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Development of 70 MW class superconducting generator with quick-response excitation ☆

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Abstract

The development of a superconducting generator had been carried out for 12 years under the first stage of a Super GM project. The 70 MW class model machine with quick response excitation was manufactured and evaluated in the project. This type of superconducting generator improves power system stability against rapid load fluctuations at the power system faults. This model machine achieved all development targets including high stability during rapid excitation control. It was also connected to the actual 77 kV electrical power grid as a synchronous condenser and proved advantages and high-operation reliability of the superconducting generator.

Keywords: Superconducting generator; Quick-response excitation; Power system stability

1. Introduction

The superconducting generator using superconductors in the field winding is superior to the conventional generator in terms of power system stability, generator efficiency, and generator dimensions and weight. In Japan the superconducting generator has been studied in R&D project on superconductor power application technologies as a part of the New Sunshine Program of the Ministry of International Trade and Industry (MITI)/Agency of Industrial Science and Technology (AIST). Toshiba had been engaged in R&D of the rotor for a 70 MW class model machine with quick-response excitation in the phase I of the project. The R&D activity had continued for 12 years from fiscal 1988–1999. This paper describes the development results of the 70 MW class model machine with quick-response excitation.

2. Technical issues of model machine with quick-response excitation

The superconducting generator with quick-response excitation has higher power transfer limit than the superconducting generator with constant excitation, because in the former generator the field current can be changed quickly according to the requirement of a power system. Therefore, it is expected to be applied to the medium and large capacity base load units installed in remote places. The development items were focused on solutions to the technical issues arising from capacity enlargement and excitation control for this type of the superconducting generator. Fig. 1 shows the development items based on these technical issues. The development items involve various key technologies such as structural materials, superconductors, cooling technologies, electric insulation, and damper system.

3. Development program

Fig. 2 shows the development program. After elemental technologies were studied for each development item, in fiscal 1994, a rotor model with the same core

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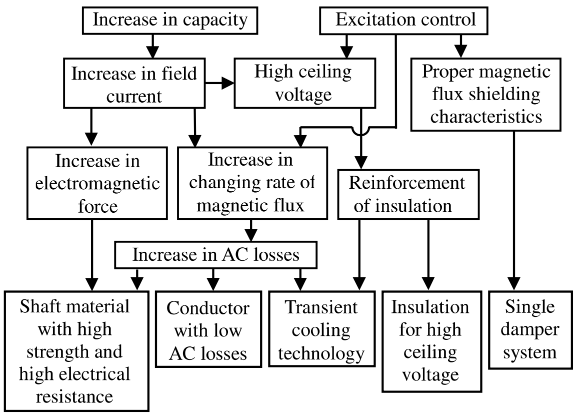

Fig. 1. Technology for superconducting generator with quick-response excitation.

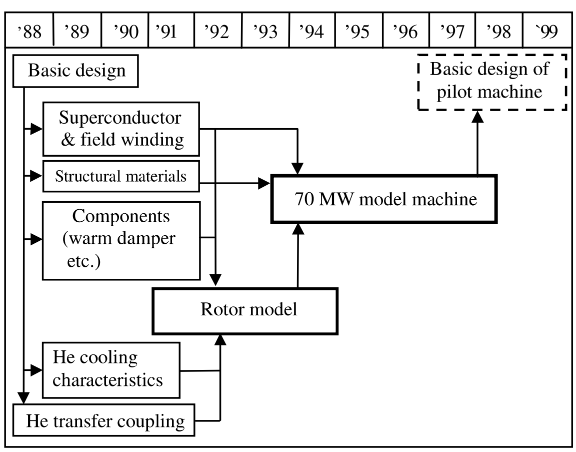

Fig. 2. R&D program of quick-response excitation model machine.

diameter and a shorter core length compared with the 70 MW class model rotor was manufactured and tested in rotating and excitation condition to verify the effectiveness of elemental technologies. Applying these results and refining, the model rotor was completed. The model machine was successfully tested in rotating and excitation condition at factory in fiscal 1997. It was combined with a stator, which was commonly used together with low-response machines, and generator tests were carried out at the Super-GM Test Center built in the Osaka Power Station of Kansai Electric Power Company in December 1998.

