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Design and evaluation of 275 kV-3 kA HTS power cable

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Abstract

A 275 kV 3 kA high temperature superconducting (HTS) cable has been developed in the Materials & Power Applications of Coated Conductors (M-PACC) project. The cable is expected to be put to practical use as the backbone power line in the future because the capacity of 1.5 GW is about the same as overhead transmission lines. The 30 m cable has been designed on the basis of design values that had been obtained by various voltage tests, AC loss measurement tests, short circuit tests, and other elementary tests. Cable insulation was determined by the design stresses and test conditions based on IEC, JEC (Japan electrical standards), and other HTS demonstrations. This cable was also designed to withstand the short circuit test of 63 kA for 0.6 seconds and to have low losses, including AC loss and dielectric loss of 0.8 W/m at 3kA, 275 kV. Based on the design, a 30 m cable was manufactured, and short samples during this manufacturing process were confirmed to have the designed characteristics.
Furukawa Electric prepared a demonstration of the 30 m cable with two terminations and a cable joint. The long-term test under a current of 3 kA, and test voltage determined from 30 years of insulation degradation has been conducted since November 2012 at Shenyang in China.

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Keywords: HTS power cable; High Voltage; Electric Insulation; Partial discharge; YBCO

1. Introduction

A lot of High temperature superconducting cables (HTS cables) have been constructed and tested throughout the world. In Japan, mainly 66/77 kV HTS cables have been developed because the HTS cables for voltages above 66 kV up to 110 kV have been the most compact while designing the insulation thickness and cross section of the conductor as a parameter for voltage and current [1]. The cable can be installed in a cable duct that is only 150 mm in diameter and constructed at lower cost in a shorter period of time.

On the other hand, transmission voltage classes are different around the world. The voltage classes for HTS cables under development are also different, from a low voltage of 22 kV to a high voltage of 154 kV. If an electrical power system was made from the beginning, suitable voltage and current for HTS cables could be chosen. However, HTS cables will be installed in existing systems, so appropriate specifications are required. In Japan, 275 kV HTS cable will be required to replace the aging 275 kV conventional cables; such cable has been under development since 2008 in the Materials & Power Applications of Coated Conductors (M-PACC) project [2]. YBCO tapes with high current

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density, high performance in high magnetic fields, and excellent cost performance have been expected to be applied for various kinds of electrical devices as well as cables. The 275 kV-3 kA HTS cable using YBCO tapes will have the world's greatest capacity at 1.5 GW, which is about the same capacity as overhead power lines.

The technical targets for the development of the 275 kV HTS cable system are as follows: (1) To reduce the AC loss and dielectric loss less than 0.8 W/m at 3 kA_{rms} and 275 kV (operating voltage of 160 kV, U_0); (2) Development of the cable insulation, termination and joint (PD free at AC 310 kV_{rms}, no breakdown at impulse 1155 kV); (3) Endurance against an over-current of 63.0 kA_{rms} for 0.6 s; and (4) To be compact less than 150 mm in outer diameter.

This paper describes the design, evaluation, fabrication, and demonstration system of the 275 kV HTS cable.

2. Design of 275 kV-3 kA HTS cable

The specifications of the 275 kV-3 kA HTS cable are shown in Table 1 and Fig. 1. The former was a hollow copper stranded conductor of 400 mm^2. The HTS model cable using copper stranded former of 325 mm^2 withstood the over-current condition of 63 kA_{rms} for 0.6 s [3]. There was no degradation of HTS tapes, but a temperature increase of 70 K was observed. Using 400 mm^2 former was expected to suppress the temperature increase.

In order to reduce AC loss, a two-layer conductor with 60 pieces of narrow tapes was adopted, where the narrow tapes of 3 mm-wide YBCO were obtained by removing the both edges of 5 mm-wide tapes with low electrical current density (J_c) using a laser. On the other hand, 43 pieces of YBCO tapes were used for the shield layer. The designed AC loss of the conductor layers and the shield layer were estimated at 0.12 and 0.08 W/m at kA_{rms}, respectively [3, 4].

