Recent Progress of the High-Temperature Superconducting Cable Project in Japan

Tomoo Mimura¹, Takato Masuda², Hiroharu Yaguchi³, Hiroyuki Fukushima⁴

¹ Tokyo Electric Power Company Holdings, Yokohama, Japan
² Sumitomo Electric Industries, Ltd, Osaka, Japan
³ Mayekawa Mfg. Co., Ltd, Ibaraki Prefecture, Japan
⁴ Furukawa Electric Co., Ltd, Tochigi Prefecture, Japan

Email: Mimura.Tomoo@tepco.co.jp

Abstract. We have spent considerable time studying high-temperature superconducting (HTS) cable for a long time. In Japan, a national project of the HTS cable system in a real grid operation, funded by the New Energy and Industrial Technology Development Organization (NEDO), started a decade earlier, which meant we could carry out real system operation for a year several years ago. We subsequently studied two issues on a new national project. One involved improving the performance of the cooling system, while the other involved safety verification against events possibly occurring in a system such as a ground fault or a short circuit. I will report on the outline.

1. Introduction

HTS cables have significant advantages of compactness and larger power transmission capacity and are expected to be installed in a power grid to replace existing power cables in future. In Japan, a national project funded by NEDO for HTS cables was established for about a decade, during which, despite already having a presence in the Asahi substation, actual grid operation continued for more than a year. Consequently, two further issues arose and the focus shifted to a new project several years ago. One of the issues involves recognizing the relevant aspects when troubles that can occur in the real grid also occur in the HTS cable. These include, for example, a short-circuit current flowing into an HTS cable, whereupon a ground fault occurs. It is crucial to understand the behavior of the HTS cable when the troubles occur. Other issues involve developing high-efficiency large-capacity refrigerators and confirming their reliability. In the new national project, we changed the existing Stirling type to Brayton-type refrigerators, re-energized the grid for a further year and reconfirmed efficiency, performance and reliability.

2. Outline of the research to date and the main points of this paper

The project schedule of the AC superconducting cable we are conducting is shown in figure 1. Phase 1 of the research ran up to the year 2013, while Phase 2 covered the rest of the study and in Phase 1 we connected the 240 m 66 kV superconducting cable to the real grid for the first time in Japan and reconfirmed its reliability through system operation [1], [2]. Among them, we confirmed the need to check for grid accidents, high refrigerator efficiency and problems in realizing long-term maintenance intervals. In Phase 2, to confirm these problems, we replaced the conventional Stirling refrigerator with a Brayton type developed in this research and confirmed its capacity performance and reliability [3]. The results of the short-circuit current test using a 40-m cable, its analysis and ground fault test results using a short cable were also partially reported[4], [5], [6]. The goal of the project is to create a guideline for using a superconducting cable in a real grid based on these results and summarize the high performance and reliability of the refrigerator. In particular, for the short-circuit and ground-fault
currents, we examined how to handle superconducting cables after summarizing the method in the case of conventional cables. The essence of the safety guidelines of HTS cables and an evaluation of the refrigerator check test will be described below.

3. Measures against short-circuit currents and ground faults of conventional cables
The conventional cable we study is the XLPE cable, which is currently the major choice. Regarding the short-circuit current, when introducing the XLPE cable into the actual grid, the copper cross-sectional area is decided comprehensively with the short-circuit current based on the value from the user side (constant current, short-time operation current). In the case of the XLPE cable, the three allowable temperatures are set for the purpose of securing the long-term insulation performance of crosslinked polyethylene and the specific temperatures used in Japan are shown in Table 1. The key point here is the very considerable temperature difference between the constant time and the instant. The reason for the high instantaneous temperature is that it allows a temperature up to the melting point of the crosslinked polyethylene. Accordingly, it is rare for the copper cross-sectional area to be determined by the instantaneous temperature, which means the cable itself is rarely damaged due to bearing the short-circuit current.