4. Technical data of the model machine

Table 1 shows the rating of the 70 MW class model machine with quick-response excitation. Table 2 shows the major technical data of the machine. Figs. 3 and 4 show the cross-section of the model rotor.

5. Structure and elemental technologies of the model rotor

5.1. Field winding

The field winding was wound in the slots cut around the winding mounting shaft in the form of a saddle-shape and fixed with insulation and wedges. The major technical issues of superconducting field winding were superconductor, support and fixing of superconductors, cooling, and electrical insulation.

We developed Rutherford type cable with two stage cabling, which was a low AC loss type and could be electrified stably without quench, even if field current changes quickly during quick-response excitation. Table 3 shows the major technical data of the superconductor for the model machine.

Since the double twisted conductor is not rigid enough, the conductor must be supported and fixed to stably conduct electric current. We developed the structure and the winding process so that conductors might be supported and fixed by pre-load that was greater than the centrifugal force and electromagnetic force during operation (Fig. 5).

The superconducting field winding is bathed and cooled by supercritical helium. The cooling paths were arranged so as to make up the fixing of the conductors. The cooling characteristics of supercritical helium in the high centrifugal field were provided with the verification test using a rotation model [1].

Table 1
Rating of quick-response excitation model machine

Generator rating		Field winding	
Capacity	73 MVA	Field voltage (at rating)	5 V
Output	65 MW	Field current (at rating)	3200 A
Voltage	10 KV	Max. flux density (at rating)	3.8 T
Current	4215 A	Field current (at forcing)	4500 A
Power factor	0.9	Max. flux density (at forcing)	5.3 T
Reactance Xd	0.45 p.u.	Max. field current changing rate	3200 A/s
Number of pole	2	Max. flux density changing rate	3.8 T/s
Frequency	60 Hz	Self inductance	0.39 H
Rotating speed	3600 Rpm	Ceiling voltage	1250 V

Table 2
Major dimension of model machine rotor

Rotor diameter	885 mm
Winding support shaft diameter	677 mm
Field winding length	2500 mm
Rotor weight	18,500 kg
Cold rotor weight	7500 kg

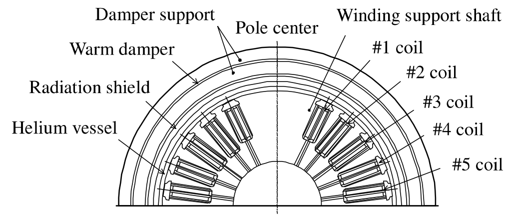

Fig. 4. Cross-section of model machine rotor.

Table 3
Specification of superconductor

Critical current	≧18.7 kA at 4 T
	≧15.8 kA at 5 T
	≧12.8 kA at 6 T
Copper ratio	≧1.5
Residual resistivity ratio	≧100
AC loss at 4 T → 6 T, 10 T/s	≧15 kW/m^3

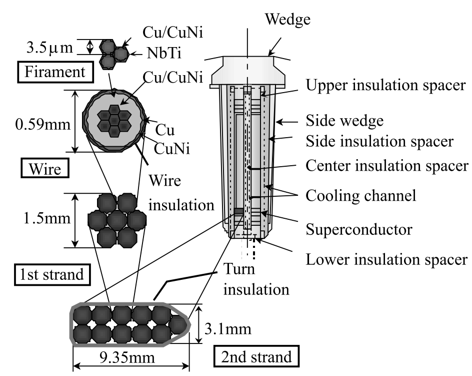

Fig. 5. Superconductor compacted in slot.

A high voltage of up to 1.8 kV including spike voltage of power source may occur in quick-response excitation. Accordingly we developed a suitable insulation structure for both ground and interlayer insulation.

Fig. 6 shows the load characteristics of the field winding, including the quench current data derived in the static excitation test. We verified that the maximum field current of 4500 A could be conducted stably, before field test.

5.2. Winding mounting shaft

The shaft for a superconducting generator, which is a high-speed rotating part, must withstand both centrifugal and electromagnetic force acting on the field winding. In the case of a quick-response excitation machine, in particular, a high strength is required, because an electromagnetic force more than twice the rating acts on the field winding in quick-response excitation. In addition, eddy current and the resultant loss are generated on the shaft in quick-response excitation. To reduce the eddy current loss, the winding mounting shaft must have a high electric resistance. To meet these requirements, we selected the precipitation hardening Ni-base alloys. Composition of this material was repeatedly improved considering productivity of large ingots and weldability. We developed successfully such material that yield stress was 800 MPa at room temperature and 1000 MPa at 4 K, and electric resistance was higher than 90 μΩ cm at 4 K.