The target insulation design was PD free at an AC voltage of 310 kV_{rms}, and no breakdown at an impulse voltage of 1155 kV. These testing voltages were determined on the basis of IEC62067 [5], JEC3408 [6] (Japan electrical standards) and other HTS cable demonstrations. The AC testing voltage of 310 kV_{rms} was derived from the highest voltage of 300 kV_{rms} and the increased coefficient at the load rejection of 1.79/√3 [6]. This cable could remain PD free even under an abnormal voltage during the operation. The impulse testing voltage was 1155 kV, which was derived from the maximum lighting withstand voltage of 1050 kV and tolerance of 1.1. As a result, the insulation thickness was designed as 22 mm using the selected PP laminated paper described in the next section.

Table 1. Design of 275 kV 3 kA HTS cable.

Structure	Specifications	Diameter (mm)
Former	Hollow copper stranded conductor of 400 mm^2	
HTS conductor	Two-layer conductor, 60 YBCO tapes with 3 mm-wide, copper plated, estimated I_c of 6 kA at 77.3 K, estimated AC loss at 3 kA_{rms} of 0.12 W/m at operating temperature of 72 K.	35.4
Insulation	PP laminated paper, thickness of 22 mm Dielectric loss of 0.60 W/m	79.4
HTS shield	One-layer conductor, 43 YBCO tapes with 5 mm-wide, copper plated, estimated I_c of 6 kA at 77.3 K, estimated AC loss at 3 kA_{rms} of 0.08 W/m at operating temperature of 72 K.	81.0
Cu shield	Copper braided tapes of 210 mm^2	
Protection	Paper	90.0
Cryostat pipe	Double-corrugated pipe with super insulation	150

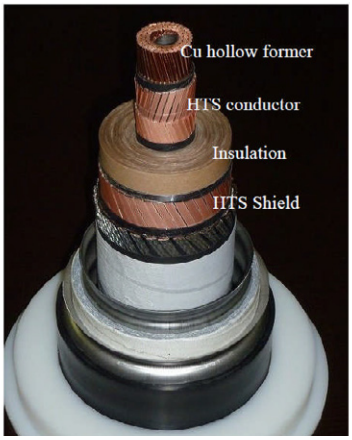

Fig. 1. Structure of 275 kV–3 kA HTS cable.

3. Evaluation of the dielectric properties of the cable insulation for 275 kV cable

The cold dielectric insulation composed of liquid nitrogen (LN_2) and polypropylene (PP) laminated paper was similar to the insulation of the oil filled cables composed of oil and PP laminated paper. It was regarded as the most promising insulation system for HTS cables. In the development of electrical insulation for 275 kV, the PP laminated paper having higher pp ratio of 60% was selected to reduce dielectric loss [3].

The long-term (V-t) characteristics were very important components of a reliable insulation design. The V-t characteristics were measured using two model cables with insulation thicknesses of 1 mm that were immersed in pressurized LN_2 of 0.3 MPa (abs.) and cooled by atmospheric LN_2 of 77.3 K in the outer vessel. These 1 mmt cables were composed of a copper electrode in a diameter of 20 mm as high voltage, two-layer carbon paper as an inner semi-conductive layer, nine-layer PP laminated paper as insulation, and two-layer carbon paper as an outer semi-conductive layer, and copper-braided tapes as the ground [3].

The V-t characteristics measured around PDIE (Partial Discharge Inception stress) was shown in Fig. 2(a). The V-t test was continued for 720 hours, and the lifetime coefficient n as calculated by (1) was 80.

$$V^n \cdot t = const. \tag{1}$$

where V is the testing voltage (kV_{rms}/mm) and t is time during the voltage. After the V-t test of PDIE, PDIE was evaluated, but there was no degradation of the PDIE as shown in Fig. 2(b). Therefore, the test was continued, and the V-t of breakdown was conducted as shown in Fig. 2(a). The testing voltage was raised to 42.3 kV_{rms}/mm, and breakdown in one of the model cable occurred after 65 hours. The other model cable survived, but the $PDIE_{50}$ corresponding to the 50% PD inception probability decreased from 26.0 kV_{rms}/mm to 22.8 kV_{rms}/mm. The voltage tests continued while the voltage of 42.3 kV_{rms}/mm was maintained for 32 hours. No breakdown occurred, but further degradation was observed. The $PDIE_{50}$ decreased to 19.8 kV_{rms}/mm as shown in Fig. 2(b). In this case, lifetime coefficient n as calculated by (1) was 50.

