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Results of Japan's first in-grid operation of 200 MVA superconducting cable system

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***Abstract*—A high-temperature superconducting (HTS) power cable demonstration project was started in 2007 to evaluate the cable's performance, stability and reliability. This project aims to operate a 66 kV, 200 MVA HTS cable system in a real power grid of the Tokyo Electric Power Company. A 240-meter-long HTS cable was successfully installed and other system components — such as a cable-to-cable joint, terminations and a cooling system — were also constructed at the Asahi Substation in Yokohama. After several completion tests and performance tests on the system, the HTS cable was connected to a real grid from October 29, 2012 to December 25, 2013. The in-grid operation had continued for more than one year without any accidental interruption of the operation or troubles of this system. The temperatures and pressures of liquid nitrogen flowing in the HTS cable were controlled to within the target values. After the in-grid operation, the critical current of the HTS cable was measured and it was confirmed that there was no degradation compared to the initial one. In addition, no partial discharge was observed in periodical measurements. It is concluded that the HTS cable system has good performance and stability for long-term, in-grid operation.**

***Index Terms*—High-temperature superconductors, power transmission cable, Superconducting devices, Cooling**

I. INTRODUCTION

High-temperature superconducting (HTS) cables can transmit large amounts of electricity while having a compact size and incurring minimal losses. They can thus reduce the construction cost of underground lines in urban areas and decrease transmission losses. Several HTS cables have recently been demonstrated in networks around the world [1]-[4]. In Japan, the development of compact HTS cables suitable for urban deployment has been underway since the early 1990s. In 2007, a national project was begun to verify their operational performance and long-term reliability in the grid [5]. After construction of a 66 kV - 200 MVA HTS cable system at the Asahi substation of Tokyo Electric Power Company (TEPCO), it was connected to the grid for the first time in Japan. Although, the intermediate condition of in-grid operation has been reported [6], this paper describes and discusses the results of long-term, in-grid operation.

II. OUTLINE OF THE PROJECT

This project was started in 2007 to evaluate the performance, stability and reliability of an HTS cable system. During the first two years, the fundamental technologies were developed for all elements of the HTS cable system, including the cable structure. The structure provides a large current capacity with reduced transmission losses, and offers the ability to withstands short-circuit currents. At the same time, the demonstration site was determined and the grid conditions carefully scrutinized. In 2009, a 30-meter cable system was manufactured to verify the design and several tests were completed successfully [7]. Then the cable for the Asahi Substation was manufactured and shipped to the site in 2011. Simultaneously, at the same time, a cooling system was developed and tested to check its operation, maintenance requirements and efficiency. Both the HTS cable and the cooling system were installed at the site in 2011, followed by performance tests on the HTS cable in combination with the cooling system in 2012. After these completion tests and performance tests on the system, in-grid operation began on October 29th 2012 [8]- [10].

III. HTS CABLE SYSTEM DESIGN

A. *Layout of HTS cable system*

Fig. 1 shows the circuit diagram of the HTS cable system at the Asahi Substation. The HTS cable was connected between a lower voltage side of a 154/66 kV transformer, whose capacity is 200 MVA, and a 66 kV bus line. The rate current and short-circuit current of this line are 1750 A_{rms} and 20 kA_{rms}, respectively. Fig. 2 shows a layout of the HTS cable system in this substation. The two installed HTS cables are connected to each other with a cable-to-cable joint and the total length of the HTS cable is about 240 meters. The cooling system including 6 refrigerators and, 2 pumps and the reservoir are located in a house near the HTS cable.

B. *Alarm and protection system for HTS cable*

Critical failures of the HTS cable system are listed in Table I. If one of these critical failures occurs, the critical alarm will be sent to a control center of TEPCO and the HTS cable will be quickly separated from the grid.

