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Status of Superconducting Cable Demonstration Project in Japan

Shoichi Honjo, Tomoo Mimura, Yutaka Kitoh, Yu Noguchi, Takato Masuda, Hiroyasu Yumura, Michihiko Watanabe, Masamitsu Ikeuchi and Hiroharu Yaguchi

***Abstract*—The HTS cable demonstration project, called the Yokohama Project, supported by Ministry of Economy, Trade and Industry and the New Energy and Industrial Technology Development Organization, was initiated in Japan in 2007. The aim of this project is to operate a 66 kV, 200 MVA high-temperature superconducting (HTS) cable in a network of the Tokyo Electric Power Company to demonstrate cable reliability and stable operation. Total project period was changed from 5 years to 6 years. Chosen as the demonstration site was the Asahi substation in Yokohama. Based on the analysis of the network conditions of the demonstration site, specifications of the HTS cable system were determined. Element technologies were developed and various preliminary tests using short core samples were conducted to confirm the HTS cable design. A 30-meter HTS cable system was manufactured and tested prior to initial demonstration tests. Long-term demonstration tests of the HTS cable system in an actual grid at the Asahi substation are scheduled to be started in 2011.**

***Index Terms*— High-temperature superconductors, Superconducting cables, Superconducting transmission lines, Power cables.**

I. INTRODUCTION

High Temperature Superconducting (HTS) cable is expected to transmit larger amounts of electric power having lower power loss despite smaller cable size due to the higher critical current density property of the HTS conductor.

As underground space is almost unavailable and present space is already congested in populated urban areas in Japan, it will become highly difficult to construct new tunnels for underground power transmission cables to cope with the growing increase in power demand. In addition to this problem, the need for replacement of over-aged larger capacity cables, such as oil-filled cables (OF cables) and pipe-type oil-filled cables (POF cables), will grow larger year by year. Replacing these cables with low-capacity cross-linked polyethylene vinyl sheath cables (XLPE cables), however, requires additional circuits, thereby causing impracticality due to the difficulties inherent in constructing new cable tunnels.

If HTS cables having a diameter small enough to be installed in existing ducts are realized, they can offer innovative solutions to these technical bottlenecks. They have therefore been identified as a key technology for the development of next-generation power transmission lines.

The Tokyo Electric Power Company (TEPCO) and Sumitomo Electric Industries (SEI) have been conducting research and development of HTS cable systems since 1990. Based on these studies, they began this new HTS cable demonstration project in 2007. This paper describes the summary and the development status of this project.

To realize the practical use of HTS cable systems, several HTS cable demonstration projects have been undertaken around the world [1]-[4].

II. Summary Of The Yokohama Project

A. Project members

The HTS cable demonstration project, called the Yokohama Project, funded and supported by Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology Development Organization (NEDO), got underway in 2007. Target of this project is to operate a 66 kV, 200 MVA HTS cable system in a real grid in order to demonstrate its reliability and stable operation.

TEPCO provides an actual power grid for demonstration tests and verifies system operation and maintenance techniques. TEPCO also studied what influences the connecting HTS cable had on the power grid. At the same time, SEI has developed element technologies for the HTS cable system, and is responsible for the manufacturing, construction and operation of the HTS cable system. Also, Mayekawa MFG. Co. has designed and assembled a cooling system, and is now conducting verification tests of the cooling system prior to the long-term tests. A steering committee, comprising university professors, researchers of electric utilities and personnel of research institutes, has been holding regular meetings to obtain opinions, advice and comments regarding this project.

B. Project schedule

The project began in 2007. In order to secure the time for

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S. Honjo is with Tokyo Electric Power Company, Yokohama, 230-8510, Japan (phone: +81-45-394-6301; fax: +81-45-585-8693; e-mail: honjo.shoichi@tepco.co.jp). T. Mimura (e-mail: Mimura.Tomoo@tepco.co.jp), Y. Kitoh (e-mail: kitoh.yutaka@tepco.co.jp) and Y. Noguchi (e-mail: noguchi.yu@tepco.co.jp) are with Tokyo Electric Power Company, Yokohama, 230-8510, Japan.

T. Masuda (e-mail: masuda-takato@sei.co.jp), H. Yumura (e-mail: yumura-hiroyasu@sei.co.jp) and M. Watanabe (e-mail: m-watanabe@sei.co.jp) are with Sumitomo Electric Industries Ltd., Osaka, 554-0024, Japan.