5.3. Single damper system

As far as the damper system of the quick-response machine is concerned, high penetrability of magnetic flux is required for flux change in quick-response excitation and high magnetic shield against negative phase or asynchronous magnetic field, which occur in an asymmetric fault of power system. Eliminating the cold damper, we realized the required magnetic shield characteristics by only warm damper.

High strength is also required for the warm damper, because it is subject to a crushing force in the elliptical form by transient magnetic flux change during power

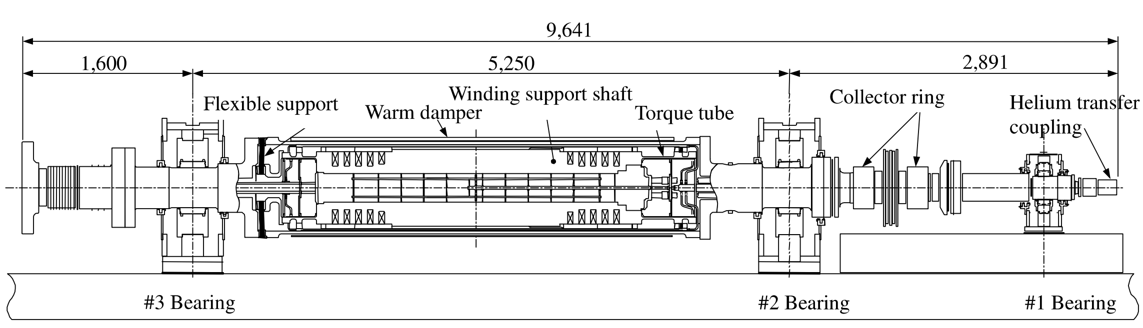

Fig. 3. Construction of quick-response excitation 70 MW class model machine rotor.

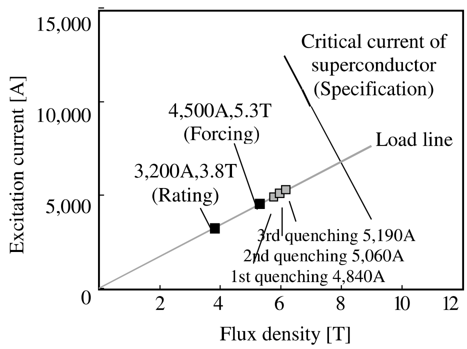

Fig. 6. Load line of model machine and quench current at static excitation test.

system fault such as a short-circuit accident. We developed the three-layer warm damper that is the most suitable for meeting above requirement. A CuCr cylinder with an adequate conductivity is sandwiched between an inside and an outside cylinder made of high-strength nonmagnetic alloy (A286). To integrate the three-layer cylinder, we used the hot isostatic pressing diffusion bonding.

We also provided a radiation shield that didn't have the damper function to reduce heat radiation from warm damper to winding mounting shaft. The A286-made radiation shield is provided with internal ventilating paths for cooling of gas helium. Fig. 7 shows the helium paths in the generator.

5.4. Other structures

The winding mounting shaft thermally shrinks approximately 10 mm relative to the warm damper when it is cooled by liquid helium. To absorb thermal shrinkage, we developed a system called flexible support consisting of spoke-like Inconel 718 sheet lamination to support the winding mounting shaft.

The helium transfer coupling to supply liquid helium into the rotor and discharge gas helium from the rotor is designed to cope with the increased helium flow in quick-response excitation.

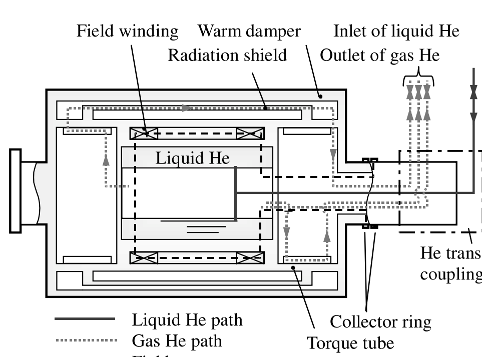

Fig. 7. Helium cooling system.