In Fig. 1, the protection system of the HTS cable is shown. If a short circuit or ground fault occurs in the transformer protection area including the HTS cable, this fault will be

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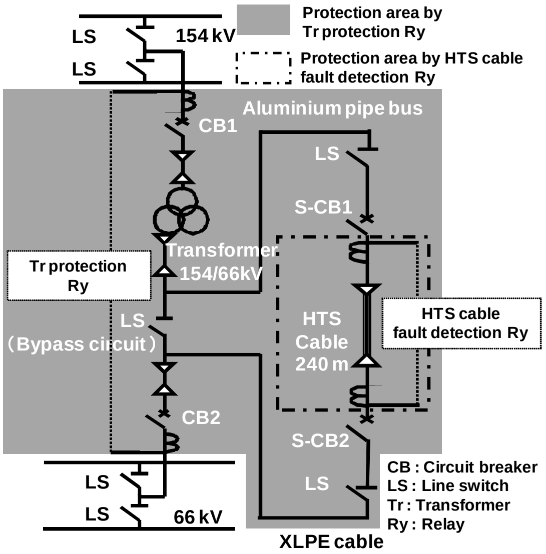


Fig. 1. Circuit diagram and protection system for HTS cable

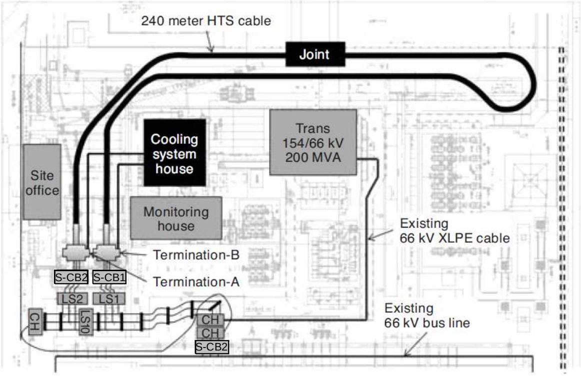


Fig. 2. Layout of HTS cable system in Asahi Substation.

TABLE I
LIST OF THE CRITICAL FAILURE IN HTS CABLE SYSTEM

Critical failure item	Conditions
LN_2 temperature rise	A total of 2 of the 13 pressure sensors indicate more than 83 K at the same time.
LN_2 pressure fall	A total of 2 of the 4 pressure sensors indicate less than 0.1 Mpa at the same time.
LN_2 volume fall in reservoir tank	The following accidents occurred at the same time. ·LN_2 volume sensors which are set in reservoir tank indicate less than 15%. ·Temperature sensor which is set in reservoir tank indicates more than 85 K
LN_2 circulation pump failure	The following accidents occurred at the same time. ·Trouble at circulation pump A or B. ·Volumetric flow is less than 30 liters/min
Power failures of cable system controller and monitor	Power failures of cable system controller and monitor continuing for more than 5 minutes
Monitor error	Communication and alarm failure
Errors of cooling system controller and monitor	Communication and control failure
Cooling system emergency stop	Pushing the emergency button
HTS cable fault detection relay	Short or ground fault is occurred in HTS cable

detected by the transformer protection relay and the protection area will be separated automatically from the grid by opening circuit breakers CB1 and CB2 which are connected to the higher voltage side of the transformer and the 66 kV bus bar respectively. Furthermore, if this fault occurs in the HTS cable, it will be detected by the HTS cable-fault-detection relay and only HTS cable can be separated from the grid by the circuit breakers S-CB1 and S-CB2 which are connected to both ends of the HTS cable. After separating the fault point, the power will be transmitted by connecting the bypass circuit.

In the case of the cooling system alarm, since the HTS cable can be continue operating for about an hour after an alarm has sounded, the HTS cable can be separated from the grid after the bypass circuit is closed. Accordingly, in this case, the HTS cable can be separated without any power transmission break by using the bypass circuit.

C. *Design of cooling system*

To operate the HTS cable in a superconducting state, the HTS tapes must be stably kept below 77 K with LN_2. In this project, LN_2 was selected for the coolant. The LN_2 is cooled by refrigerators and circulated by pumps to the HTS cable as shown in Fig. 3 [11]. After the cooled LN_2 flows into one HTS cable termination, it passes through the HTS cable, the joint and another termination. Finally, it returns back to the cooling system and is re-cooled and circulated again. In this circulation, LN_2 is sub-cool status by these refrigerators so as to avoid vaporization and maintain dielectric properties. In this cooling system, six Stirling-type refrigerators of 1 kW at 77 K class are employed and one or two of them are standbys. The cable inlet temperature is regulated to within +/-1K of the target value by controlling the number of refrigerators in operation. Furthermore, the flow rate is maintained by the circulation pumps. The layouts of these refrigerators and pumps were designed in a way that make it possible for them to be replaced without shutting down the whole cooling system during maintenance or repair.

