Electrical Insulation of 500-m High-Tc Superconducting Power Cable

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Abstract. Electrical insulation is one of the essential technologies for the electric power apparatus. Determination of testing voltages and design method of the electrical insulation layer are inextricably linked each other, and are critical to developing and realizing a cold dielectric (CD) type high-Tc superconducting (HTS) power cable. The authors had proposed the electrical insulation design method with concepts of partial discharge-free designs for ac voltage condition. This paper discusses the testing voltages for a 77 kV 1000 A HTS power cable with a length of 500 m, and describes results of various voltage withstand tests. As a result, it is concluded that the proposed electrical insulation design method is appropriate for the HTS power cable.

1. Introduction
A high-Tc superconducting (HTS) power cable has a lot of features, such as low impedance characteristics and large power transmission capacity with smaller cable diameter and lower rated voltage compared to conventional XLPE (Cross-linked polyethylene insulated polyvinyl-chloride sheathed) cables and oil-filled cables having the same transmission capacity [1,2]. Moreover, a cold dielectric (CD) type HTS power cable with HTS shielding layer is capable of reduction of the leakage magnetic field from the HTS power cable [1 - 3]. Thus, it is considered to be a major candidate of the bulk power transmission in the next generation and a few developing and practical use projects are in progress [3 - 5]. However, design and testing methods for the HTS power cable has not been established yet, which are essential to the practical application.

From these viewpoints, the authors developed and proposed the electrical insulation design method for the CD type HTS power cable with a concept that partial discharge (PD) should be absent in operation because PD is considered to be a major electrical cause of degradation, especially with rated voltage and current of 77 kV and 1000 A, respectively, and a length of 500 m [6 - 8]. Its verification and demonstration tests including electrical insulation tests had been executed for one year and more.

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in Yokosuka site, CRIEPI, Japan [8 - 10]. This paper discusses the determination of the testing voltages and results of voltage withstand tests for the CD type 500-m HTS power cable.

2. Definition of testing voltages for the 500-m HTS power cable

2.1. Structure of the 500-m HTS power cable

Figure 1 shows the cut model of the 500-m HTS power cable. The electrical insulation layer consist of polypropylene (PP) laminated papers with a nominal thickness of 125 µm wound on a high voltage conductor with 1/3 wrapping, immersed into liquid nitrogen (LN2) [1, 6 - 8].

In the previous literature [7], the design stress for ac and lightning impulse voltages for the PP laminated papers / LN2 composite insulation system were proposed to be 15 kVrms/mm and 88 kV/mm, respectively. Then, the testing voltages for ac type test was determined to be 55 kVrms based on V-t characteristics for breakdown, testing duration of one month and a standard of Japanese Electrotechnical Committee JEC-3408-1997. As for the testing voltage, the lightning impulse voltage was determined to be 440 kV. Thus, the insulation thickness of 6 mm was proposed [7].

However, influences due to mechanical stresses during cool-down and warm-up processes and so forth were not considered. Thus, the insulation thickness of the 500-m HTS power cable was determined to be 8 mm, and testing voltages for the 500-m HTS power cable had to be redefined due to the difference of the insulation thickness. In order to redefine the testing voltages, the electric field strength on the high voltage conductor for the actual 500-m HTS power cable with an insulation thickness of 8 mm should be the same as that for the designed HTS power cable with an insulation thickness of 6 mm, because the insulation thickness was determined that the electric field strength on the high voltage conductor should be a design stress. Thus, the testing voltages can be redefined by the product of a coefficient and the testing voltages defined for the HTS power cable with 6-mm electrical insulation thickness. The coefficient can be obtained as equation (1).

\[
\ln\left(\frac{t_{act}}{r_w} + 1\right)/\ln\left(\frac{t_{design}}{r_w} + 1\right)
\]

where
- \(r_w\): outer diameter of the high voltage conductor, 15.9 mm
- \(t_{act}\): electrical insulation thickness of the constructed HTS power cable, 8 mm
- \(t_{design}\): electrical insulation thickness of the designed HTS power cable, 6 mm

2.2. Voltage withstand tests and definition of corresponding testing voltage

In the testing procedure of the 500 m HTS power cable, a factory test and a field test were carried out in order to verify the electrical insulation performance. The former one aimed to verify the soundness of the production, and the latter one the soundness of the installation.