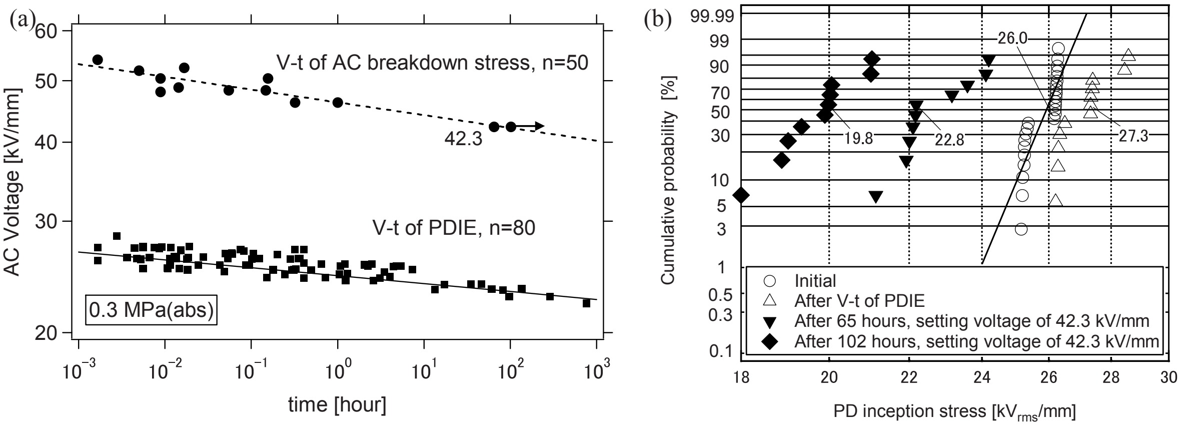

Fig. 2. (a) V-t of PDIE for model cable using pp laminated paper (solid line), and V-t of breakdown (dashed line and circle). (b) PDIE after V-t tests. The insulation degradation was not observed after the V-t of PDIE, but observed after the V-t of BD.

4. Fabrication and Demonstration of 275 kV-3 kA HTS cable

The 50 m cable shown in table 1 was fabricated by VISCAS Corporation at the Furukawa Chiba factory, as shown in Fig. 3(a)(b). Its outer diameter was confirmed to be 150 mm, which was our target value. The 30 m length from the 50 m was used for the demonstration system, and the extra cable was used for various electrical characteristic tests. The critical current (I_c) of the conductor and shield in the left cable was 6440 A and 5920 A at 77.3 K, respectively, which almost agreed with the sum of all the used YBCO tapes. The YBCO was based on the TFA-MOD process [7] having minimum length and I_c of 50 m and 200 A/cm-w, respectively. The 2 m cable withstood the over-current of 63.0 kA_{rms} for 0.6 s, which was the worst situation in the 275 kV systems. The temperature increase was suppressed to 20 K , and no I_c degradation was observed. Additionally, the 5 m cable was confirmed to be PD free at 310 kV and to withstand 400 kV for 30 minutes. Therefore, the extra cable was confirmed to have the designed characteristics.

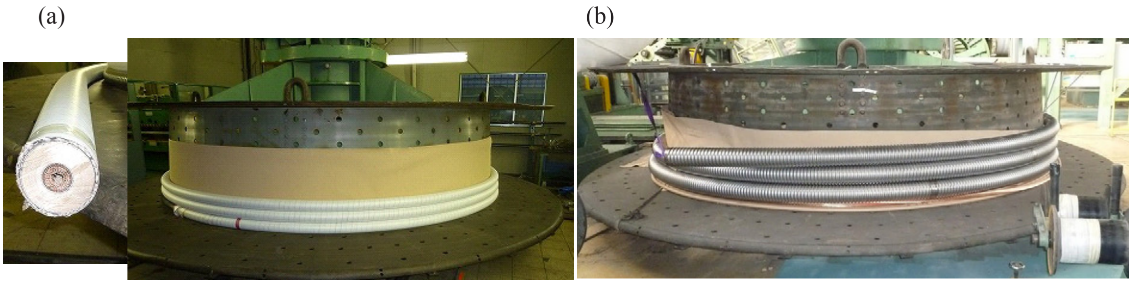

Fig. 3. (a) Fabrication of HTS core including HTS conductor electrical insulation and Shield layer. (b) Fabrication of HTS core with cryostat pipe.