IV. HTS CABLE SPECIFICATIONS

A. *HTS cable structure*

A photograph of the HTS cable is shown in Fig. 4 and the specifications of this cable are listed in Table II. The three

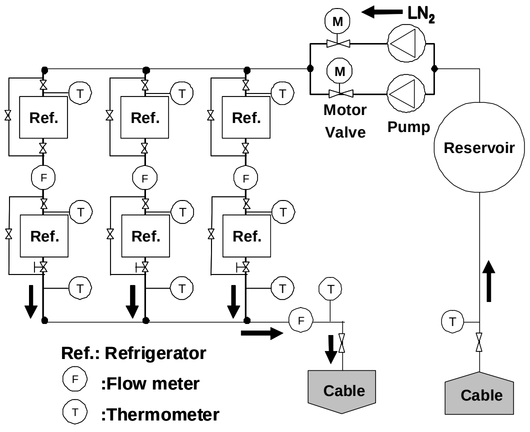


Fig. 3. Diagram of the liquid nitrogen cooling system..

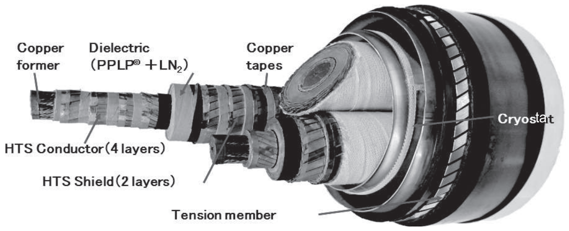


Fig. 4. Photograph of HTS cable.

TABLE II
SPECIFICATIONS OF HTS CABLE

Item	Contents
Cable geometry	3 cores in one pipe
HTS conductor layer	4 layers, I_c = about 6400 A at 77 K
HTS shield layer	2 layers
HTS tape	Bi-2223
Dielectric material	Laminated paper
Capacitance C	0.267 nF/m·ph
Relative permittivity ε_r	2.29
tan δ	0.08 %

cable cores are housed in one cryostat pipe in order to reduce the size of the structure. The cable core consists of a former made from stranded copper wires, an HTS conductor, an electrical insulation layer, an HTS shielding part, and a copper shielding part, all of which are coaxially wound around the former. A thermal insulation layer is provided with a high vacuum between stainless double-corrugated cryostat pipes.

B. HTS cable's performance

The measured critical current (I_c) of the HTS cable installed in the Asahi Substation is about 6400 A at 77 K. The I_c was designed to have a value large enough to handle the maximum current of an overloading transformer which is about 2600 A_{rms}.

The capacitance (C) of the HTS cable installed in the Asahi Substation was measured by the Schering Bridge method and its value was 0.262 nF/m/ph. This measured value and designed value, which is calculated by the relative permittivity (ε_r) of the laminated paper measured in a 30-meter-long HTS cable test [2], are in good agreement each other.

The tan δ measured by the Schering Bridge method was 0.08 %. Since the designed value of the laminated paper is less than 1 %, it was confirmed that the characteristics of the dielectric material satisfied with the required specifications.

V. EVALUATION OF IN-GRID HTS CABLE OPERATION

A. Records of in-grid operation of HTS cable system

Table III shows the records of the grid conditions during the HTS cable's in-grid operation. The in-grid operation was continued for about 400 days with unattended operation in the Asahi Substation. During this operation time, none of the critical failures listed in Table I happened. The maximum current transmitted to the HTS cable was 1127 A_{rms} and its value was much less than the I_c of the HTS cable which is more than 6000 A.

Verifying the long-term stability of the cooling system is one of the themes of this in-grid operation. Fig. 5 shows the transitions of voltage, current, LN$_2$ temperature at the cable inlet, LN$_2$ flow rate, and pressure in the reservoir tank. The results of characteristics of the cooling system are listed in Table IV. In the first two months, the LN$_2$ temperature was controlled to within the pre-set temperature range of 69 K +/- 1K even though the current fluctuated from about 300 A_{rms} to over 1 kA_{rms} in a day. To verify the stability at higher LN$_2$ temperatures, the inlet temperature was increased to 75.5 K. This raised the outlet temperature to near 80 K, a temperature that is close to the highest allowable operating temperature which is limited by the critical temperature of the cable and the boiling point of LN$_2$ (83 K). As shown in Fig. 5, the cable transmitted the load current stably under these temperatures. Furthermore, the pressure in the reservoir tank was controlled to between 0.2 MPa and 0.25 MPa, and the flow rate of LN$_2$ was maintained at 40 liters/min, for the entire in-grid operation time.