A partial specimen with a length of 20 m that came from the top of the 500-m HTS power cable
was used as a specimen for the factory test consisting of an operational frequency voltage withstand test, a lightning impulse voltage withstand test and a partial discharge test. The testing voltage and duration of the operational frequency voltage withstand test were 95 kVrms and 10 min., respectively. The testing voltage was determined from the condition that the electric field strength on the high voltage conductor became the ac design stress of 15 kVrms/mm that is a design criterion from electrical insulation. The duration was determined by the time required to ignite PD if there would be any defects for the electrical insulation. Moreover, a voltage withstand test with 80 kV rms for 1 hour was carried out consequently to equivalently verify the soundness of the electrical insulation property for its lifetime of 30 years in 1 hour. In this case, the testing voltage was defined to be 62.6 kVrms for the HTS power cable with 6-mm electrical insulation thickness by the constant shown in equation (1) in the literature [7] with a testing duration of 1 hour, and 80 kV rms for 8-mm electrical insulation thickness multiplied by equation (1). The lightning impulse voltage test was carried out with positive and negative lightning impulse voltages of 440 kV for 3 times each. As for the partial discharge test, which performed to verify the soundness of the electrical insulation performance after the impulse voltage application, the testing condition was set the same as that for the operational frequency voltage withstand test.

On the other hand, the field test had an initial voltage withstand test, a long-term voltage withstand test and an overvoltage withstand test. The initial voltage withstand test was carried out with testing voltage of 95 kVrms for 10 min. application, which was the same basis as the operational frequency voltage withstand test in the factory test mentioned before. In the long-term voltage withstand test with the duration of 30 days, the testing voltage for the HTS power cable with 6-mm electrical insulation thickness was calculated to be 54.7 kVrms [7], which was 70 kVrms for the HTS power cable with 8-mm electrical insulation thickness, converted by product of a coefficient shown in equation (1) and 54.7 kVrms. The overvoltage withstand test aimed to confirm the PD inception voltage and to assess the marginal performance of the electrical insulation layer. In the overvoltage test, the applied voltage increased gradually to the limit, so that the upper limit of the applied voltage was 150 kVrms due to the limitation of the terminal sections.

3. Result of the electrical insulation performance tests

The testing conditions for each test and their results are summarized in table 1. PD measurement was carried out all through the testing except the lightning impulse voltage withstand test, using a coupling capacitor under the noise level of 70 pC for the factory tests and foil electrodes embedded in the terminal sections under the noise level of 250 pC for the field test. LN2 condition was controlled with an average temperature of 77 K and LN2 pressure of 0.3 MPa. At the field test, LN2 flow rate was set constant to 30 l/min.

As can be seen in table 1, no PD with a charge above the noise level could be obtained for both factory and field tests except for the lightning impulse voltage withstand test. As for the lightning impulse voltage test, no breakdown occurred. Therefore, it can be concluded that the electrical insulation design method proposed in the literature [7] would be sufficient.

4. Conclusion

In this paper, procedure of the testing voltage is described firstly. The testing voltage mainly conformed to the Japanese standard JEC-3408-1997 and V-t characteristics. Then, several kinds of the voltage withstand tests had been carried out for the 20 m HTS power cable specimen in the factory test and actual 500 m HTS power cable in the field test. PD measurement was combined with the tests under the ac voltage application. As a result, PD above noise level was absent from any tests under ac voltage application, and no breakdown occurred at the lightning impulse voltage withstand test. Therefore, proposed electrical insulation design method would sound enough for the CD type HTS power cable.
**Table 1. Verification testing items for electrical insulation and testing results.**

| Testing item | Testing condition | Result |
|--------------|-------------------|--------|
| 1. Operational frequency voltage withstand test | 95 kV_{rms} × 10 min. → 80 kV_{rms} × 1 hour | No PD was obtained more than noise level of 70pC. |
| 2. Lightning impulse voltage withstand test | ± 440 kV × 3 times | Good |
| 3. Partial discharge test | 95 kV_{rms} × 10 min. → 80 kV_{rms} × 1 hour | No PD was obtained more than noise level of 70pC. |
| 4. Initial voltage withstand test | 95 kV_{rms} × 10 min. | No PD was obtained more than noise level of 250pC. |
| 5. Long-term voltage withstand test | 70 kV_{rms}, 1000 A × 30 days | No PD was obtained more than noise level of 250pC. |
| 6. Overvoltage withstand test | 150 kV_{rms} × 10 min. | No PD was obtained more than noise level of 250pC. |

※Factory test specimen was tested after 2-times 180°-reciprocating bend (bending radius of 17.5Ds, under room temperature).

- 95 kV_{rms}: verification of absence of PD generation under ac stress of 15 kV_{rms/mm}.
- 80 kV_{rms}: verification of lifetime equivalent to 30 years in 1 hour.
- 70 kV_{rms}: verification of lifetime equivalent to 30 years in 30 days.
- 150 kV_{rms}: Maximum voltage limit of the terminal section.

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