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Development of a 1kWh/1MW Module-type SMES

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Abstract *—Superconducting magnetic energy storage (SMES) systems utilize superconducting coils to store electricity as magnetic energy. This method of storing electricity is highly efficient, and the system can be charged or discharged very quickly. SMES systems can therefore be used to respond to a variety of needs, including load leveling and the control of power systems. We have been developed a 1kWh/1MW module-type SMES system (ESK: Experimental SMES of Kyushu Electric Power Co., Inc.) as a full system to be tested in power line. ESK was installed early in 1998, and is now being in test at Imajuku substation in Fukuoka. ESK is originally planned as a first step in scaling up SMES technology to that of practical one. Performance tests for compensation for load fluctuation, stabilizing of power system etc. were already made. Details of those results will be shown.*

1. INTRODUCTION

SMES was originally planned to be used for diurnal load leveling which needs very large storage energy encountered big wall for financing. However there are increased needs for stabilizations of power system, compensations for load fluctuation, and voltage control in power line systems, which can be treated by SMES's with much smaller storage capacity than those of the former (See Fig.1). We are advancing the development tentatively aiming at the power stabilization SMES of 1～10MWh/100MW. ESK is meant to be the first step towards practical applications of SMES to power system control. At least a full SMES system of 1kWh/1MW is considered to be necessary for the one that would allow required tests in the power system. We have completed a full SMES system named ESK to be tested in a power line early this year. Manufacturing and testing of the elementary equipments of ESK have already been reported. ESK already passed the governmental examination conducted by the Ministry of International Trade and Industry (MITI) at the site of Imajuku substation in Fukuoka City, which is connected to 6kV commercial power line. Fundamental tests of SMES system have been made. Some preliminary performance tests of compensation for load fluctuation in a power line have also been taken place.

2. COMPOSITION OF ESK

A. Design concept and System configuration

The design concept of ESK was shown in Fig.2. For scaling up the SMES, we must solve technical problems for each step. In order to extend the capacity up to a practical scale, high voltage and large current of SMES are required. However, it is hard to realize for larger scale SMES. The idea of "modular-type SMES"[1],[2] ,which is composed of some smaller units with smaller voltage and current, is not only an advantageous method to solve this problem but also useful for flexible operations such as independent operations of each module and energy transfer between the two. For the module-type SMES system having many leads, reducing heat load by leads is very important. "High-Tc superconductor (HTS) leads" are very attractive for this purpose. Since SMES system for power system control have to be operated in a pulse mode, pulse loss of the conductor should be as small as

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possible. From this point of view, three types of NbTi conductors of Rutherford cable type are developed.

For the SMES coils we developed a "modified D-shaped coil" which is stable against magnetic forces. This coil is supported at its middle section by support structures of stainless steel. The resulting mechanical disturbance should be smaller than that of circular coil or that of existing D type one. This is due to the smaller tension in conductors caused by the support structures, and also by the shape with no bending moment. [3],[4]

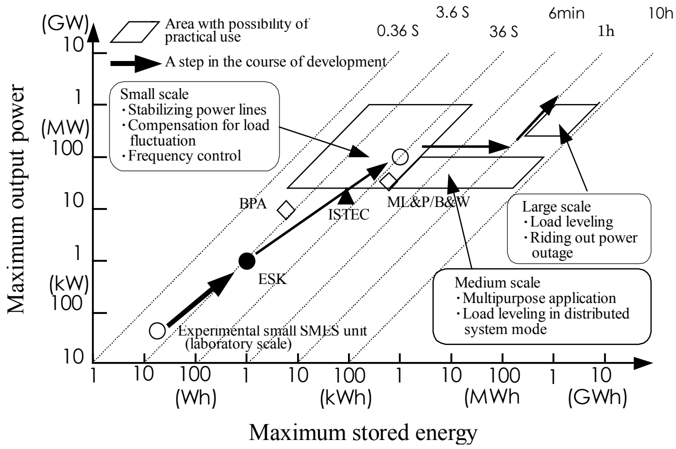


Fig.1. Applications of SMES and their corresponding positions in a power-energy map

For coil cooling, we developed a new cooling system. It has a "individual liquid helium (LHe) vessel" for each coil, all of which are contained in the same cryostat. Points of this design are to reduce LHe quantity, which is also effective for preventing local heating of the coil by fast exhaustion of LHe, and to have a large gas helium (GHe) space which is effective for a stable operation of recondensatior by keeping the pressure in the space constant. For environmental problem, higher harmonics current in the line generated from AC/DC converters should be reduced. Reduction of leakage magnetic field by means of toroidal structure is to be achieved.