6. On-site verification tests

The field verification tests were performed using the M–G system shown in Fig. 8. The angle of the coupling between loading synchronous machine and superconducting generator was variously adjusted to simulate change in generator loading condition. The rotor measurement items included temperature, strain, flux density, liquid helium level, pressure, quench detecting voltage, vibration, flow rate of supplied liquid helium, flow rate of exhausted helium gas, and exhausted helium gas temperature.

6.1. Cooling characteristics and thermal load

At the cool down stage, helium gas of 80 K was initially supplied for approximately 45 min, followed by supply of liquid helium of 4 K. The field windings reached the superconducting condition after 75.5 h in all (Fig. 9). Thermal load at the rated operation was 85 W (equivalent liquid helium was 119 l/h). This includes 10 W increase due to electric current flow, and approximately 20 W increase due to rotation. At the warm up stage, the temperature was increased to 273 K in 58 h by supplying 200 and 320 K helium gases.

6.2. Basic electrical characteristics

We verified that the machine could be stably operated at the rated load (64.8 MVA, 0.885 power factor, and

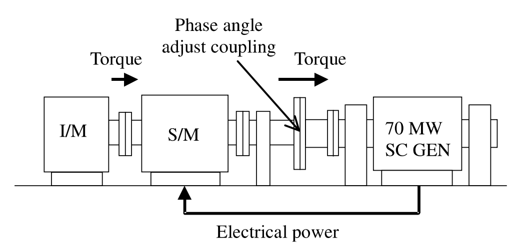

Fig. 8. Arrangement of field test.

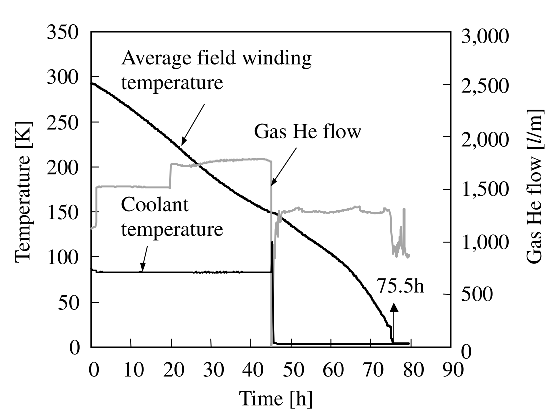

Fig. 9. Cool down performance.

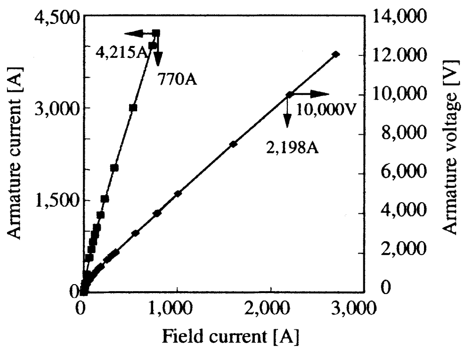

Fig. 10. No-load saturation characteristics and sustained three-phase short-circuit characteristics.

2740 A field current), and also at a wide range of leading and lagging power factor operation points.

We verified the output characteristics of the generator by the no-load saturation test and three-phase short-circuit test. In these tests we confirmed the nonlinear relation between excitation current and generator output voltage and current in the low excitation region (Fig. 10). This non-linearity is due to magnetization of the Ni-base alloy steel used for the winding mounting shaft (Fig. 11). This magnetization of the shaft decreased excitation current at rating output by approximately 10%. As the result of these tests, we also confirmed that the synchronous reactance Xd was 0.35 p.u., which sufficiently satisfied the development target of 0.5 p.u. or below.

6.3. Vibration characteristics

We verified that the machine could be stably run with below 50 μm_{p-p} vibration amplitude at all bearings almost equal to the conventional machine throughout the operation speed range up to 111% overspeed test (3996 rpm).

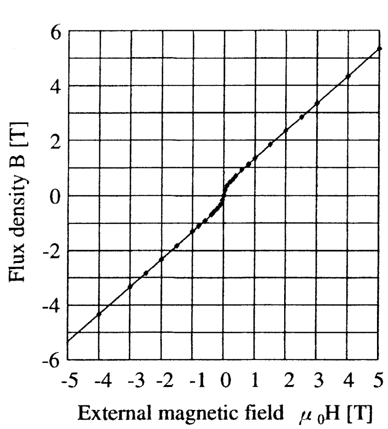

Fig. 11. Magnetization characteristics of Ni base alloy.