TABLE III
RECORDS OF GRID CONDITION IN HTS CABLE 'S OPERATION PERIOD

Item	Details
Operation period in grid	2012.10.29–2013.12.25 About 400 days: Excluding maintenance term
Maintenance period	2013.6.10–6.21、2013.7.22–7.31
Max current	1127 A_{rms} (2013.8.10)
Voltage in grid	63.9–67.1 kV
Unbalanced current rate	About 6.9 %
Shielding current rate	About 89 %
Network switching	More than 50 times
Overloading	Not detected
Impulse	Not detected
Fault current	Once (Caused by ground fault in external part of the HTS cable)

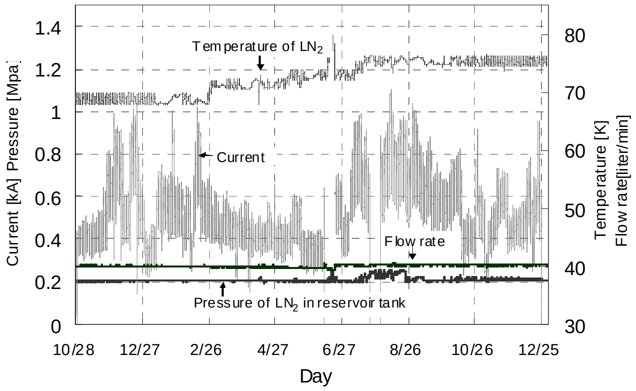


Fig. 5. Transitions of loading current and LN$_2$ characteristics.

TABLE IV
RESULT OF COOLING SYSTEM CHARACTERISTICS

Items	Details
LN$_2$ temperature at inlet of HTS cable system	Controlled to within +/- 1K of the target value Operated between 69 to 75.5 K in-grid operation of HTS cable
LN$_2$ pressure in reservoir tank	Controlled in between 0.2 and 0.25 MPa
Flow rate	Kept at 40 liters/min
Pressure drop	Required pump head; 145 kPa (HTS cable; 31 kPa, Cooling system; 114 kPa)
Velocity of LN$_2$	About 8 m/min
COP	0.04

B. Fluid characteristics of LN_2

While the HTS cable was connected to the grid, the LN_2 had been flowing in the HTS cable system at a flow rate of 40 liters/min and the velocity of LN_2 was 8 m/min, so that about 30 minutes was required for the LN_2 to flow from the cable inlet to the outlet.

The measured pressure drops of LN_2 of the HTS cable including terminations and cooling system are shown in Fig. 6. The values of the HTS cable and the cooling system were 31 kPa and 114 kPa at 40 liters/min, respectively as shown in Fig. 6, so that the required pump head was 145 kPa, in the case of this flow rate.

C. Effect of sudden change in the current on cooling system

The effect of a suddenly fluctuating in the current by the network switching on the cooling system was evaluated. Fig. 7 shows the operation records of the time of re-connecting the HTS cable to the grid after the cable had undergone maintenance. Although a current of about 800 A and 66 kV suddenly flowed in the HTS cable, the temperatures and pressures of LN_2 at each part of the HTS cable hardly fluctuated. Moreover, although the HTS cable experienced this suddenly fluctuating current 50 times or more as shown in Table III, it was confirmed that stable operation of the HTS cable system had continued in all cases.

