Superconducting Feeder Cable Laying and Stress Relaxation Method for Cooling

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Superconducting feeder cables shrink because of thermal stress during the cooling process. When a long superconducting feeder cable is laid along a railway line, measures must be taken to prevent cable shrinkage. This paper therefore introduces a method which was used to lay a 300-m class superconducting feeder cable along a test track. This paper also reports that the method is suitable for similar cables, because no buckling or rupture points were observed after X-ray radiographs were taken over the whole length of the cable after its installation, and that transmission tests were conducted successfully with the cable.

Key words: superconducting feeder cable, X-ray radiography, laying method, cooling force

1. Introduction

Superconductivity describes a phenomenon where electrical resistance falls to zero when a material is cooled below a certain temperature. Generally superconducting material is processed into the form of a wire or bulk and used in different types of equipment [1]. It is assumed that superconducting cable can also be used in railway feeder systems. We therefore produced a prototype cable by using superconducting tapes and performing characteristic evaluation tests [2-5]. A superconducting cable has zero electrical resistance. Therefore, using this type of cable in the railways may increase regeneration efficiency, reduce power loss, equalize loads between substations, and cut the number of substations needed, because of smaller voltage drops [6, 7].

For commercial operation, cables with the length of several kilometers will be required. Therefore it is necessary to examine how to extend the cable length. When a long cable is laid along a railway line, heat shrink force must be taken into consideration. Consequently, we first studied suitable methods for installing cables along railway lines. Secondly, we actually installed a 300-m cable along a test track, and measured in detail the displacement of the cable as it cooled. Thirdly, an X-ray radiograph was taken over the whole length of the cable after it was installed to check whether this laying method was suitable.

2. Cooling stress relaxation method of superconducting feeder cable

A stress relaxation method of long superconducting cable was investigated [8]. The structure of the superconducting cable is shown in Fig. 1. The superconducting core of a cable is composed of several layers: a copper protective layer, a superconducting layer, an insulating paper layer and a core protection layer wrapped around the cable former. This cable core structure is then inserted into an insulation pipe, to form the superconducting cable. If the cable core and insulating pipe shrink by 0.3% during the cooling process from room temperature to the temperature of liquid nitrogen, then the 300-m class cable will shrink 0.9 m. In total, this means that a cable would shrink 6 m over 2 km, which is the distance between substations. In this case, heat stress was added to the cable, raising the possibility of damage to the cable and the current terminal. Below,

three solutions are described as possible measures against heat shrinkage.

The first solution is to make the current terminal movable. A wheel is placed under the current terminal, allowing the current terminal to move according to the heat shrinkage (Fig. 2). However, the distance that a current terminal can move, is restricted by its environment when it is set, to only about half a meter. Therefore, this solution is unsuitable for longer kilometer-class cables. The second solution is to lay the cable in snake fashion. If the snaking offers a margin of movement which corresponds to length of cable lost through heat shrinkage, then the snaked cable can absorb the heat shrinkage as the cable cools, until it becomes straight (Fig. 3). The third solution is to offset part of the cable, like an arc. This arced offset then absorbs the shrinkage during cooling, and the cable becomes straight (Fig. 4). These heat shrinkage countermeasures are important for laying superconducting cable along railway lines.

Fig. 1 Structure of superconducting cable

Fig. 2 Heat shrink solution by a movable current terminal

Fig. 3 Heat shrink solution by snaked laying

Fig. 4 Heat shrinkage solution using offset

3. Laying and evaluation test of the superconducting feeder system

3.1 Laying test of the superconducting feeder system

A 310-m superconducting cable was installed along a test track. When this cable was made, it was assumed that it would be laid along an actual railway line. This meant taking into account roads and railway crossings along the layout. The cable was laid to curve in several places, to absorb heat shrinkage. In addition, the cable was laid with offsets and the current terminal was made to be mov-

able.

Figure 5 shows the shape of the offset part of the cable. The superconducting cable is fixed onto sliding cleats. The offset part is arranged to avoid exerting excessive force on the cable, by fixing it at around the center of the offset part, making the cable extend on both the sides equally, when a cable length increases when the temperature rises. Trough bridges were installed along the laying route in advance. The superconducting cable was sent out using a caterpillar and cable rollers placed on trough bridges before the superconducting cable was installed on the test track. The radius of the curve used for sending out the cable was more than 2.5 m, and a railway line crossing point with a height difference of 2.4 m was set up in addition to a road crossing point. At the railway line crossing point and a point just before the current terminal, the cleats were not used and only guides were set up, to make the cable movable. This provided the cable with a simple offset. Figure 6 shows the laying location of the cable, and Fig. 7 shows the cable after being laid. The distance between the east side current terminal and the west side current terminal was 310 m. Using this method, it was possible to lay the cable.

Fig. 5 Structure of offset point of the superconducting feeder cable

Fig. 6 Laying location of the 300-m superconducting feeder cable

3.2 Cooling stress evaluation of superconducting feeder cable

The superconducting cable was installed on the trough bridge by the method described in Section 3.1. The cable was cooled gradually by controlling the gasified nitrogen temperature so as not to apply sudden thermal stress to the cable. Optic fiber wound into the superconducting layer with superconducting tapes was used to measure the temperature of the cable. Initial cooling was completed in 80 hours, as shown in Fig. 8. A visual check after cooling revealed no traces of large displacement as well as excessive stress in the cable.