6.4. Damper shield characteristics

We verified the magnetic shield characteristics of the damper, supplying the armature winding current connected with an external constant current source in the open or short-circuit state of the field winding, and changing the rotating speed. We then measured the change of the armature winding impedance, and the change of induced voltage or short-circuit current in the field winding [2]. The results showed that the asynchronous armature flux at sliping frequency of 120 Hz was reduced to the 1/1000 level, and that flux at the frequency of approximately 1 Hz was well penetrated, as expected at design. We confirmed that the system's damper characteristic was suitable for the quick-response excitation machine (Fig. 12).

6.5. Quick-response excitation characteristics

We conducted the test of changing the field current rapidly by raising and lowering field voltage in a rectangular waveform during load operation. The field current changing rate was 3200 A/s, which is the development target, to perform one- through three-pulse excitation test [3]. Such rapid change in field current causes eddy current losses in the superconductor and rotor structural materials, and the resultant heating, which makes the liquid helium in the rotor evaporate quickly, and results in increase of rotor internal pressure and exhausted helium gas quantity. Fig. 13 shows the waveform of field voltage and field current at the one-pulse excitation test. Fig. 14 shows the rotor temperature rise. Fig. 15 shows the change of rotor internal pressure and liquid level. Table 4 summarizes the condition of rotor in the one-through three-pulse excitation test. In all tests, the field winding did not quench and continued to conduct current stably. The soundness of the rotor behavior such as vibration and rapid evaporation of liquid helium in pulse excitation tests was also confirmed, verifying that the development target of the quick-response excitation machine was fully achieved.

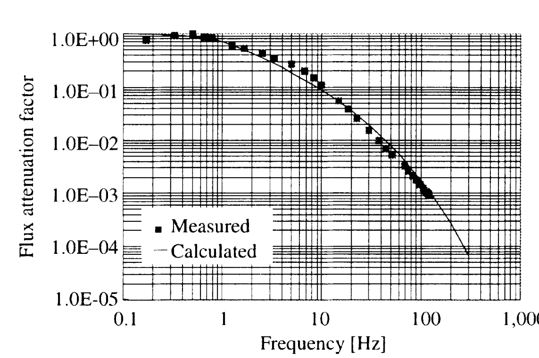

Fig. 12. Damper electromagnetic shield characteristics.

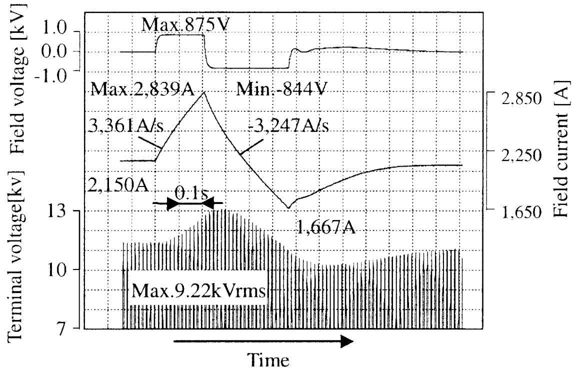

Fig. 13. One-pulse excitation test at rated load.

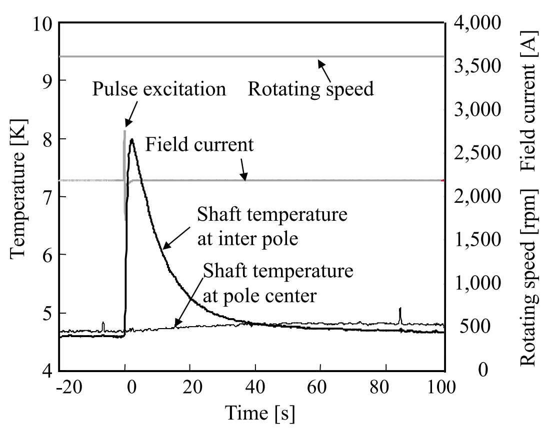

Fig. 14. Temperature rise at one-pulse excitation test.

