Development of the Prospective Power Transmission Model System Integrated under Superconducting Environment–PROMISE

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***Abstract*—A "prospective power transmission model system integrated under superconducting environment", abbreviated to the PROMISE, has been constructed to verify a technical possibility of superconducting power transmission for next generation. The PROMISE is composed of a superconducting transformer, a superconducting fault current limiter and superconducting power cable of length 5m. Three superconducting apparatuses are enclosed all together in a long scale cryostat to be kept at the liquid helium temperature of 4.2K. The major insulation is provided by liquid helium. The PROMISE withstands AC voltage of 6kV for 2 minutes with quite low partial discharge. A voltage-current synthetic test has proved that the PROMISE has the transmission capability of 6,000V–1,000kVA. The fault current limiter actually limits overcurrent and prevents the other apparatuses from quenching. Quench current level coordination is actually realized in the PROMISE.**

I. Introduction

The superconducting power transmission is one of promising candidates in the future power system because it has an ability to carry extraordinary larger current than the conventional high voltage overhead or underground transmission lines. Many researches and developments to introduce superconducting technology into electric power field have been carried out [1]–[5]. However, most of them are concerned with individual superconducting electric apparatuses, such as a superconducting transformer, a superconducting fault current limiter, superconducting power cable and so on. Few experimental researches have been reported in superconducting power transmission system composed of several superconducting apparatuses.

The authors have developed "a prospective power transmission model system integrated under superconducting environment–PROMISE". This model system is composed of a superconducting transformer (SC–Tr), a superconducting fault current limiter (SC–FCL) and model superconducting power cable (SC–power cable) of length 5m. Its objective capacity was intended to be 1,500kVA at 3,000/6,000Vrms with the commercial frequency of 60Hz. Three apparatuses are enclosed all together in a long scale cryostat to be kept at the liquid helium (LHe) temperature of 4.2K. The major insulation is provided by the LHe.

Several fundamental experiments have been carried out on the PROMISE and the following performances have been confirmed. The PROMISE has the capability to withstand AC voltage of 6,000Vrms. It is able to carry AC current of 170Arms in stable superconducting state without any problem. The superconducting fault current limiter can protect other superconducting apparatuses against overcurrent.

II. Outline of PROMISE

Fig.1 shows a profile of the PROMISE, where the composite units of the SC–Tr and SC–FCL are hoisted up from the left-hand part of the cryostat. The SC–Tr is of core type. Since the core is immersed in LHe together with the windings, it is made of accumulated strip of a high-level grain oriented silicon steel to reduce core loss as possible. According to our measurement, the core loss of this type of grain oriented silicon steel is less by 15% than that of the conventional silicon steel in the LHe temperature. The SC–FCL is composed of 8 units of superconducting coils to realize a resistor with less inductance. The SC–FCL transits to the normal conducting state at once if an overcurrent passes through it. The produced

Manuscript received October 20, 1994.

This work was supported by a Grant–in–Aid for Scientific Research, Experiment Research (B) (2) (No.03555051) from the Ministry of Education, Science and Culture, Japan.