The displacement of the cable during the cooling period was measured in detail. Figure 9 shows the longitudinal displacement of the cable. Since the vacuum insulating pipe was evacuated by a vacuum pump, there were locations displaced even before cooling. It was found that there was displacement over the entire length of cable after cooling, and the displacement direction became reverse between the left-hand side and right-hand side of the rail and underground crossing points which functioned as fixed points. Figure 10 shows the radial displacement of each laying point. The displacement in the longitudinal direction was zero because the offset point was fixed with a cleat. On the other hand, the displacement in the radial direction was 27 mm. At the design stage, we assumed that

Fig. 7 Laying of the 300-m superconducting feeder cable

Fig. 8 Cooling test of the superconducting feeder cable

Fig. 9 Longitudinal displacement of the superconducting cable

Fig. 10 Radial displacement of each laying point

the displacement of the cable would be absorbed at the offset point during cooling. However, the displacement in the offset point was small due to displacement being absorbed by parts laid out in snaked fashion and the simple offset points.

An X-ray radiograph was taken inside the cable by using an X-ray generator device to observe the displacement of the cable core in the insulating pipe after construction [9]. Figure 11 shows an

Fig. 11 X-ray generator equipment

Fig. 12 X-ray radiograph of the superconducting cable

X-ray generator device. Figure 12 shows an X-ray radiography image taken at the offset point. X-ray photography can distinguish between a cable core, heat insulating inner pipe and outer pipe. Figure 13 shows the vertical displacement of the cable at the offset point. It was found that the cable core was displaced in the opposite direction between the right-hand side and the left-side hand of the central cleat point and it was in contact with the insulating inner pipe. Mechanical force was generated in the cable at the point of contact, so a device was needed to ease the force. An X-ray radiograph was taken over the whole length of the cable after it was laid, and there were no buckling or rupture points.

Fig. 13 X-ray radiograph at the offset point

Fig. 14 Diagram of superconducting cable and current terminal

Fig. 15 Withstand voltage test

3.3 Electric property evaluation of superconducting feeder cable

In order to confirm the electrical properties of the laid superconducting feeder cable, withstand voltage tests and power transmission tests were performed. Figure 14 shows the diagram of the superconducting feeder cable and the current terminal. Figure 15 shows a picture of the withstand voltage test. The part of the super-

conducting cable where the current flowed was divided into two layers. One was the P layer where current flows from a substation to a train. The other was the N layer where current flows in the opposite direction.

Using cables with P- and N-layers, we evaluated withstand voltages between P and N, P and the ground, and N and the ground by applying DC voltages to each two layers using a DC voltage application device. In this test, it was confirmed that the withstand voltage of each of the two points was over 5 kV. Hence, it was confirmed that the created superconducting cable had a withstand voltage of 5 kV or more between the layers and that there was no short circuit or discharge between the two layers of the superconducting feeder cable.

Next, we performed circulation cooling with liquid nitrogen using the laid superconducting cable and the cooling system. As shown in Fig. 16, the cooling system was composed of the cryocooler, the reserve pump unit and the flow meter. After cooling, we constructed a feeder circuit using a superconducting cable and then conducted running tests using a train [10]. Figure 17 shows the results of the train running tests. The figure shows data of current which flowed in the superconducting cable when the train was running, the speed of the train and the voltage of the train. It was con-

Fig. 16 Circuit of the superconducting feeder system

Fig. 17 Test of transmission to the train using the superconducting feeder system

firmed that the current value increased as the train ran faster and that electric power could be supplied to it via the superconducting cable while it ran at a maximum speed of 45 km/h. It was possible to transmit electricity to the train through the superconducting feeder cable, confirming that the cable of 300 m was laid soundly.

4. Conclusions

When a long cable is laid along a railway line, heat shrinkage force must be taken into consideration. Different cable laying methods were considered, and then laying the cable in snaked fashion, and introducing offset points in the cable layout when installed, were chosen and carried out experimentally. The 300-m class superconducting feeder cable was laid along the test track. The cable was given road and railway line crossing points because it was assumed that it was laid along an actual railway. After setting up, the cable was cooled gradually by controlling the cold gas temperature with an evaporator to avoid sudden cooling stress to the cable. As a result of an examination of the cable after cooling, it was found that there were no traces of large displacement or excessive stress. X-ray radiography also confirmed that the laying method was suitable for this cable.

In order to confirm the electrical soundness of the superconducting cable, withstand voltage tests and power transmission tests were performed. As a result of the withstand voltage tests, it was confirmed that there was no defect in the insulation performance. And as a result of the power transmission tests, it was confirmed that laying the 300-m class superconducting feeder cable was not affected by acceleration of passing trains or increases in the current flowing through the superconducting feeder cable. In the future, we will perform durability tests and running tests of the superconducting feeder cables and will aim at practical use of long-distance superconducting cable using this laying method.

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