M. Ikeuchi (e-mail: masamitsu-ikeuchi@mayekawa.co.jp) and H. Yaguchi (e-mail: hiroharu-yaguchi@mayekawa.co.jp) are with Mayekawa MFG. Co., Ltd., Moriya, 302-0118, Japan.

verifying the performance of the cooling system, the total project period was given a one year extension from the initial 5 years to the present 6 years. The time schedule is shown in Fig. 1.

During the first two years, technologies were developed for all elements of the HTS cable system, including the decision of cable structure. The structure provides large current capacity with lower AC losses, and withstands short circuit currents. At the same time, the demonstration site was determined and the grid condition was carefully scrutinized. In 2009 and early 2010, a 30 meter cable system was constructed and assessed at SEI's facility to verify its performance before manufacturing and constructing the HTS cable system at the demonstration site. Performance test of the cooling system is scheduled in 2010 in order to confirm system characteristics. Finally, the cable system will be installed and operated at the demonstration site over a one year period.

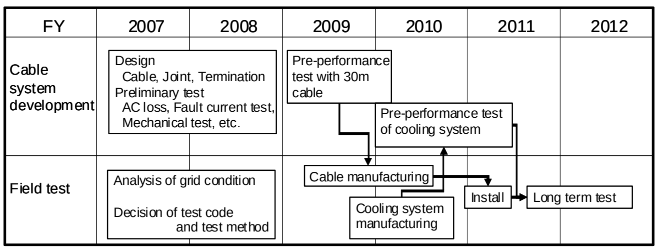

Fig. 1. Time schedule of the HTS cable demonstration project.

C. System specification

The specifications of the HTS cable system are summarized in Table 1. Some of these specifications are determined in consideration of the results of power network analysis described in the next section.

Since the major target of the development of a HTS cable is to realize a large power cable having a compact size, the cable structure was determined to be the "3-in-One" type. Cable diameter is designed to make it possible to be installed in a 150 mm conduit. Total length of the cable is to be about 250 meters, with a cable-to-cable joint box and terminations at both ends.

AC loss target of the cable used for the demonstration tests is 1 W/m/ph at 2 kArms. Most importantly, the project's ultimate goal is to reduce AC loss to less than 1 W/m/ph at 3 kArms.

TABLE 1 SPECIFICATIONS FOR THIS PROJECT

Items	Specifications
Cable structure	Three cores in one cryostat ("3-in-One")
Rated voltage and current	66 kV, 1.75 kArms, 200 MVA
Withstanding over-current	2.6 kArms
Cable length	About 250 m
AC loss	1 W/m/ph @ 2 kArms (for long-term test) 1 W/m/ph @ 3 kArms (final target)
Fault current condition	Maximum fault current: 31.5 kA, 2 sec Maximum through fault: 10 kA, 2 sec
Accessories	Terminations, Cable-to-cable joint
Outer diameter of cable	150 mm conduit
Cooling system	Direct circulation system with sub-cooled pressurized LN2

III. POWER NETWORK ANALYSIS

A. Demonstration site

The demonstration site chose the Asahi substation, located in Yokohama, in consideration of space, current capacity and other factors. Asahi substation is an outdoor type, and has three set of 200 MVA, 154/66 kV step down transformers which connect 154 kV bus lines and 66 kV bus lines. As shown in Fig. 2, the HTS cable is connected between the low voltage side of the transformer and the 66 kV bus lines, with circuit breakers (CB1 & 2) and line switches (LS1 & 2) on both sides of the HTS cable. Another line switch (LS3) is added in parallel to the HTS cable to form a by-pass circuit for emergency use.

Fig. 3 shows the layout of the demonstration system at the Asahi substation. Installed are two HTS cables connected to each other with a cable-to-cable joint. Total HTS cable length is to be about 250 meters. A portion of the cable will be installed above ground and a portion remaining underground with multiple bends in both the vertical and horizontal planes.