B. System Configuration and Elemental Equipments

The schematic circuit diagram and the design parameters of ESK are shown in Fig.3 and Table1. For ESK we adopted torus arrangement of 6 superconducting coils to reduce leakage field, and 2 modules composition to reduce voltage and current for the same stored energy, which each module has 3 coils and one converter. Each module is connected with 6kV power line separately. Major components of ESK comprises superconducting coils, AC/DC converters, a refrigerator, current leads and a monitor and control system.

1) Superconducting coils : We built 6 modified D-shaped coils of which were made by 3 manufacturers. Each coil is about 75 cm wide and 100cm high. [5]-[9] The toroidal arrangement of 6 coils with liquid helium vessel is shown in Fig.4 and Fig.5.

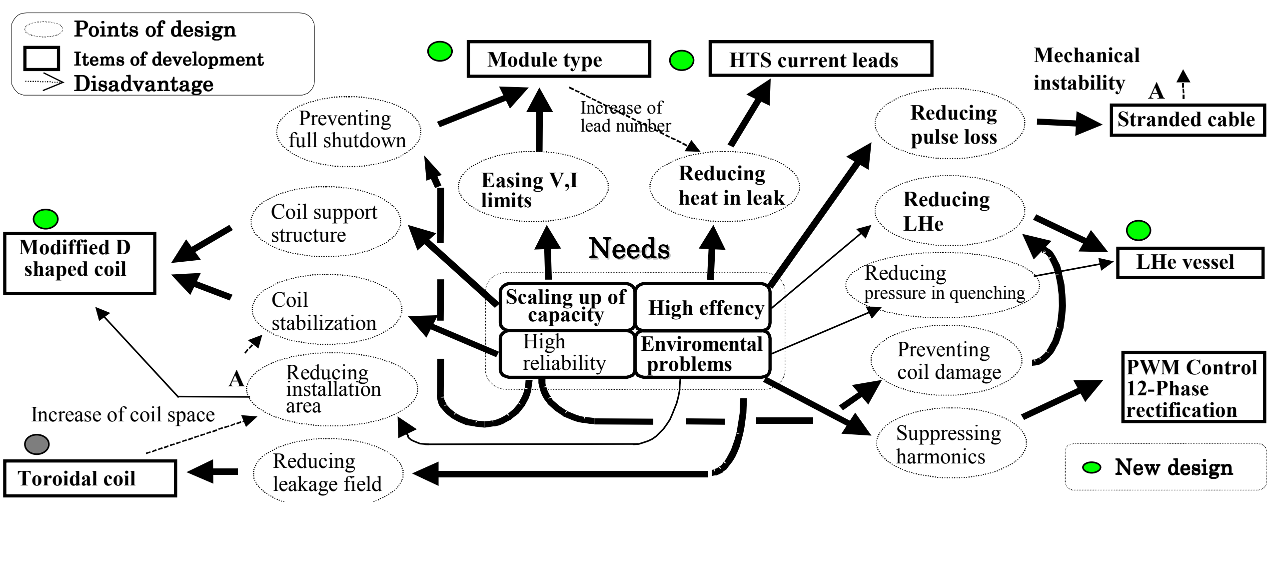


Fig.2 .Design concept of ESK.

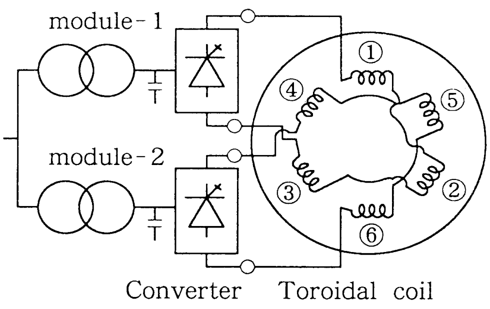


Fig.3. Electrical circuit of ESK.