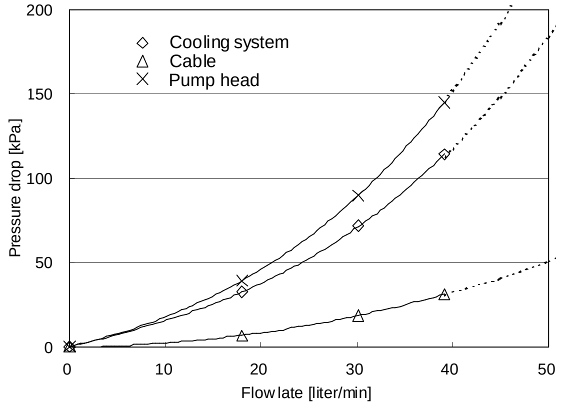


Fig. 6. Pressure drop of LN_2 flowing in HTS cable

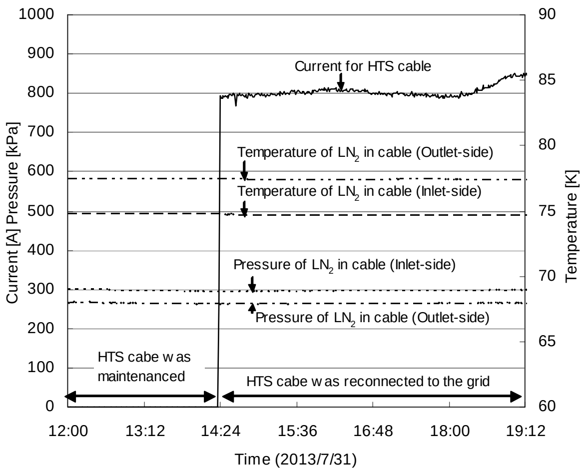


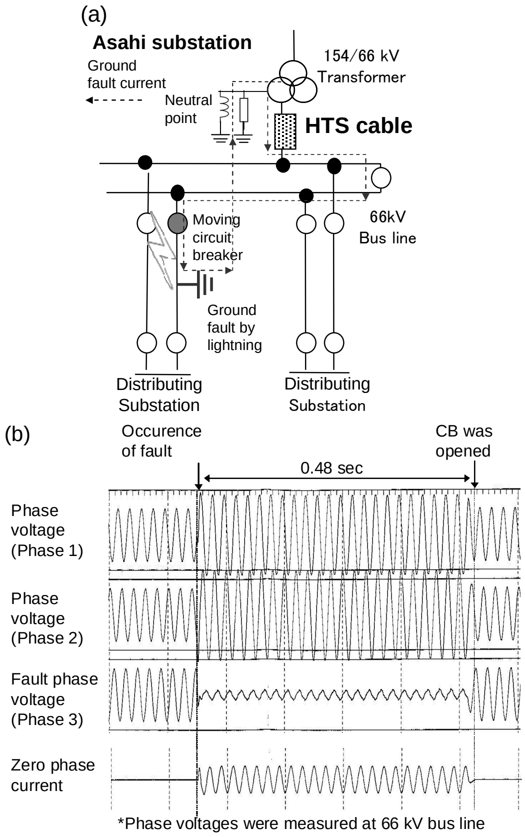
Fig. 7 Effect of sudden current fluctuating on LN_2 flowing in HTS cable.

D. Influence of ground fault in external transmission line

During the in-grid operation, lightning caused a ground fault to occur in an overhead transmission line connected to the 66 kV bus line in the Asahi Substation. An outline of this fault is listed in Table V. The ground fault current flowed into the HTS cable as shown in Fig.8 (a). Fig. 8 (b) shows the waveforms of each phase voltage observed at the 66 kV bus line and of the zero-phase current observed at the neutral point of the transformer in the substation. Until the ground fault point was separated from the grid by a circuit breaker, the sound phase voltages were rising from the rated 38.1 kV to

TABLE V
GROUND FAULT

Items	Details
Date and time	2013/8/12 19 : 36 : 38
Type of fault	One line ground fault by lightning
Fault place	66 kV overhead transmission line
Duration of fault	0.48 s (24 cycle of 50 Hz)
Working CB	CB for 66 kV transmission line in Asahi Substation (10 s later, CB was re-closed successfully)
Phase voltage (before fault→ during fault)	Phase 1: 38.1 kV → 54.5 kV Phase 2: 38.1 kV → 64.6 kV Phase 3: 38.1 kV → 7.2 kV (Fault phase)
Line voltage	No change (66 kV)
Ground fault current	415 A
Loading current	About 1000 A (Each phase)



*Phase voltages were measured at 66 kV bus line
Zero phase current was measured at neutral point

Fig. 8. (a) Schematic of ground fault, (b) Waveforms measured by oscilloscope during the ground fault.