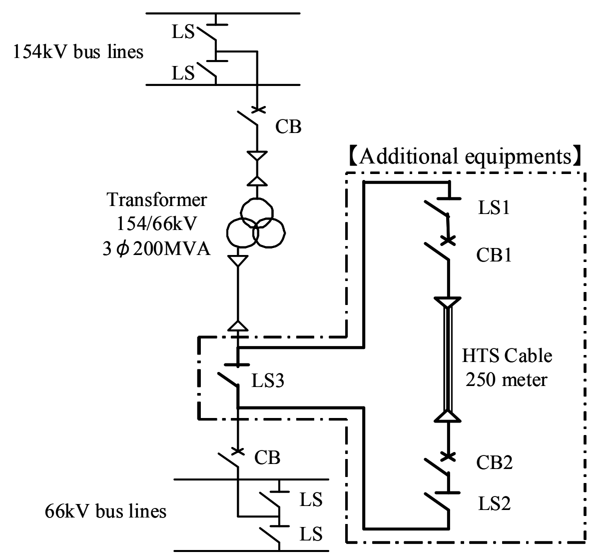

Fig. 2. Simplified power network diagram added the HTS cable and other equipment at the Asahi substation.

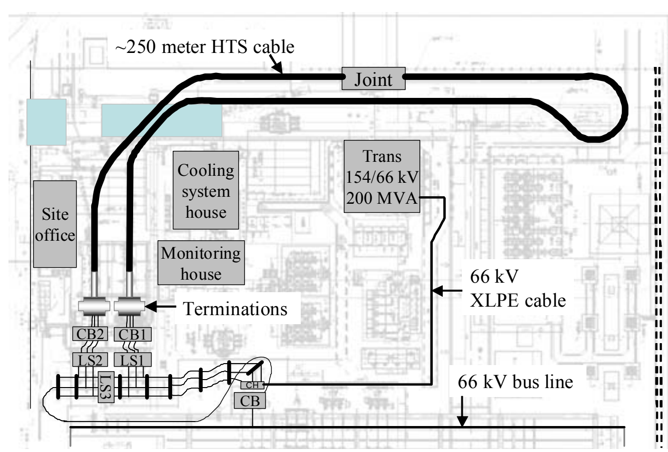

Fig. 3. Layout of the demonstration system in the Asahi substation.

B. Fault current condition

Fault current conditions in the Asahi substation, which will influence the HTS cable, were calculated by a fault current calculation program. Times of fault current duration were determined considering the protection sequences comprising main protection relay working and back-up protection relay working, for example, failure of a circuit breaker.

Fig. 4 shows the results of calculation. Circle plots represent the case in which the HTS cable is disconnected from the grid at the same time as the fault point's being cut away. The maximum fault current condition in this case is about 20 kA for 2 sec. This energy is much less than 31.5 kA for 2 sec, which is a rating short-time withstand current value defined for equipment of a 66 kV power network in TEPCO. This means that the HTS cable must be designed to withstand the fault current flow from the mechanical viewpoint, although the HTS cable need not be required rapid recovery in the superconducting state from the thermal viewpoint, as a certain amount of time may elapse before the HTS cable is reconnected to the grid.

On the other hand, triangle plots represent the case in which the load current flows again to the HTS cable promptly after the fault point is cut off. The maximum fault current condition of this case (called the "through-fault") is less than 10 kA for 2 sec. In other words, the HTS cable should operate at its rated current even after a fault current flow of 10 kA for 2 sec.

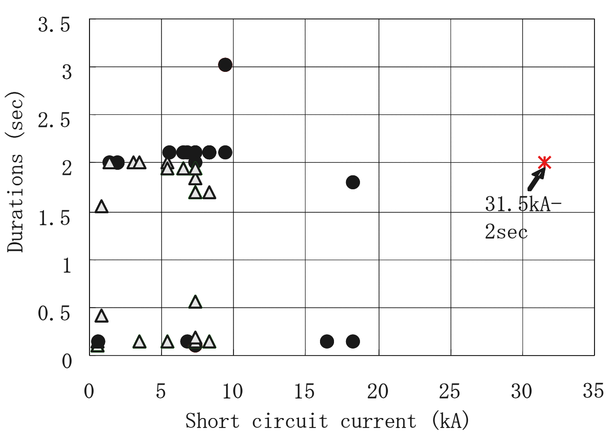

Fig. 4. Simulation results of fault current conditions. Circle and triangle plots correspond to non rapid re-close case and rapid re-close case, respectively.

C. Surge condition

Lightning surge propagation characteristics in the HTS cable were calculated and compared with those of conventional XLPE cable, since the resistivity and surge impedance of the HTS cable conductor are both smaller than those of the XLPE cable having the same capacity, which could affect the surge propagation characteristics. For example, surge impedance of the HTS cable used for this project is about 0.11 ohm/m, while that of XLPE cable is about 0.27 ohm/m. On the other hand, the propagation speed of the HTS cable is about twice of that of XLPE cable.

