The 2nd in-grid operation of superconducting cable in Yokohama project

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Abstract. The superconducting cable system was installed and operated in the real grid of Tokyo Electric Company (TEPCO) Holdings from 2012 to 2013, successfully. At this operation, the system had no degradation of its electrical and mechanical performances. After then, its cooling system was replaced to new turbo-Brayton refrigerator and the cable was re-connected to the grid in 2017. The cable system was successfully operated for another one year. In this operation, stable cooling system controlling, heat loads and vacuum rates of the cryostats etc. were observed continuously. After the operation, No Ic degradation of whole length was measured. In addition, the short sample cables cut from the system after the dismantlement, were applied with AC 90 kV and Imp 385 kV, successfully as the same condition of the shipping test in 2011. These results are one of the credibility confirmations for long time superconducting cable system operation.

1. Introduction
For the purpose of commercialization of superconducting cable, a 66 kV / 200 MVA superconducting cable was developed and conducted a grid operation at a TEPCO’s substation in Yokohama, Japan, from 2012 to 2013. It was proved that the electricity transmission with the superconducting cable was very stable and reliable because of the operation without any trouble or any unexpected suspension [1]. As the results, some subjects for the commercialization were remained, such as safety and reliability at the accidents, development of new refrigerators with higher efficiency, and so on. For studying these subjects, the national project was launched in 2014 [2][3]. In this project, Mayekawa Corporation succeeded in the Brayton cycle refrigerator [4], which was installed in the substation with the superconducting cable to clarify its long term performance. Then, the 2nd in-grid operation was conducted from 2017 to 2018. In this paper, the results of the 2nd operation regarding to the superconducting cable and its remained performance evaluated after the operation are reported.

2. Outline of Yokohama project
The project started in 2007 to clarify stability and reliability of superconducting cable operation in the real grid with a 66 kV / 200 MVA cable. The outline of the project is described below.

2.1. Cable structure and System layout
The superconducting cable has 3 cores as shown in Fig. 1. The conductor and shield conductor are composed of BSCCO wires, made by Sumitomo electric. The electrical insulation is made with
Polypropylene laminated paper (PPLP®). The three cores are stranded and housed in a cryostat made with double corrugated stainless pipes and thermal insulation in vacuamed space.

The superconducting cable was installed at Asahi substation of TEPCO’s network located in Yokohama, Japan. The cable system was composed of the cable, joint, two terminations and a cooling system in Fig. 2. The cable has 240 m length and is separated to two parts, Cable A with 80 m and Cable B with 160 m. The cable was installed in the conduit on the ground except some of Cable B which was under the ground. The cable is also cooled with liquid nitrogen circulated by the cooling system, so called as a closed cycle.

Fig.1 Superconducting cable structure

Fig.2 System layout at Asahi substation

2.2. Test records of Yokohama cable
The test records are shown in Fig. 3. The superconducting cable was manufactured at Osaka Works of Sumitomo Electric. All of the shipping tests were conducted successfully [5]. Then it was shipped and installed at Asahi substation in 2011. Before the 1st in-grid operation, the performance tests (PT) were conducted to check the critical current (Ic), the D.C. voltage performance and so on. According to the Japanese regulation, A.C. voltage test at 1.1 x Vm (maximum operated voltage) or D.C. voltage test at 2.2 x Vm to the ground should be applied to the installed cable for checking its insulation performance in case that any voltage test for whole length cable is not conducted before shipping. In this case, as
the cable had no voltage test with whole length before shipping, the DC test was conducted at 151.8 kV with \( V_m \) of 69 kV in view of easier test device. Such performance test was conducted three times with experiences of heat cycle between the room temperature and the liquid nitrogen temperature (PT (1)(2)(3) in Fig. 3). As the cable had no degradation, the cable was connected to the grid in 2012, and operated for one year, successfully. Then, the cable Ic was checked in the PT (4) without any degradations. As the result of the 1st in-grid operation, it was clarified that the operation was very stable and reliable in the normal condition of the network. On the other hand, some degradation of the refrigerators, which are in Starling type, were observed. So, Mayekawa started to develop a new refrigerator in Brayton cycle in 2013.

During the development, the cable was maintained at room temperature for about two years. The new refrigerator was replaced for Yokohama cable in 2016 to be operated with the cable in the grid. Following the PT (5) without no degradation of Ic or D.C. voltage performance, the 2nd in-grid operation was started in 2017.

3. Result of 2nd in-grid operation
After the cable was maintained at room temperature for two years, the PT (5) in Fig. 3 with checking cable Ic or D.C. voltage performance was conducted to find no degradation. Then the cable cooled with the new refrigerator was connected to the grid again.