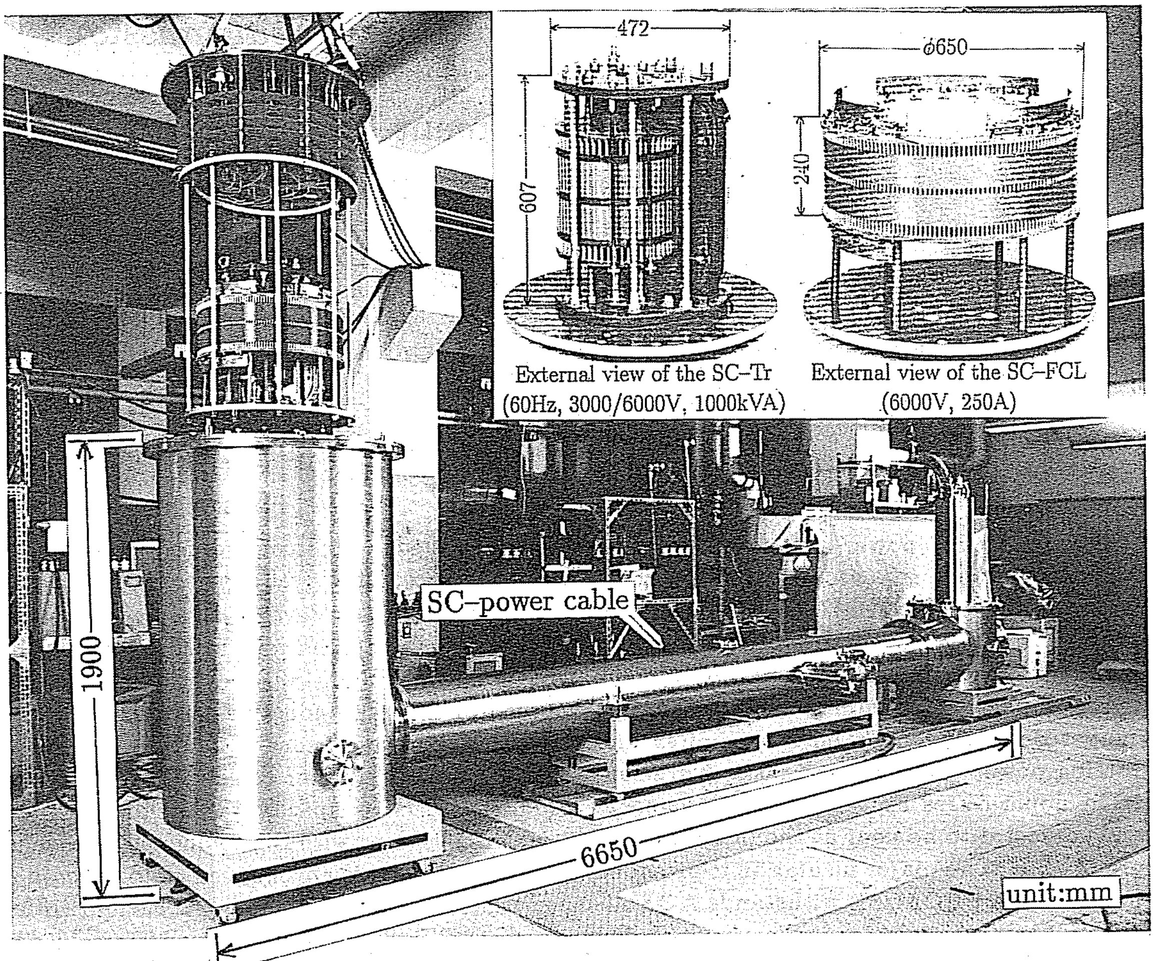

Fig. 1. The profile of the prospective power transmission model system integrated under superconducting environment–PROMISE. Photographs of the SC–Tr and SC–FCL are inset in the upper column. The SC–power cable is enclosed in the horizontal cylindrical section.

TABLE I
TECHNICAL DATA OF THE SC-STRAND

Parameter	Value
NbTi filament number	23,749
NbTi filament diameter	0.744 μm
Diameter	0.193 mm
Matrix ratio	CuNi/NbTi=1.8
Twist pitch	1.83 mm

normal conducting resistance suppresses the overcurrent. The SC–power cable is of 5m in length.

Table I summarizes the technical data of the superconducting strand which is used in the three apparatuses. NbTi ultra-fine multi-filaments with diameter of 0.744μm are embedded in a CuNi matrix. In order to obtain a large normal resistance after the superconducting strand transits to a normal conducting state, the stabilizing copper layer is not utilized.

Fig.2 shows the cross-sectional view of the superconducting cables used in every apparatuses of the PROMISE. In Fig.2, shaded circles represent single superconducting strands (SC-strand) and black circles subcables (SC–subcable). Different number of SC-strands are used for each windings in the three apparatuses. The number of SC-strands in the SC–FCL is a fewer than that in the SC–Tr and the SC–power cable to keep a quench current level coordination[6] in the PROMISE, i.e. the quench current level of the SC–FCL was intended to take the lowest among three apparatuses. Both the inner and outer conductors of the SC–power cable consist of three parallel SC–subcables.

III. Fundamental performances of the PROMISE

A. Cooling down of the PROMISE

Prior to cooling down the PROMISE with LHe, the adiabatic vacuum layer is evacuated to about 2.6×10^{-5} torr. This takes about 1 weeks for repetitive evacuation, 12 hours a day. Then, liquid nitrogen (LN_2) is poured into the LHe vessel for preliminary cooling and into the LN_2 vessel for heat shield. After exhaust of LN_2, LHe is injected into the LHe vessel. It takes about 5 hours to cool down the whole system to LHe temperature of 4.2K

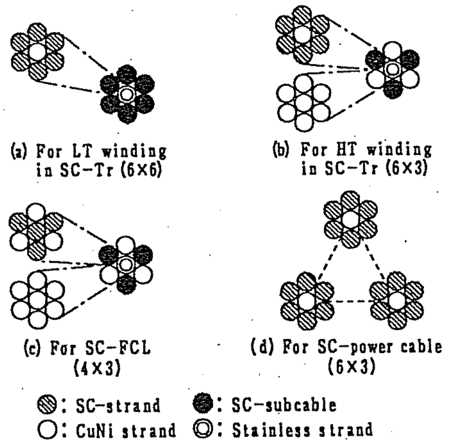

Fig. 2. Cross-sectional view of the superconducting cables

from the beginning of LHe injection.