The analysis condition was a lightning strike to a pylon of 66 kV line nearest the substation having a lightning current of 30 kA. Fig. 5 shows the results of the lightning surge voltage wave patterns in the HTS cable and the XLPE cable. The peak over voltage of the surge reached 196 kV about 17 μs after the lightning strike in case of the HTS cable. Its speed was 206 m/μsec. There is no significant difference in the lightning surge characteristics between the HTS cable and the XLPE cable. The lightning impulse withstand voltage (LIWV) of the 66 kV network is 350 kV. Calculation revealed that the maximum peak voltage of 196 kV is small in comparison with the LIWV value, indicating that superconducting properties do not affect insulation design of the HTS cable.

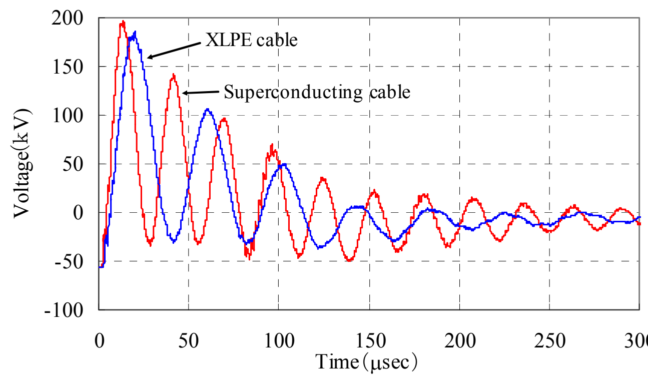

Fig. 5. Lightning surge voltage wave forms of HTS cable and conventional XLPE cable. Propagation speeds of HTS cable and conventional XLPE cable are 206 m/μs and 121 m/μs, respectively.

IV. Development Of Element Technologies

Various element technologies were developed and various preliminary tests were conducted to determine the cable system designs, such as the HTS cable itself, the joint, the termination and the cooling system in the first two years. In this section, the major technologies regarding electrical properties of the HTS cable are summarized. Other element technologies have been described in detail by Ohya, et al [5].

A. HTS cable design

Fig. 6 shows the structure of the "3-in-One" HTS cable. Three cores are housed in a stainless steel double corrugated cryostat. Each core consists of a former made of copper stranded wires, an HTS conductor, electric insulation, an HTS shield and a copper shield, all of which are coaxially wound around the former. HTS conductor and HTS shield consist of 4 layers of Bi-2223 HTS wires and 2 layers of the same wires, respectively. In the steady-state, a transmitted current flows through the HTS conductor layers. Current nearly identical to the HTS conductor but opposite in phase flows in the HTS shield layers. The copper former and copper shield layers work as by-pass circuits of over-current in case of fault.

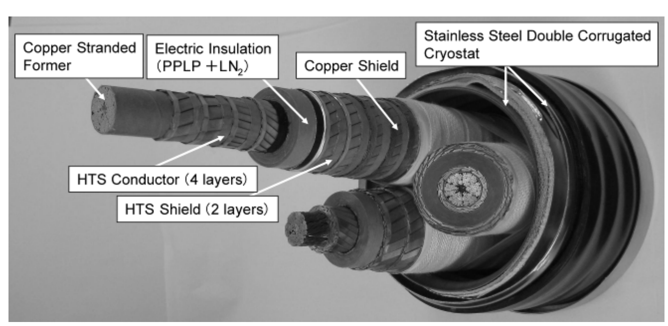

Fig. 6. HTS cable structure to be installed at the Asahi substation.

B. AC loss measurement

In order to reduce AC losses of an HTS cable, low AC-loss type wires, "Type ACT", and high critical current type wires, "Type HT", were used as the HTS conductor layers. Fig. 7 shows the results of AC loss measurements. AC loss was reduced to 0.8 W/m/ph at 2 kArms, which meets the required specifications of 1 W/m/ph.

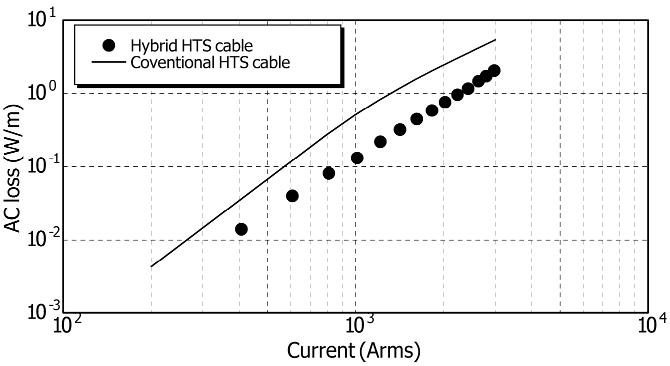

Fig. 7. AC loss test results for hybrid HTS cable core. AC loss of the hybrid core is much smaller than that of conventional cable core.