The 30 m length from the 50 m was used to make a circuit. This circuit included the 30 m HTS cable, two terminations, an intermediate joint, and three XLPE cables that were used for the flowing current of 3 kA_{rms}. The circuit was constructed in Shenyang Furukawa Cable Ltd. in September 2012 as shown in Fig. 4. After the installation and cooling, I_c of the HTS conductor and HTS shield were confirmed to be 6800 A and 7000 A at 77.3 K, respectively, which meant that there was no degradation during the fabrication and transportation from Japan to China. The I_c of the 30 m was better than that of the extra cable, because we had set the YBCO tapes to have high I_c in the 30 m preliminary measuring I_c distribution along the length. On the other hand, the current waveforms of 3 kA_{rms} are shown in Fig. 5. The rate of shield current to conductor current was about 75%, because the shield circuit included not only the HTS cable of 27 m but also the normal conduction part of 13 m. To increase the amplitude of the shield current, longer HTS cable and shorter conduction part were required. It was possible to shorten the conduction part from 13 m to 9 m, the rated of shield current of 82% was estimated.

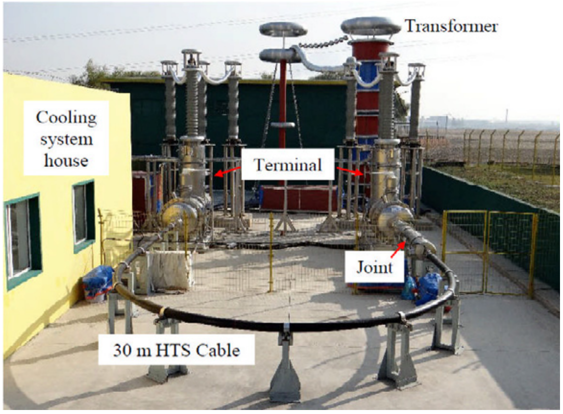

Fig. 4. Demonstration system of 275 kV-3 kA HTS cable.

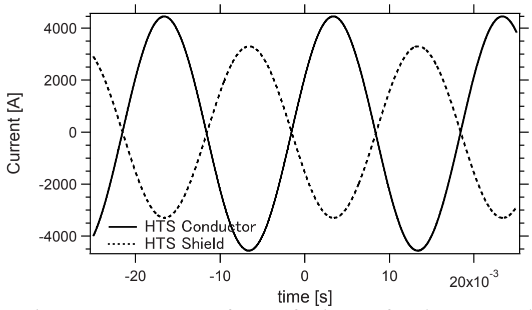

Fig. 5. Current waveform of 3 kA_{rms} for the HTS cable.

The long-term test has started since November 2012. The long-term voltage (V_{typeAC}) for one month that corresponds to the 30 years of operating voltage was calculated by (2).

$$V_{typeAC} = \left(\frac{U_m}{\sqrt{3}}\right) \cdot \left(\frac{30years \cdot 365days}{30days}\right)^{\frac{1}{n}} \quad (2)$$

where U_m that was the maximum voltage between any two conductors was 300 kV_{rms}, and n was the lifetime coefficient of 50 from Fig. 2(a), V_{typeAC} was 200 kV_{rms} in one month. During the long-term test, the current of 3 kA_{rms} will be applied for 8 hours followed by no load for 16 hours. This current cycle will be carried out at least 20 times.

5. Conclusion

The 275 kV- 3 kA HTS cable was designed and fabricated. The fabricated cable was confirmed to have the designed characteristics, such as small outer diameter, I_c, PD free, withstand properties, and over-current characteristics. The 30 m HTS cable was installed in Shenyang in China, and the long-term test has been conducted since November 2012. The test voltage during the long-term test was 200 kV_{rms} for one month that was determined from 30 years of insulation degradation.

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