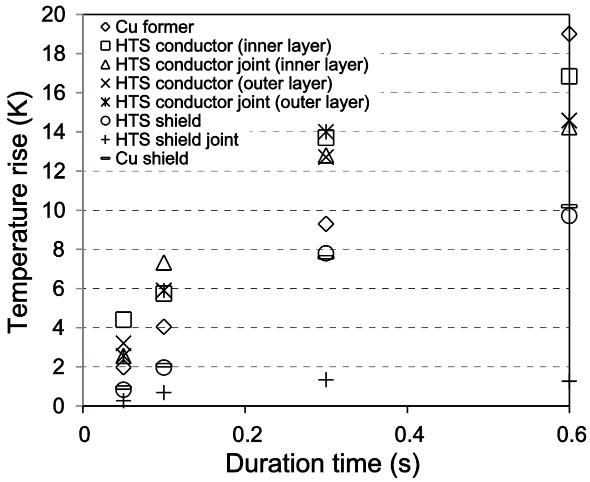

Fig. 6. Temperature rise in response to over-current

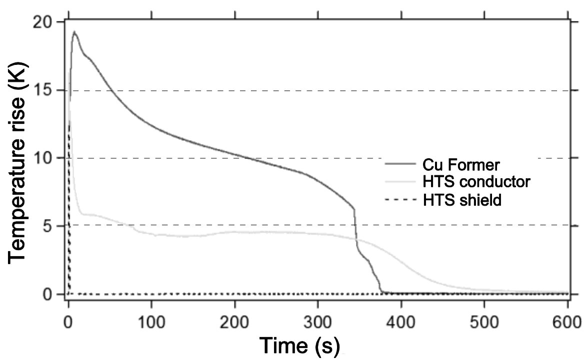

Fig. 7. Temperature raise after application of over-current

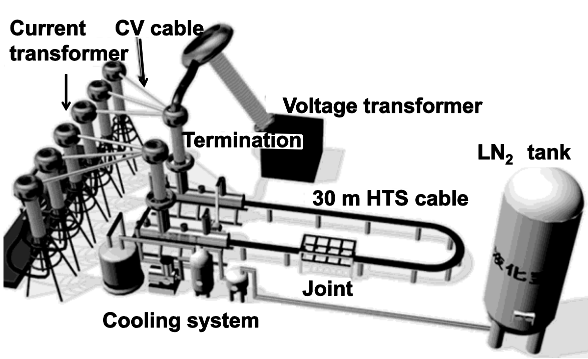

Fig. 8. System configuraton of 30-m-long HV cable system

TABLE VI
TEST SPECIFICATIONS OF 30 M-LONG HV CABLE SYSTEM

	Test items
Electrical test (including sample test)	• I_c measurement • Power frequency withstanding voltage test: 310 kV $_{rms}$ for 10 min PD-free (Reference IEC62067： 320 kV $_{rms}$ for 15 min and 400 kV $_{rms}$ for 30 min） • Impulse test: ±1155 kV for 3 shots, etc.
Thermal tests	• AC loss measurement at 3 kA$_{rms}$ loading by calorimetric method, etc.
Long-term operation test	• 200 kV $_{rms}$ (to ground) • 3 kA$_{rms}$; 8 hours on, 16 hours off
Cooling capacity	• 3 kW@70 K