Development of Tri-axial superconducting cable system for type test

Tasuku Kitamura¹, Kazuhisa Adachi¹, Hideo Sugane¹, Tatsuhisa Nakanishi¹, Yuji Aoki¹, Nobuhiro Mido¹, Masataka Iwakuma² and Takayo Hasegawa¹

¹ SWCC SHOWA CABLE SYSTEMS CO., LTD, No. 4-1-1, Minami-hashimoto, Chuo-ku, Sagamihara-city, Kanagawa, 252-0253 JAPAN
² KYUSYU UNIVERSITY, 744, Motoooka, Nishi-ku, Fukuoka-city, Fukuoka, 819-0395, JAPAN

e-mail: t.kitamura311@cs.swcc.co.jp

Abstract. We developed a tri-axial superconducting cable system with the rated voltage of 22kV and operating current of 3 kA at liquid nitrogen temperature. We designed the superconducting cable and the termination that was cooled subcooled liquid nitrogen. We used in-house YBCO tapes and a winding machine to prepare the conductor that the $I_c$ -value of 4,200 A or more per phase at liquid nitrogen temperature. The outer diameters of the conductor and the cryostat were approximately 50 mm and 130 mm, respectively. The length, the diameter and weight of each termination were approximately 4,000 mm, 450 mm and 600 kg. The thickness of the insulation layer, which was made from made from PPL paper, was determined by estimation of minimum break down electrical field from Weibull distribution analysis of results, which were obtained by break down tests of the model cables. Regarding the cooling condition of the cooling system, the liquid nitrogen temperatures of the inlet and the outlet of cable system was designed to be 65 K and 70 K, respectively. We manufactured a 25 m tri-axial superconducting cable, and cut out it to get 2 m samples for the $I_c$ test and voltage test at liquid nitrogen temperature. The critical current of each phase was higher than 4,500 A. There was no break-down of each insulation phase at 52 kV for 30 minutes the voltage test. We also manufactured a pair of termination connection for system test and no break-down occurred each insulation phase at 52 kV for 30 minutes. We performed type test of cable system including the superconducting cable and the termination, based on “Recommendations for Testing of Superconducting cables (CIGRE Technical Brochures 538)” [1].

1. Introduction

The superconducting cables have been developed in Europe, USA, and Asia. The AC loss and heat invasion loss are a very important issue to be solved in superconducting cables. Tri-axial superconducting cables are superior in AC loss and the heat invasion properties [2]. A 11 kV-3 kA tri-axial super-conducting cable was developed and tested in Ohio state in USA [3]. A 13.2 kV-3 kA one was also tested at Essen in Germany [4]. In this paper, 22 kV- 3kA tri-axial superconducting cable system is developed as the busber between a generator and a step-up transformer.
2. Development of Tri-axial superconducting cable system for type test

2.1 Construction of Tri-axial Superconducting Cable

YBCO tape is manufactured by Trifluoroacetic acid - Metal Organic Deposition (TFA-MOD) method. The YBCO tape has 0.2 mm thick and 4 mm in width.3). The construction of the tri-axial superconducting cable is shown in Fig.1. The cable has inner cold pipe made of stainless steel in center of the cable section. And it has 3 phase layer superconducting layer, insulation layer and outer of inner cold pipe. The AC loss of the cable is little because the cable is axial construction. The returnable pipe is not needed because the cable has inner and outer cold layer, and be able to apply GO/RETURN cooling.

![Fig. 1 Schematic illustration of the superconducting cable prototype](image)

| TABLE 1 CONSTRUCTION OF TRI-AXIAL SUPERCONDUCTING CABLE Prototype |
|---------------------------------------------------------------|
| ITEM | DIAMETER (mm) |
| Inner cooling SUS corrugated tube | 24 |
| U phase / YBCO superconducting tapes | 25 |
| U phase / PPL paper insulation | 32 |
| V phase / YBCO superconducting tapes | 34 |
| V phase / PPL paper insulation | 41 |
| W phase / YBCO superconducting tapes | 42 |
| W phase / PPL paper insulation | 49 |
| Earthling phase Cu tapes | 52 |
| Inner aluminium corrugated tube | 83 |
| Multi layered insulation | 85 |
| Outer aluminium corrugated tube | 121 |
| Oversheath | 131 |

2.2 Fundamental test of cable insulation material

Cable insulation is used with PPL paper (Polypropylene laminated paper). At first, we manufactured model a cable which has insulation 1.2mm thickness. And we examined AC voltage breakdown test and lighting impulse breakdown test, calculated $E_L$ with Weibull plot. The Weibull plots are shown in Fig. 2. Fig. 2 shows that the minimum break down voltage of AC breakdown is 36.9 mm/kV and the minimum breakdown voltage of lightning impulse is 87.4 kV/mm. Using these results we designed that the insulation thickness of each phase was 2.0mm.
2.3 Short circuit test for superconducting cable

The completed tri-axial superconducting cable has no normal conductor for protection against the excessive fault excess current. Here, a new protection method was studied out. A XLPE by-pass cable was connected to the tri-axial superconducting cable in parallel for each phase. The cross-sectional area of the XLPE copper cable was 250 mm². The three phases of the XLPE cable were located in a room temperature space. The parallel connection of the XLPE copper cable with an insufficient current capacity against the excessive fault current which amounts to several tens of kg produces a tremendous function as the after-mentioned. It was predicted by numerical simulation in advance to the short circuit test. The block diagram of the test circuit of the short circuit test for the tri-axial superconducting cable is shown in Fig. 3. The arrangement of the tri-axial cable connected with the XLPE copper cables. To observe the transport current in each current path, CTs were arranged both on the superconducting cable and the XLPE copper cable.