B. Voltage applying tests

1) Partial discharge test: The SC–power cable are connected to the HV–side of the SC–Tr through the SC–FCL. The far end terminal of the SC–power cable is short-circuited by connecting the inner conductor with the outer one. The voltage to ground is applied from the far end terminal with a test transformer of 150kV. The partial discharge is initially detected at about 4,000Vrms. A maximum voltage of 6,000Vrms is successfully applied for 2 minutes without insulation flashover. At this voltage, partial discharge pulses about 300pC are detected around the voltage crest and a few pulses of about 1,000pC are intermittently detected in both the positive and negative voltage. There is occasionally a large pulse up to 5,000pC. These large partial discharge pulses are likely to take place at the junction connecting the transformer terminals and the conductors of the SC–power cable. No partial discharge is detected in the partial combined set of the SC–Tr and the SC–FCL without the SC–power cable.

2) No-load test: The SC–power cable and SC–FCL are connected in series to the HV–side of the SC–Tr in the same manner as the above test except that the far end terminal of the SC–power cable is opened. The objective voltage of 6,000Vrms is induced in the HV winding when 3,000Vrms is applied at the LV–side for 2 minutes. During this period, no accident in insulation is observed, partial discharge is detected to be weaker than that in partial discharge test.

The core loss of the SC–Tr is measured to be 178W when voltage of 3,000/6,000Vrms is applied.

C. Current carrying tests

1) Current carrying ability: Current carrying tests of the SC–Tr, SC–FCL and SC–power cable are carried out separately. The SC–Tr keeps its superconducting state in short-circuit tests until the magnitude of the carrying current is gradually increased up to be 340/170Arms. It transits to the normal conducting state at 354/177Arms. It is not distinguished whether the transition occurred in the LV–winding or in the HV–winding. It is noticed that the quench current level is quite lower than that expected. The SC–FCL transits to the normal conducting state at 250Arms. This current value is the current limiting level of the SC–FCL. It is lower than that of the LV winding of the SC–Tr but larger than that of the HV winding. The SC–power cable is confirmed to be capable of carrying the current of 670Arms without quenching.

2) AC losses: The total of AC losses in the SC–Tr is evaluated to be about 50W when the current in the HV–side is kept at 150Arms, 60Hz. This is done by comparing the evaporating rates of the LHe in the current carrying test with that of no current state.

D. Voltage-current synthetic test

We have carried out a voltage-current synthetic test to verify the transmission ability of the PROMISE. A large circulating current and a high voltage to ground are applied at the same time from two separate power sources of 60Hz. The connection of the SC–Tr, SC–FCL and SC–power cable are the same as that in the partial discharge test. The AC high voltage is applied from the far end terminal with a test transformer of 150kV and the large circulating current is supplied from the LV–side of the SC–Tr.

At this synthetic test, the PROMISE withstands a high voltage of 7,100Vrms and carries a large circulating current of 170Arms in the high voltage circuit simultaneously for about 2 minutes without flashover and quenching. It is equivalently proved that the PROMISE has a transmission capability of 6,000V–1,000kVA.

IV. Quench Current Level Coordination

It is experimentally verified in the next stage that the SC–FCL actually operates as a quench protector for the SC–Tr and SC–power cable. In the PROMISE, as described above, the quench current level of the SC–Tr is 354/177Arms, the SC–FCL 250Arms, and the SC–power cable 670Arms. Thus, the SC–FCL can not protect the HV–side of the SC–Tr winding. If the SC–FCL is connected to the LV–side of the SC–Tr, it is expected to operate as a protective device. The quench protection coefficient κ is $354/250 = 1.4$, where, κ is defined as the ratio of quench current level of the protected apparatus to the current limiting level of the protecting apparatus [6]. Thus, Fig.3 shows the circuit diagram for this experiment. The SC–FCL and the SC–power cable are connected in series to the LV–side of the SC–Tr. Current with a magnitude larger than the quench current levels of the SC–Tr and SC–FCL is supplied from the HV–side of the SC–Tr. In order to supply a large current to the PROMISE from a