C. Withstanding fault current

Fault current withstanding tests were conducted using short length sample cores in a saturated liquid nitrogen bath. Fig. 8 shows the temperature rise (ΔT) both of the HTS conductor and the HTS shield. ΔT of the conductor and the shield reached 120K and 110K, respectively, in the case of 31.5 kArms for 2 sec, with both falling within the expected range of simulation results. Furthermore, no deterioration in critical current characteristics was observed in both the conductor and the shield after the tests. This indicates that the sample possesses the required over-current withstanding characteristics.

Other tests which simulated through-fault accidents were also conducted. (1) Continuous rated current of 1.75 kArms was applied to the test sample immediately after a fault current flow of 10 kA for 2 sec. (2) A continuous rated ground-to-phase voltage of 38 kV was applied to the test sample immediately after a fault current flow of 10 kA for 2 sec. In both cases, ΔT of conductor and shield were less than 5 K immediately after the fault current flow, and their temperatures rapidly returned to the bath temperature. No thermal runaway or electrical breakdown was observed during the tests.

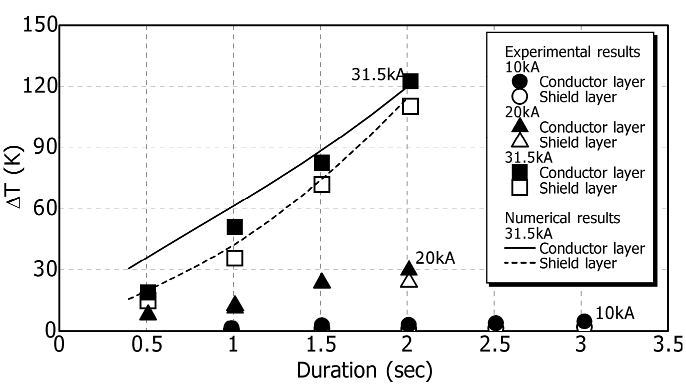

Fig. 8. Fault current test results of HTS cable core sample. Temperature rise (ΔT) was measured at the over- current flows of 10 kA, 20 kA and 31.5 kA under various time durations.

D. Electrical insulation characteristics

Polypropylene laminated paper ("PPLP") impregnated with pressurized liquid nitrogen was chosen as an electrical insulation layer. This structure has worked well in many voltage impression tests, and exhibits good heat cycle (cooling and heating) characteristics.

In order to verify the electrical insulation performance, a model cable having an insulating layer of 6 mm in thickness was prepared to conduct the voltage impression test. An AC withstand voltage of 90 kV for 3 hours and impulse withstand voltage of 385 kV for 3 times were applied to the model cable. No partial discharges were observed in the AC withstand voltage tests, and electrical breakdown did not occur in the impulse withstand voltage tests. Considering margin, the thickness of the electric insulation layer of the demonstration cable was determined as 7 mm.

V. Performance Verification Tests

A. 30-meter cable system tests

In order to evaluate and verify the characteristics of the cable system in its final form, the cable and each piece of equipment were combined and a 30 m-long cable system was developed. Fig. 9 gives an overview of the cable system. The cable has a ninety-degree bend of 5 m in radius, terminations at both ends, and a cable-to-cable joint. By using this system, various electric tests, mechanical tests, thermal tests and tolerance confirmation tests were conducted [6]. Temperature and pressure characteristics during and after fault current flows were also measured. The test results are being analyzed in detail and being compared with simulation results [7].

As an example, Fig. 10 shows the test results of a 30-day long-term operation. During the test period, a ground voltage of 51 kV was continuously applied as an accelerated test condition to simulate thirty years of operation, while at the same time a current application cycle test was conducted. Namely, a rated current of 2 kA was applied for 8 hours and then turned off for 16 hours. During the test, no significant change was observed in the temperature of the cable or other sections, and the 30-day long-term operation was completed successfully.