Regarding countermeasures for ground faults, it is difficult to define general countermeasures based on the varying laws and regulations in each country. In Japan, countermeasures are taken to adopt a flame-retardant sheath or place it in a rugged container to avoid any serious impact on other equipment.

| Table 1. Allowable temperatures of XLPE cables |
|-----------------------------------------------|
| Items                                        | Value [degrees] |
| Continuous allowable temperature             | 90             |
| Short-term allowable temperature             | 105            |
| Instantaneous failure temperature            | 230            |

4. Important results in creating the safety guideline
4.1. About items necessary for guideline
Since few reports exist of a short-circuit current flow of HTS cable and ground faults at the pre-project stage, many tasks have been done to check what happens when each event occurs. Although we considered countermeasures from the subsequent test results, a trial and error approach was also used when finalizing countermeasures such as cases where it was difficult to put into practical use and cases where the appearance differed for long-distance cables. Accordingly, elements initially considered important were not and vice versa, making it very difficult to find general versatility to finally compile a guideline. Each mode is described below.

4.2. **Short-circuit current flow**

To discuss cable system safety due to the passage of a short-circuit current, we constructed a 40-m cable system. Temperature and pressure data were acquired and compared with the calculation results by a simulation code to simulate the passage of the short-circuit current via the long-distance line and the subsequent process. As described in Section 3, the current always flows after the passage of the short-circuit current, so the superconducting cable must be capable of transmitting the rated current with the temperature rising after accommodating the short-circuit current. In Japan, the maximum short-circuit condition for 66-kV class cables is 31.5 kA, 2 sec, so the calculation result under each condition using the above simulation code, with this as the upper limit, is shown in the figure 2. Although this is a design example, in the cable used for the actual grid interconnection, the upper limit temperature at which the rated current of 2kArms can flow is 92 K and the time intersecting with 92 K denotes the maximum condition under which the rated current can flow, even after a short circuit. Therefore, when a short-circuit current stricter than a certain short-circuit condition flows, the HTS cable needs to be disconnected from the grid since it cannot conduct the current constantly thereafter. Of course, since the rated current does not necessarily flow, a sequence for judging from the temperature and pressure in that situation must be provided. Also, of course, there is scope to ease the condition by the amount of copper of the former and the margin of Ic and application of the fault current limiter. However, it goes without saying that a comprehensive cost comparison is required and where the fault current limiter is not applied, there is a need to incorporate these points into the cable design.

![Figure 2. Condition for allowable short-circuit current](image)

**4.3. Ground Fault**

As well as superconducting cables, power cable troubles mostly involve ground-fault destruction. Although the factors vary, as described in Section 3, it is important to prevent the spread of fire due to ground faults and refrain from breaking the other infrastructures with a ground-fault cable, as described in Section 3. For HTS cables, leakage of liquid nitrogen is certainly a concern during a ground fault. So
with prevention in mind, a ground-fault simulation test with a short cable was performed to confirm whether or not it would be possible to prevent a hole from being drilled by applying a protective layer inside the cable. Figure 3 shows the structure of the 275-kV cable and the state in which the protective layer is wound 1 cm immediately above the SUS inner pipe. Figure 4 shows the conditions of the inner and outer SUS pipes when the ground-fault current condition is 30 kA, 0.06 s. Although this condition is sufficiently feasible in our company, consequently, the direction to prevent external leakage of liquid nitrogen means an increased cable diameter, which has led to the loss of flexibility. Accordingly, we decided to rely on the leakage countermeasure described in the next section.

In addition, since the ground-fault current at the 66-kV class is standard at our level, several hundred amperes, puncturing is not done in some cases depending on circumstances. In this case, the internal pressure increased, which impacted on the pressure-resistant design of the SUS pipe itself and the range of pressure propagation in a longitudinal direction, but experiments and simulation confirmed that this level would not hinder the current design. From a user maintenance perspective, there is a need to identify the cable ground-fault position because we cannot watch the position directly, particularly in the case of installing in a duct. Also, for early restoration, there is a need to realize temperature rise and re-cooling at high speed.