Table Ⅰ2 SPECIFICATIONS OF ESK

Max. stored energy	1kWh (3.6MJ)
Rated output power	1 MW
Rated DC current	1000 A
Rated voltage	500 V
Number of modules	2 units
Superconducting coils	
-Conductor	NbTi
-Size	Width 75cm,Height 100cm
-Arrangement	Toroid
-Number of coils	6 (3 per module)
-Inductance	7.2H (6 coils)
-Cooling system	FRP LHe vessel for each coil
AC/DC converter	
-Type	Self-excited current , PWM
-Rated output	500 kVA
-Power device	GTO (1S-1P-6A ,2 bridge)
-Number of units	2 unit

2) Current leads : HTS (Bi2212 ,bulk) leads have been newly developed for ESK. Points of the development are the minimization of total heat load in the condition that it has cooling gas flow in it and a shunt conductor (SUS304) for protection connected in parallel with the HTS lead. These are essential for modular SMES having many current leads. Protection system for its quenching was also devised and installed. [10]

3) Cryogenic system : It is composed of a refrigerator, tubes to transfer the generated mixed phase He, and a phase separator in the dewar. The refrigerator have a capacity of 40ℓ/h as a He liquefier. It is shown in Fig.7.

4) AC/DC converter : The converter is a self excitation type with GTO thyristor of 12 phase PWM control. The converter consists of two sets of 500 kW, each of which is connected to 3 coils connected in series. A current type control is adopted in the converter. (See Fig.6)

5) Monitor and control system : The system is composed of a block of sequencers, 2 work- stations (WS) and 3 personal-computers (PC). For controlling converters operate according to the instructions from a WS via a sequencer. Other line of control can be made from one of PCs separately. For many kinds of measurements, a WS is used together with PC's. Another PC is used for data logging. (See Fig.6)

All equipments were settled at Imajuku substation. Overview of the installed ESK is shown in Fig.6. [11]

3. TEST RESULTS OF ESK SYSTEM

Tests for fundamental characteristics such as cooling test, system operation test response tests of active and reactive power and leakage of magnetic field test etc. were carried out.

A. Cooling Test

The test result of initial cooling down of the coil system is shown in Fig.7. For cooling down from room temperature to 77K in 100hour 12000 ℓ liquid nitrogen (LN_2)

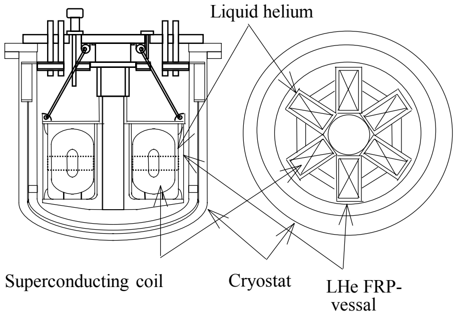


Fig.4. Arrangement of 6 coils with LHe vessel in a cryostat.

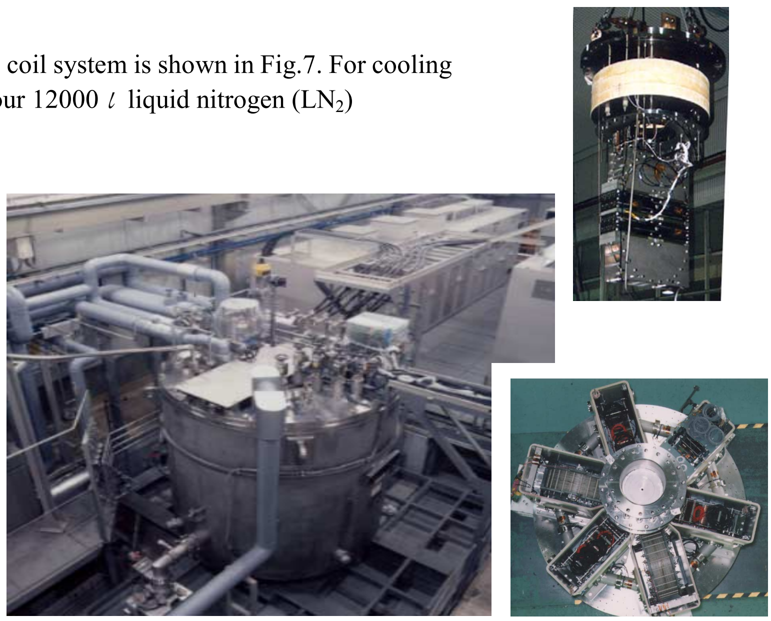


Fig.5. Overviews of installed ESK, single coil and arrangement of 6 coils.