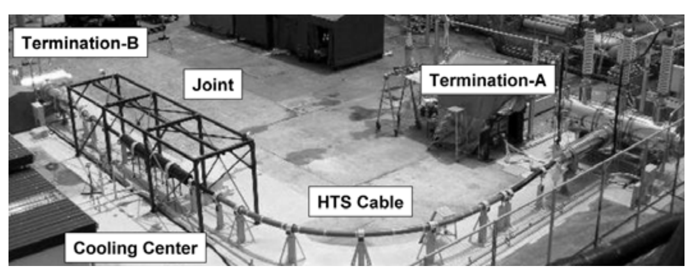

Fig. 9. Overview of the 30 meter HTS cable system.

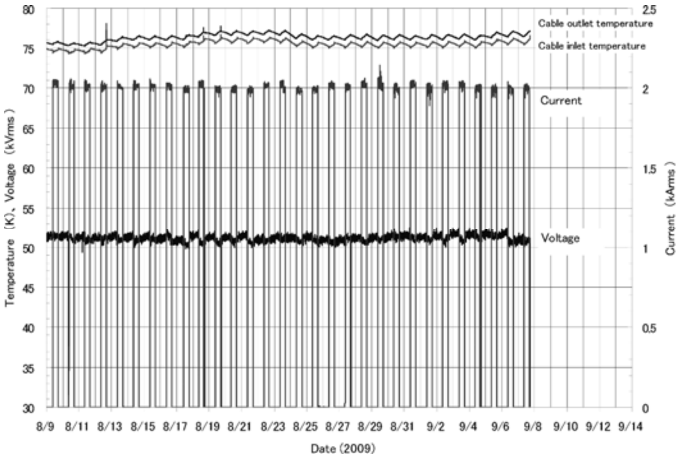

Fig. 10. Status of long- term operation test. 30 day long-term operation tests were completed successfully, with no significant changes in the temperature of the cable or other sections.

B. Cooling system tests

In this project, the direct cooling method has been selected as the refrigeration system. In this system, liquid nitrogen flows out from one cable termination, through the circulating pumps and refrigerators, and then back to the other cable termination directly. The number of pumps and refrigerators is determined by system conditions and redundancy factors. Fig. 11 shows the flow diagram of the cooling system for the Asahi substation. A Stirling type cryocooler, having the capability of 1 kW @77 K or 0.8 kW @67 K, is applied. The number of cryocoolers was determined to be 6. Four are used in normal operation and two are retained in a stand-by state. Two liquid nitrogen pumps are placed in parallel and driven alternatively for a set period of time.

Prior to the long-tem test at the Asahi substation, the minimal cooling system, which consists of two refrigerators and a pump, was tested by connecting it to the 30 meter HTS cable system [8]. After this element test, as shown in Fig. 12, the cooling system consisting of three refrigerators and two pumps was constructed at a factory of Mayekawa. The configuration of this cooling system is same as that for Asahi substation. Dummy load made of a heater inserted in a short length insulation-pipe is used instead of connecting an actual HTS cable to the cooling system. Using this cooling system, various performance tests are being carried out.

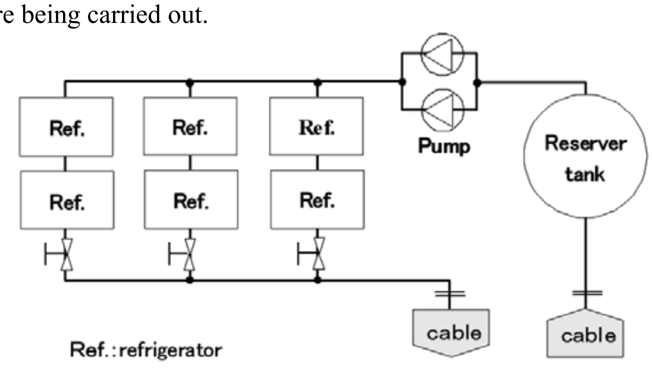

Fig. 11. Flow diagram of the cooling system for the Asahi substation.


Fig. 12. Overview of the cooling system constructed at Mayekawa's factory. This cooling system has the same configuration as that for Asahi substation, though the number of refrigerator is three instead of six.

VI. CONCLUSION

Prior to the connection to the actual grid in the Asahi substation, performance verification testing of the 30-meter HTS cable system was completed in April, 2010. Following that, performance verification testing of the liquid nitrogen cooling system is now underway. After completing the test, the cable system will be installed and constructed at the Asahi substation for the long-term demonstration test to be started in 2011.

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