3.1. Operation results
Fig. 4 shows the results of the 2nd in-grid operation from March 2017 to April 2018, such as operated current, the inlet temperature of liquid nitrogen, the pressure of reserved tank and liquid nitrogen flow rate. As is shown in Fig. 4, the temperature, pressure and flow rate of liquid nitrogen were controlled as constant stably despite of fluctuating operating current. Amount of electricity were transmitted to the customers stably without any unexpected suspension by the superconducting system except two stops by the operation management and inspection of network apparatus.
3.2. Heat invasion and Vacuum state of the cable cryostat

In this operation, the heat loads and the vacuum state of the cable were observed for one year to check the cable performance. Fig. 5 shows the vacuum states and heat loads of the Cable A and Cable B during the 2nd in-grid operation. Heat load of Cable A can calculate with temperature difference between inlet temperature and outlet temperature of liquid nitrogen in Cable A and flow rate of liquid nitrogen. This heat load has some AC loss, dielectric loss and friction loss. In this case, the friction loss was negligible. So, the heat invasion of Cable A is calculated by the heat load subtracted by the AC loss calculated with the operation current and dielectric loss calculated with the operated voltage. The heat invasion of Cable B is acquired by the same manner as Cable A. Unfortunately, as shown in Fig. 5, there is some duration without data of heat invasion, because of some sensor disorders. In addition, the vacuum states of Cable A and Cable B are also shown in Fig. 5. In this system, the vacuum areas are separated to Cable A, Cable B, joint, Termination A and Termination B. All of the vacuum areas were sealed and their states were observed by vacuum sensors which are attached at each section.

The heat invasion of Cable A has slight increase in summer season because the higher ambient temperature and strong sun light make the temperature of the conduit surface higher. Then it was back to the initial heat invasion in the winter. In the operation, the vacuum state of Cable A was maintained at higher vacuum degree as the order of $10^{-4}$ Pa. On the other hand, the heat invasion of Cable B was increased highly. It was not back to the initial level. It is estimated that the reason comes from the vacuum degree getting worse to the order of $10^{-2}$ Pa. After the grid operation, we found no vacuum leakage of the Cable B, so we estimate the reason is due to some out gas inside of the cryostat.
Fig. 5 Heat loads and vacuum rates of the Cable A and the Cable B

Note 1: no data of vacuum rate of Cable B due to disorder of vacuum sensor
Note 2: no data of heat loads of Cable A and B due to disorder of temperature sensors

4. Residual performance of the cable
After the grid operation, Ic measurement for whole length cable was conducted in PT (6). Fig.6 shows the results of Ic measurement for all phases with other measurements in PT (1) ~ (5). As the results, Ic of the cable has no degradation.

Fig. 6 Results of Ic measurements for all phases
at average temperature of 77.3 K between inlet and outlet, pressure of 0.2MPaG
and flow rate of 40 L/min

Then, the system was warmed up and deconstructed. Some voltage tests were conducted with a 5m sample cable cut from the 240m cable. AC voltage of 90kV for 3 hours and lighting impulse voltage of ±385kV for 3 times were applied to the sample cable successfully. These testing conditions are the same as the shipping test, which come from Japanese test code of Oil filled cable.
5. Conclusion
The 2nd in-grid operation was completed successfully to clarify it is stable and reliable. As the results of \( I_c \) measurements in PT (6) and voltage tests with the sample cable after the operation, it proved that the superconducting cable has a good performance for long duration because it maintained the initial performance through the experiences of two grid operation.

In the 2nd in-grid operation, the heat invasion of Cable B was increasing gradually because its vacuum degree was getting worse. We estimate the reason of deteriorating vacuum state would be the influence of out gas inside of the cable cryostat. Investigations of the out gas is reported at the reference [6]. On the other hand, the heat invasion of Cable A is almost constant without deteriorating vacuum degree. The difference of Cable A and Cable B is pointed as the installation layout. That is Cable B has a U-shape bending part with small radius of 5 m. In this U-shape part, the heat invasion through the cryostat is larger than straight part because of large side pressure caused by cable tension. So, it means steep temperature gradient in the cryostat to discharge more out gas. In actual case, such U-shape bending part in a small radius is not adopted. The actual layout is large straight part and small bending part like Cable A. Therefore, vacuum state of cable cryostat can be maintained at good degree in actual case.

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References
[1] Maruyama O, Honjo S, Nakano T, Masuda T, Watanabe M, Ohya M, Yaguchi H and Nakamura N 2015 IEEE Transactions on Applied Superconductivity Results of Japan’s First In-Grid Operation of 200-MVA Superconducting Cable System Vol. 25 Issue 3
[2] Maruyama O, Nakano T, Mimura T, Morimura T, Masuda T, Takagi T and Yagi M 2017 IEEE Transactions on Applied Superconductivity Fundamental Study of Ground Fault Accident in HTS Cable Vol. 27 Issue 4
[3] Masuda T, Morimura T Nakano T, Maruyama O, Mimura T, Yasui T, Agatsuma K and Ishiyama A 2017 IEEE Transactions on Applied Superconductivity Safety and Reliability of 66-kV Class HTS Cable Systems in Short-Circuit Current Accidents-Experimental Results on 40-m Cable System Vol. 27 Issue 4
[4] Tanaka G, Shimoda M, Yaguchi H and Nakamura N 2018 the 9th Asian Conference on Refrigeration and Air-conditioning COOLING SYSTEM FOR HIGH TEMPERATURE SUPERCONDUCTING CABLE proceedings
[5] Masuda T, Yumura H, Ohya M, Ashibe Y, Watanabe M, Minamino T, Ito H, Honjo S, Mimura T, Kitoh Y and Noguchi Y 2011 IEEE Trans. Appl. Supercond Test Results of a 30m HTS cable for Yokohama Project Vol. 21, No. 3
[6] Watanabe M, Masuda T, Yamaguchi H, Tanazawa M and Mimura T 2019 EUCAS 2019 Adoption of getter pump for HTS superconducting cable system