Fig.6. AC/DC converter and control system.

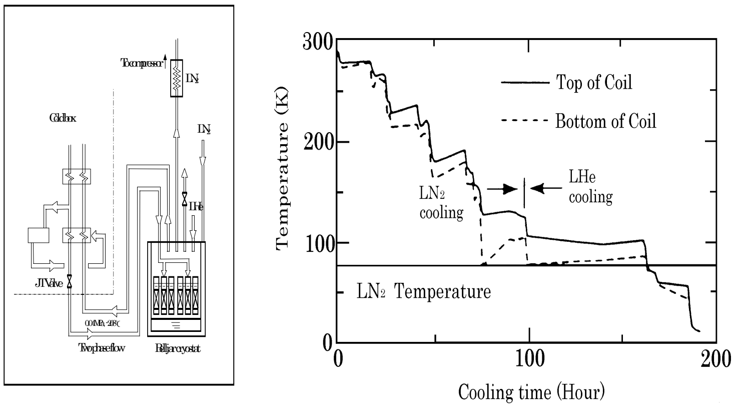


Fig.7. Cryogenic system and the test results of initial cooling

was required. For further cooling down to LHe temperature 4.6K in 3days 4000ℓ LHe was needed. After initial cooling, the refrigerator for recondensation was started to operate. It worked continuously about 1,500 hours. The LHe fiber reinforced plastic (FRP)-vessel system was found to be stable, through some LHe was needed to introduce at the bottom of the cryostat for stable operation. The temperature fluctuation in the gas-space that might lead to instability of cooling was found to be very small. Better performance of this system will be expected by further study, though frequent adjustments were needed in operation.

B. System Operation Test

Energization tests of repeated pulse mode were made between the coil current of 500A and 1000A, where the rate of current increase was 10A/s and that of decrease was 50A/s. This is shown in Fig.8. Some kinds of measurement were taken place in these tests as shown next. [12]

C. Response Tests of Active and Reactive Power

To confirm the characteristics of the converter itself, its responses for the step input of active and reactive power were measured. The results are shown in Fig.9. A delay time of 20msec for both active and reactive power input was seen, which is sufficient for the propose of power line compensation. From these results, it is confirmed that the response of the converter is sufficient enough for the compensation control in our case.

D. Leakage of Magnetic Field Test

The maximum leakage of magnetic field at the point of 1m from the outer surface of the cryostat was less than 5gauss which agrees with the designed value.

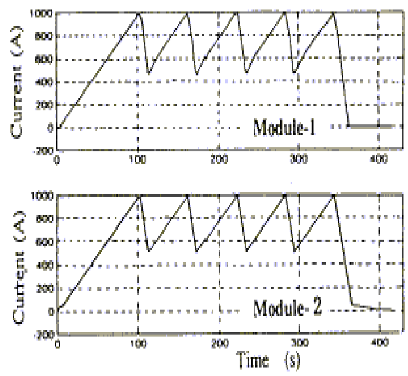
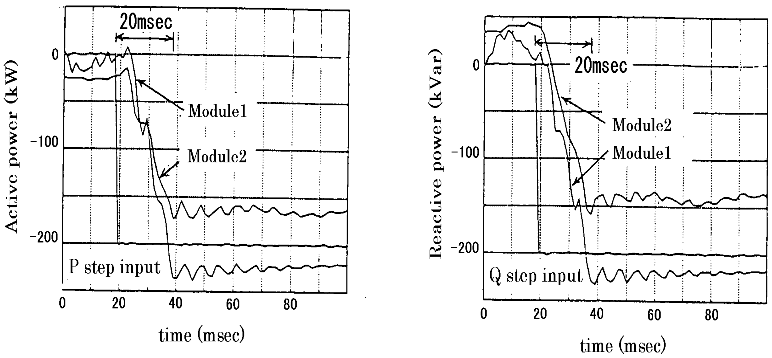


Fig. 8. Energization test of ESK..



(a) Step response of active power (b) Step response of reactive power

Fig. 9. Test result of response for the step input of active and reactive power.