55-65 kV and a ground fault current of about 400 A was flowing into the HTS cable. After this fault, no partial discharge (PD) was observed in the HTS cable system and the in-grid operation of the HTS cable continued stably. The measured values of capacitance, tanδ and I_c of the HTS cable after the in-grid operation were not changed from the initial ones measured before the in-grid operation, respectively. Accordingly, it was confirmed that the characteristics of the electric insulation and of the superconductivity of the HTS cable were not impaired by this ground fault.

E. Heat loss of HTS cable

The total heat loss of the HTS cable (W_{all}) can be divided into the heat intrusion from the outer wall of a cryostat pipe (W_o), the dielectric loss (W_d), and the AC loss (W_a), as follows:

$$W_{all} = W_o + W_d + W_a \qquad (1)$$

W_{all} can be determined by the LN_2 temperature difference between the inlet and outlet, specific heat of LN_2 and mass flow rate of LN_2, as follows:

$$W_{all} = (T_{out} - T_{in})\, C_p\, M \qquad (2)$$

T_{out} and T_{in} are LN_2 temperatures at the inlet and outlet of the HTS cable respectively. C_p is the specific heat of LN_2 and M is the LN_2 mass flow rate. In this calculation, after T_{out} was measured, T_{in} which was measured 30 minutes later was used, because that time is required for the LN_2 to flow from a cable inlet to an outlet.

W_o was measured while the HTS cable was separated from the grid for maintenance, because the AC loss and the dielectric loss are not generated under zero current and zero voltage. Furthermore, the measured values during the night when there is no solar radiation were adopted. The results showed the measured W_o at the straight part of the HTS cable was about 3 W/m.

W_d was calculated using measured tanδ and capacitance C of this HTS cable, as listed in Table II. The calculated W_d was 0.3 W/m - 3phase at 66 kV and 50 Hz.

W_a was calculated by (1), using W_{all}, W_o and W_d which were obtained as described above. These results were plotted as shown in Fig. 9. The obtained W_a and the designed value which is the measured AC loss of a 2-meter-long cable were in good agreement with each other. Although the AC loss of the HTS cable is influenced by disorder in the spiral pitch of HTS tape caused by cooling and degradation of the tape characteristics, the measured AC loss of a cable that was more than 200 meters long was in good agreement with the designed value. It was confirmed that there was no problem with design and manufacturing quality of the HTS cable.

It is clarified that the W_o, which is about 3 W/m, is much lager than the value of W_a and W_d. It indicates that most of the heat loss generated at the HTS cable is heat that intrudes from the outer wall of the cryostat pipe. Since the W_o is generated at any time regardless of whether or no there is current loading, reducing this heat intrusion would be an effective way to improve the power transmission efficiency of the HTS cable system.

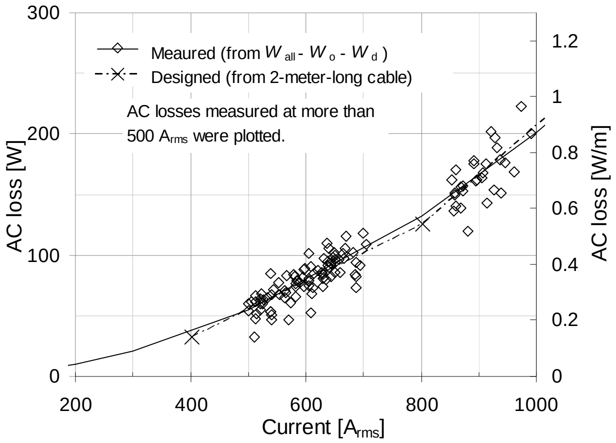


Fig. 9. AC loss characteristics of HTS cable.

F. Coefficient of performance of cooling system

The coefficient of performance (COP) of cooling system was evaluated as follows

$$\text{COP} = W_H / W_E \qquad (3)$$

Where W_H is the total heat loss of the HTS cable system and W_E is the total electric power consumption of the cooling system. The W_H and W_E are divided into the losses generated at each part as listed in Table VI. The W_H and W_E are 2.53 kW and 60.32 kW respectively. The COP calculated by (3) was about 0.04. This value was half that required for the HTS cable system to gain a cost advantage over the conventional cable. To improve the COP of the cooling system, the Brayton-cycle refrigerator system for HTS cables whose COP is 0.1 has been developed by Mayekawa Mfg. [12].