![Figure 3. 275kV cable structure (a) original structure (b) additional protective layer](image)

![Figure 4. Broken SUS pipe by ground fault](image)
4.4. LN2 leakage countermeasure

Initially, though external leakage via cables is assumed, connecting parts, valves, etc. slight leakage and excavation, etc., leakage at the time of a ground fault is thought to be the most severe condition because it is considered to be both quantitative and fast. Even when ground faults occur, the conditions to be considered include various factors, such as puncture size, cable height difference, leakage and the cable length. Given the difficulty in verifying these various cases this time, we built a concrete structure with a volume of about half the general manhole size used for 66 kV cables. Figure 5 shows a complete view of the manhole. A simulation test was then conducted to flow liquid nitrogen into the same. The flow rate was fixed to be close to real grid operation and basic data was acquired by measuring the temperature, pressure and oxygen concentration transition of each manhole part, the surface temperature of the installed CV cable, etc. together. Figure 6 shows the temperature transition of the thermometer installed in the concrete wall. The thermometer installed at 20, 50 mm from the floor, approached the temperature of liquid nitrogen in under 20 minutes and it was confirmed that liquid nitrogen had accumulated. Moreover, the temperature started to rise within about 30 minutes of stopping the leak. Depending on the size of the hole and the condition at the time of the ground fault, rapidly detecting the ground fault and quickly stopping LN 2 circulation allows some oxygen concentration deficiency in the manhole and is also feasible during normal cable operation. There is thought to be scope to handle the same without requiring work peculiar to superconductivity by ensuring sufficient ventilation in the manhole. The results of the surface temperature measurement of the CV cable are shown in figure 7 and the CV cable was installed at a height of 700 mm from the floor. This cable is not designed to a cold district specification, but one usually used at the temperature and usage condition of 0 °C or more. Following the test, the temperature dropped to about -20 °C immediately after the leakage started and rose once the leakage had ended, but under this test condition, despite the temperature going below 0 °C for less than 1 hour, no surface cracks were seen. We did not confirm the cable loading performance, but this will be future work.

Figure 5. Mock up for LN2 leak test in manhole
4-5 Outline of the guidelines

Based on the contents and findings reported to date, we have developed safety management guidelines to manage operations. The operation management includes steady and unusual states and the contents to date correspond to an unusual state, while the contents to be included in the guideline are shown in Table 2. The steady state is summarized in the next section. Regarding short-circuit events, as described above, there are cases in which operation specific to superconductivity is required, but rough knowledge about other events was obtained. We got a prospect of real system operation by operating management based on the guidelines.
5. Brayton-type Refrigerator verification result

5-1 Verification of the Brayton refrigerator

To realize a large-capacity and high-efficiency refrigerator, we developed a 5 kW @ 77 K Brayton refrigerator, confirmed it could achieve COP 0.1 at the factory test and then replaced the conventional Stirling refrigerator in the Asahi substation, which is the actual grid operation field. The system flow of the Brayton-type refrigerator and the installed equipment are shown in figure 8. Subsequently, initial cooling, including superconducting cables, was carried out and grid operation was also carried out for about one year from March 31, 2017. The results of comparing the one-year COP transition with the conventional Stirling refrigerator are shown in figure 9. Multiple Stirling refrigerators were installed to secure the refrigerator capacity, but vacuum maintenance of the on-site refrigerator, supplement of the refrigerant and overhaul etc. were required fewer than 10 times. Brayton realized operation with no maintenance at all, except for having to deliberately reduce the degree of vacuum for data confirmation. It was also confirmed that COP had twice the performance of the Stirling type. In the grid operation, since the operation was made to keep the cable operation temperature constant at 69 K, it was lower than the COP at a factory test of 77 K, but almost as expected based on temperature dependency. Although we are currently disassembling and confirming the performance deterioration at each part level, no performance degradation has occurred.