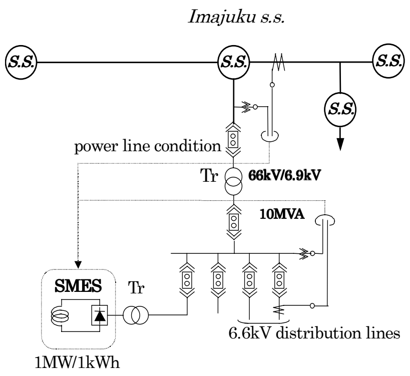


Fig. 10. The power system connected with ESK

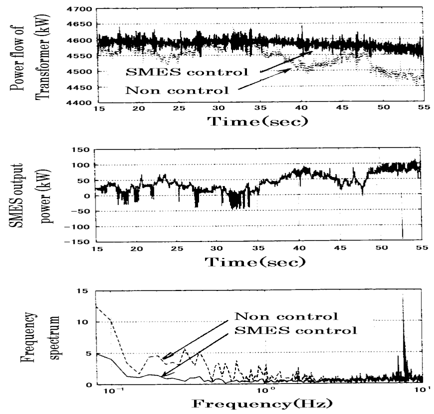


Fig.11. Test results of compensation for load fluctuation by ESK

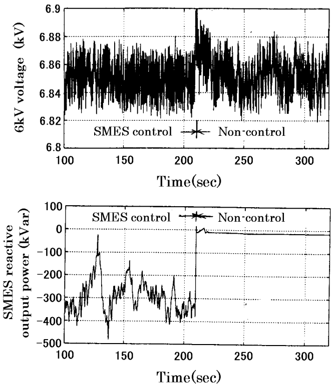


Fig.12. Test results of compensation for voltage fluctuation by ESK.

4. RESULTS OF CONNECTING TESTS TO 6kV POWER LINE

The power system connected with ESK is shown in Fig.10. Each module is connected to the 6 kV power line separately. Performance tests of compensation for load fluctuation and voltage fluctuation , and of stabilizing of power system have been made.

A. Compensation for Load Fluctuation

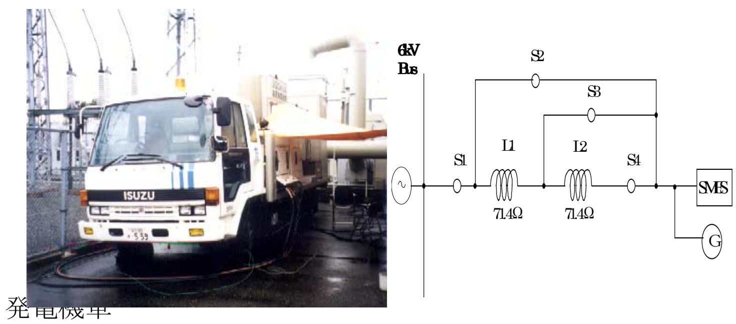
The characteristics of compensation for load fluctuation by ESK were measured in the 6 kV distribution power line at Imajuku substation, whose main load is residential demand of 4.5～4.7 MW. The measured wave forms of the power flow through the 10 MVA transformer are shown in Fig.11 together with the SMES output power and frequency spectrums. Clear effect of the control can be seen in the figure of the transformer power flower in time.The above result suggests the applicability of practical SMES for active power control with large capacity that can stabilize fluctuations of the longer period in power line. [13]

B. Compensation for Voltage Fluctuation

The test results of voltage compensation for fluctuation at the 6 kV power line are shown in Fig.12. The effect of compensation for voltage fluctuation can be seen by the comparison of wave forms in the left and right side the figure. Clear effect of the control can be seen. The above results suggest the applicability of practical SMES for reactive power control that can stabilize voltage fluctuation in power line.