The short circuit test was carried out by using a 200 MVA short circuit generator. One side of the terminals of the tri-axial cable was connected to the generator for each phase and the other side of the terminals was shorted with each other. The observed voltage and the current waveforms of W-phase are shown in Fig. 4. We can see that the total short circuit current decayed slowly during the short circuit. The current of superconducting cable was rapidly reduced because the current of HTS cable transferred to the XLPE cable. We can see that the current waveform of the superconducting cable is non-linear against the applied voltage. It suggests that the superconducting cable did not shift to a normal state and the temperature of every phase of superconducting cable did not exceed the critical temperature, Tc of YBCO. However, since the current exceeded critical current(B, T) and the flux-flow resistance was generated the transport current in the superconducting cable was decreased. We also conducted the short circuit test on other phases. We obtained the results of V and U phase. We also find similar tendency of V and U phase, compared to the results of W phase.

![Fig.2 Weibull Plot data of PPL paper in LN2](image)

![Fig.3 Block diagram of the circuit of the short circuit test of the tri-axial superconducting cable](image)
2.4 Construction of Tri-axial Superconducting cable Termination

We designed superconducting bus termination is designed. Each conducting layers are connected to outer termination with current lead. Each insulation layers are electric field control with stress relief cone by paper. Fig.5 shows the view of the performance test of the model sample of bus termination.
3. Type test of Tri-axial superconducting cable system

We performed type test of cable system including superconducting cable, termination connection and cooling system based on “Recommendations for Testing of Superconducting cables (CIGRE Technical Brochures 538)”

3.1 Cable bending test and electric characteristic test of superconducting cable

The manufactured cable was tested by the cable bending test described in “3.0 Type Tests on Cable Systems” of CIGLE TB 538. We conducted the bending test the 20m length cable. We bent the cable around a mandrel with specified outer diameter. The minimum diameter of the mandrel is 4,675 mm from the test condition of TB538. We used a cable drum with 3,200 mm outer diameter as the mandrel. Our test condition was severe, compare to the specified condition CIGLE TB 538. We bent the cable around cable drum using the winding machine in our factory. At first, the 20 m cable was wound around the cable drum. Then the cable was drawn out from the drum. And the cable was rotated 180 degrees. Then the cable was wined around the drum again. After that, the cable was draw out from the drum. This process was a one cycle of winding. We repeated this process three times. Fig. 6 shows the view of the bending test at our factory.

![Fig. 6 A view of the bending test](image)

Based on “3.0 Type Tests on Cable” in CIGLE TB 538, we measured DC critical current of the cable after the bending test. We cut the 2 m length conductor from the 20 m length. We attach the 6 current terminals to the edge of each conductor. Fig. 7 shows a schematic draw of the critical current measurement of the W-Phase conductor. We measured the DC critical at the liquid nitrogen temperature. We used a DC current source and a DC voltage meter. We also recorded the temperature of liquid nitrogen in the measuring container. The criteria of the critical current is 1 μV/cm.

![Fig. 7 A schematic of DC critical current measurement](image)
DC critical current of the U-phase is 3,800 A. \( I_c \) of V-phase is larger than 4,300 A. \( I_c \) of W-phase is also 4,300 A. The requirement of critical current should be more than 95\% of 3,000 A. It is 2,700 A. Those measurement values are larger than the requirement. We confirmed the DC critical currents of the cable after the bending test larger than recommended value in TB 538.

### 3.2 Assembling of superconducting cable system for type test

By using the 18m superconducting cable after the bending test and two terminations, we constructed the cable system for type test. Fig. 9 shows a schematic draw of the cable circuit for the type test.

The terminations were connected to the both ends of cable. The superconducting cable was bent by 3m radius. The voltage lead from the voltage transformer was connected to the U and V phase by lead cable terminals. The terminal of the U phase and the shield phase were connected together and connected to the ground. We also decided to connect lead cable with the cross sectional area of 5,000 mm\(^2\) to the U and W phase. We also selected the cross section of lead cable with AC 3,000 A capability at room temperature. When we conduct heat cycle test, subcooled liquid nitrogen flowed and was circulated into the inside of the inner corrugate and terminals. The temperature range was 70-73 K. Fig. 10 shows a view of the type test cable system.
After construction of the type test cable system, we started to introduce liquid nitrogen into the system. After a 72 hours cooling procedure, the superconducting cable and two terminations were cooled to the specified temperature. The temperature of inlet was 70 K, and the temperature of the outlet was 73 K with circulating subcooled liquid nitrogen. Then we moved next test procedure.

3.3 Type test of the cable system
After cooling process of superconducting cable system, we conducted type test.

3.3.1 Voltage loading test
We conducted Voltage loading test. TABLE 2 shows voltage loading test condition and results.

| ITEM                          | CONTENT                                      | RESULT |
|-------------------------------|----------------------------------------------|--------|
| Voltage loading test          | 42kV loading, 3,000A current flow continuous | Passed |
|                               | 8hours on / 16 hours off 20times             |        |

We confirmed that the voltage loading test was passed.

4. Conclusion
We developed a tri-axial superconducting cable system for the type test with the rated voltage of 22 kV and the operating current of 3 kA at liquid nitrogen temperature. We designed superconducting cable, termination with using subcooled liquid nitrogen. We studied fundamental characteristics of superconducting cable and terminal. Using those test results, we defined the detail of the specification of the cable system by manufacturing 20 m superconducting cable and two terminals. We constructed the superconducting system for the type test. We achieved that the loading test was passed.

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