![Brayton refrigerator system flow](image1)

**Figure 8.** Brayton refrigerator system flow(a) and installed at Asahi S/S(b)

| Items                    | Contents                                                                 |
|--------------------------|--------------------------------------------------------------------------|
| Short-circuit current    | (1) Having a re-transmission enable/disable judgement function.         |
|                          | (2) Allowable temperature of the cable is clear.                        |
| Ground fault             | (1) Restoration work centering on oxygen luck MUST ensure safety.        |
|                          | (2) Do not affect the soundness of other facilities.                    |
|                          | (3) Accident span can be reliably detected.                            |
| Excavation               | (1) The excavation span can be identified.                              |
|                          | (2) Ensuring public safety.                                             |

**Table 2.** Unusual state of safety guideline for HTS cable
5-2 Steady-state of the guideline

We have already described the guidelines at the time of unusual state in the previous chapter, but outline them at the time of steady operation. For low-temperature equipment not limited to superconducting cable systems, since the information to take out each sensor from the inside of the vacuum vessel dominates, there is a need to thoroughly examine the information to be managed when designing each piece of equipment. Also crucial is knowing what threshold at which to manage the information obtained. Since superconducting cables can handle high-capacity power transmission, constant circulation of the cooling system is indispensable, so it goes without saying that improved redundancy over conventional systems is required. From this perspective, further progress in sensors and ease of exchange are also needed, which is what underpins the steady-state guidelines summarized in Table 3. Although it is not possible to uniformly describe the specific contents due to users’ policy etc., I think that attention should be paid to installing detection sensors, etc., to keep the circulation system operational as much as possible.

Table 3. steady state of safety guideline for HTS cable

| Items                  | Contents                          |
|------------------------|-----------------------------------|
| Basically various parameters should be within the normal range | Parameters: Temperature, Pressure, Flow rate, Vacuum level |
| Parameters Range       | Organize thought of alarm setting |

6. Conclusion

To prepare guidelines concerning the safety of superconducting cable systems, possible events in the grid were verified by actual model cables and systems. Using the results, we summarized the contents to be included in the guidelines for operating the long cable system at the time of actual application by using some simulation codes. Moreover, good results such as ensuring prescribed capacity and scope to operate with almost no maintenance, etc. were obtained by conducting a one-year grid interconnection test using a high-efficiency large-capacity Brayton refrigerator. We are currently preparing guidelines, but expect that they will constitute reference data for designing and operating superconducting cable systems in future.
Acknowledgments
This work was supported by the New Energy and Industrial Technology Development Organization (NEDO).

References
[1] Honjo S, Mimura T, Kitoh Y, Noguchi Y, Masuda T, Yumura H, Watanabe M, Ikeuchi M, Yaguchi H, and Hara T, 2011 IEEE Trans. Appl. Supercond. 21(3) 967-971
[2] Ohya M, Inagaki Y, Tatamidani K, Ito H, Saito T, et al., 2013 SEI Technical review 76
[3] Tanaka G, Shimoda M, Yaguchi H, and Nakamura N, 2018 Asian Conference on Refrigeration and Air-conditioning E211
[4] Takeda N, Yasui T, Yokoo Y, Agatsuma K, Ishiyama, et al., 2017 IEEE Trans. Appl. Supercond. 27(4) 5400705
[5] Masuda T, Morimura T, Nakano T, Maruyama O, Mimura T, Yasui T, Agatsuma K, and Ishiyama A, 2017 IEEE Trans. Appl. Supercond. 27(4) 5401504
[6] Takagi T, Yagi M, Mukoyama S, Watanabe K, Mimura T, Maruyama O, and Nakano T, 2017 IEEE Trans. Appl. Supercond. 27(4) 5401205