C. Stabilizing of Power System

The test circuit is shown in Fig.13. In the test, the mobile generator of 300 kW and ESK were connected with a power feeder system through a reactor L1and L2. The switches S1 and S3 were initially closed and the switch S2 was opened. With this set-up, electrical oscillation was given to the test system by changing its impedance with S3 made open so as to insert a reactor L2 into the test system. During this test, observed was the ESK' keeping-down effect on the active-power oscillation appearing in the generator. Fig.14 shows how the active-power oscillation



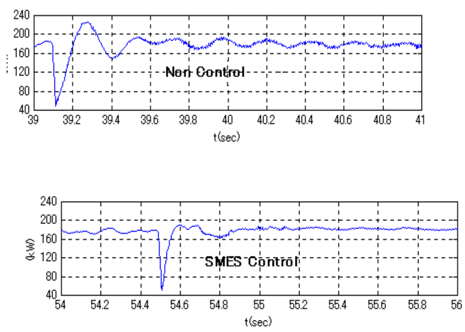
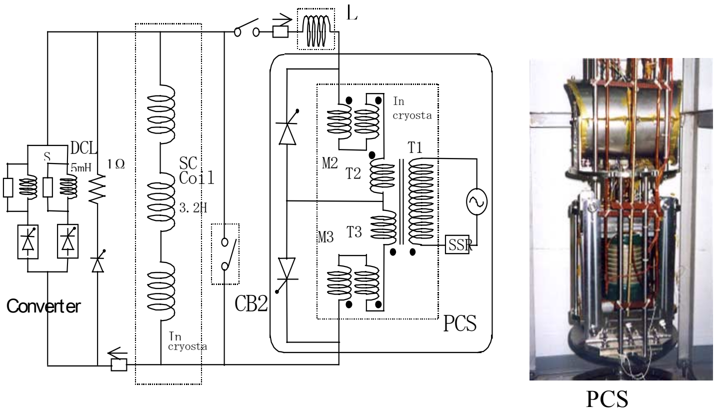


Fig.13. The mobile generator of 300 kW and test circuit for power system stabilization.

Fig.14. Test results of power system stabilization.



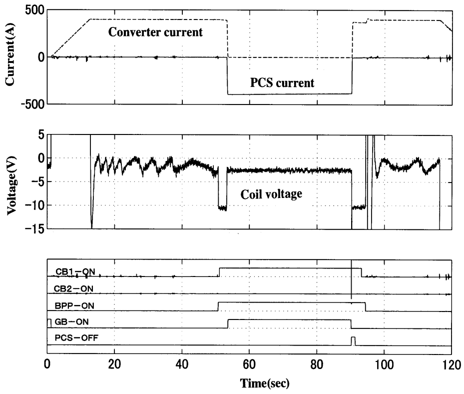


Fig.15. Test circuit of PCS(Persistent-Current-Switch). in a type of a transformer and ESK. Overview of the PCS.

Fig.16. Connecting test results of the PCS and ESK

appeared in the generator when the system impedance varied with the generator free of control by ESK , and in comparison with the generator under the control of ESK, for which the deviation ($\triangle P$) of the active power from the generator was used as the control signal. Comparing with the case free of ESK control, the case under ESK control exhibited a sooner end of such oscillation, verifying that ESK effectively worked for system stabilization.

D. Connecting Tests of PCS (Persistent-Current-Switch) to ESK

It is deemed that it should be crucial for a minimized loss during standby and an increased storage efficiency of a SMES to incorporate a PCS in the system. A PCS for a SMES system is necessary to be developed with a quick response and large current capacity. We have studied on a superconducting PCS in a type of a transformer which works according to the principle of a current transformer. A 900A class PCS was already manufactured. The test circuit of PCS and ESK is shown in Fig.15. Test results are shown in Fig.16. In the figure, at ESK operating current of 400A, secure sequential operation was verified, covering ESK in a constant-current running mode, converter BPP, closing CB1, converter GB (gate-block), PCS in a running mode, converter BPP, PCS out of operation, opening CB1 and SMES in a constant-current running mode all in the listed order. It is possible to switch over between the SMES-operation mode and the PCS-operation mode.

5. CONCLUSIONS

The construction of ESK had aimed at the development of elementary devices or technology from the point of future scaling up of SMES capacity and some new ideas were generated along this line. It has been completed and installed at the experimental site. Many tests for cooling, coil stability, loss, control system etc. have been taken place. The test results proved to be within the estimated range of the design. Performance tests for compensation for load fluctuation, voltage fluctuation of the local power line, stabilizing of power system etc. were already made as preliminary experiments. Each tests showed remarkable results. These suggest the availability of large scale SMES system for power systems. We are expecting the results of further with in the scale of ESK. We are always making challenge to the R&D of superconductivity applications for power systems.

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