G. Electrical insulation characteristic

The PD was measured five times periodically, until the in-grid operation was over. Although the sensitivity was 50 pC in this measurement, a PD signal more than the sensitivity was not observed within the HTS cable in any measurements. Accordingly, it was confirmed that the electrical insulation performance of the HTS cable was not decreased.

The measured tanδ after in-grid operation showed no degradation compared with the initial one listed in Table II, and so the good characteristics of the electrical insulating material over operations of more than for one year were

TABLE VI
HEAT LOSS OF HTS CABLE SYSTEM AND
ELECTRIC POWER CONSUMPTION OF COOLING SYSTEM

Items		Loss (kW)
Total heat loss of the HTS cable system W_H		2.53
Breakdown of W_H (0.4 kA_{rms} 66 kV)	(HTS cable)	(1.2)
	(HTS terminations)	(1.3)
	(HTS joint)	(0.02)
Total electric power consumption W_E		60.32
Breakdown of W_E	(Refrigerators)	(55.38)
	(LN_2 pumps)	(0.28)
	(Water cooling)	(4.66)

confirmed.

The capacitance *C* of the HTS cable was also measured and it was confirmed that there was no degradation compared with the initial one listed in Table II, although a contractile tension of about 3000 kgf was applied to the HTS cable due to the cooling of LN_2. It was confirmed that there was no negative influence of the cooling on the electrical insulation layer.

H. *Critical current characteristic*

I_c was measured five times in the main part of this project in order to confirm the HTS cable's superconductivity. These results are shown in Fig. 10. The first measurement was carried out when the HTS cable was cooled first after it had been installed in the Asahi Substation. The second measurement was conducted after the HTS cable had experienced one thermal cycling between room temperature and 77 K. The third measurement was taken after HTS cable experienced the second thermal cycling. The fourth measurement was conducted 9 months after from the in-grid operation had started. And the last measurement was taken after the in-grid operation had continued for 14 months. Although the design value of I_c was about 6400 A, the measured values at any time were in good agreement with the designed value. Accordingly, it was confirmed that there was no degradation in the characteristic of superconductivity at all time such as the shipping, the installation, the thermal cycling and the long-term operation, after the HTS cable was manufactured at the factory.

VI. CONCLUSION

An HTS cable system was designed and constructed at the Asahi Substation in Yokohama to evaluate the cable's performance and stability. In-grid operation of the HTS cable started and was continued for more than one year without any accidental interruption or troubles of the operation.

In this operation, although the loading current had fluctuated from 300 A_{rms} to over 1 kA_{rms} on various dates and various times, the temperature and pressure of LN_2 were controlled to within the target values by the cooling system.

Although the HTS cable experienced the influence of a ground fault in an external overhead transmission line due to the lightning, no degradation of the characteristics of the superconductivity and electrical insulation, such as the I_c and PD, was seen in a residual performance test after in-grid operation.

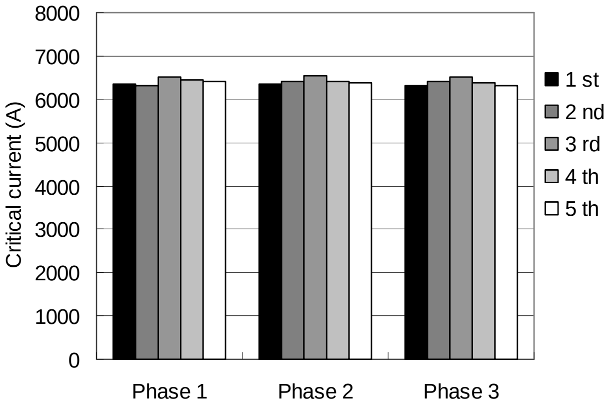


Fig. 10. Measured critical current characteristics of HTS cable.

Accordingly, it was concluded that the HTS cable system has good performance and stability for more than one year in-grid operation.

However, it was clarified that most of the heat loss generated at the HTS cable is heat that intrudes from the outer wall of the cryostat-pipe. Furthermore, the COP of the cooling system was not enough to give the HTS cable system a cost advantage over the conventional cable. Accordingly, as the next step, this heat intrusion need to be reduced and the cooling system improved in order to move toward commercializing the HTS cable system.

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