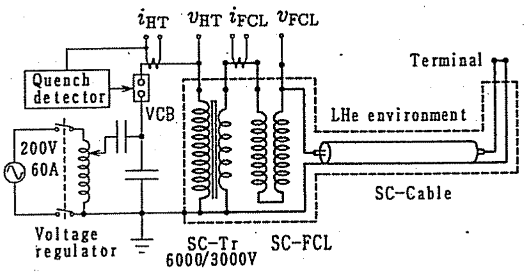

Fig. 3. Circuit diagram for the quench protection experiment.

domestic low voltage source, parallel and series condensers are used to cancel the leakage reactance of the SC–Tr as shown in the left–hand side of Fig.3.

Fig.4(a) and (b) show the current and voltage waveforms obtained in this experiment. The current is gradually increased by regulating output voltage of the voltage regulator. Before time t_q, the phase difference between v_{FCL} and i_{FCL} as well as that between v_{HT} and i_{HT} are both 90°. Three apparatuses are kept in the superconducting state. At time t_q, the current i_{FCL} reaches the quench current level of the SC–FCL. It transits from the superconducting state to the normal conducting one and suppresses the current at once. Currents i_{FCL} and i_{HT} begin to decrease. Then, the v_{FCL} quickly shifts in-phase to i_{FCL} as shown in Fig.4(a). However, in Fig.4(b), since the current is suppressed by the SC–FCL to be lower than the quench current level of the SC–Tr, both windings are still in the superconducting state. It is prevented from falling into quench by the protective performance of the SC–FCL. Similarly, the SC–power cable is also kept in the superconducting state.

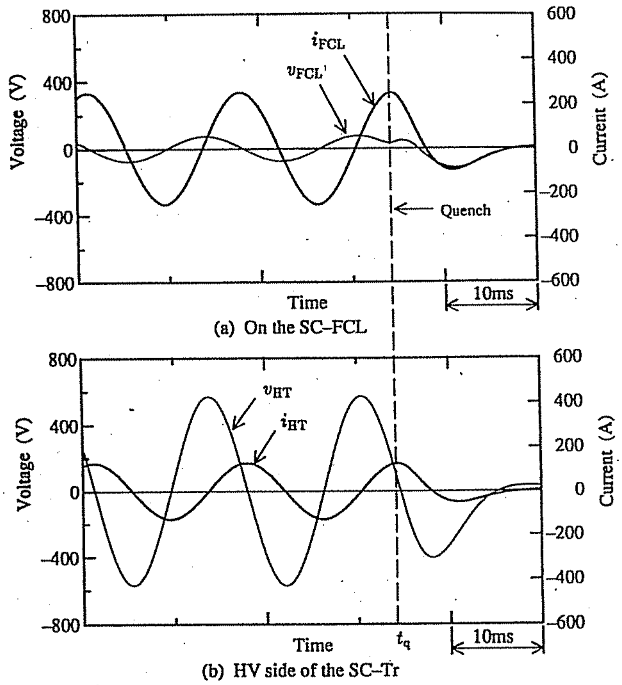

Fig. 4. Waveforms of voltage and current in quench protection experiment. v_{FCL}: voltage on the SC–FCL; i_{FCL}: current in the SC–FCL and the LV–side of the SC–Tr as well as the SC–power cable; v_{HT}: voltage on the HV-side of the SC–Tr; i_{HT}: current in the HV-side of the SC–Tr.

V. Conclusions

A prospective power transmission model system integrated under superconducting environment (PROMISE) has been developed. The PROMISE is composed of a SC–Tr (3,000/6,000Vrms, 1,000kVA), a SC–FCL (6,000Vrms, 250Arms) and a SC–power cable (6,000Vrms, 670Arms, 5m in length). A series of experiments have been carried out on the PROMISE. The following fundamental performances of the PROMISE are verified.

- The PROMISE has the capability to withstand AC voltage of 6,000Vrms with LHe insulation.
- The PROMISE is able to carry AC current of 170Arms without quenching.
- The voltage-current synthetic test has equivalently verified that the PROMISE has the transmission capability of 6,000V–1,000kVA.
- The SC–FCL actually operates against overcurrent as a quench protector for both the SC–Tr and SC–power cable in series.

Acknowledgment

The authors would like to acknowledge Mr. Y. Oue and Mr. T. Yamamoto for their cooperation in carrying out the experiments on the PROMISE during their graduate course in Nagoya University.

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