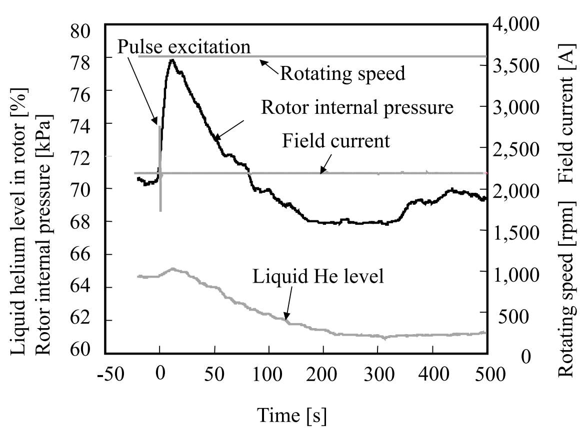

Fig. 15. Change of liquid helium level and rotor internal pressure after one-pulse excitation.

6.6. Sudden short-circuit characteristics

A severe test was performed assuming three-phase sudden short-circuit accidents. The test comprised a different phase connection test where the coupling phase with the loading synchronous machine was shifted by 180° before connecting. An electromagnetic torque of 4.88 p.u., which is greater than the torque (3.87 p.u.) that occurs in a three-phase sudden short-circuit accident on the high voltage side of a main transformer, was impressed in the test. Field current increased from 2141 to 3144 A at the maximum change rate of 8400 A/s (7 T/s) in the test, but the field winding did not quench and stayed stable. The shaft vibration did not change abruptly, nor the penetration heat changed abnormally. All these data verify that the rotor remains sound against abrupt short-circuit accidents.

Table 4
Result of pulse excitation test

	One pulse	Two pulse	Three pulse
Average field current change rate (A/s)	3674	3735	3621
Pulse excitation period (s)	0.8	1.55	2.4
He level in rotor (%)	66.2 → 59.2	69.2 → 58.5	69.4 → 56.6
Loss (kJ)	32.0	48.3	58.3
Temperature at inter pole (K)	4.58 → 9.72	4.55 → 13.0	4.53 → 16.1
Temperature at pole center (K)	4.68 → 6.29	4.64 → 6.13	4.63 → 6.48

6.7. Negative-phase withstand

A negative-phase current corresponding to $I_2^2 t = 19.9$ was conducted in the short-time negative-phase test. And an inverted-phase current of $I_2 = 12\%$ was conducted in the continuous negative-phase test. Temperature rise and thermal load increase of the warm damper were small, verifying that the new machine has a negative-phase withstand capacity better than that of the conventional machine (short-time negative-phase: $I_2^2 t = 10$; continuous negative-phase: $I_2 = 8\%$).

6.8. Thyristor starting characteristics

In some combined cycle plants, the generator is used as a synchronous motor to start the gas turbine. Relating to a superconducting generator, the field winding can not be electrified up to a rotating speed (approximately 300 rpm) suitable for establishing a stable liquid helium level. We therefore studied a system to start up the generator in the low rotating speed as an induction motor. We conducted a 587 A low frequency current through armature windings using a variable voltage and variable frequency (VVVF) power supply while isolating the field windings from the excitation power source. As the result, it took 16 min to increase the rotating speed from low speed for turning up to 350 rpm, and this rotating speed could be kept steadily. And the liquid helium could be stored in 85 min although eddy current losses were generated in the rotor (Fig. 16). These results

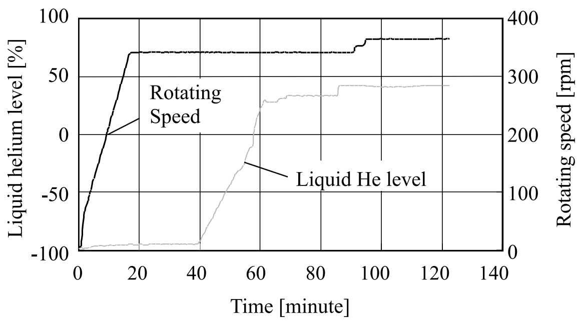

Fig. 16. Liquid helium behavior during static start by VVVF.

indicate that the superconducting generator can be applied to combined cycle plants.

7. Power system interconnection test

The final stage of the field test, the quick-response excitation model machine was operated as a synchronous condenser being connected to an actual power system of 77 kV. The model machine could run for the cumulative total of 52.9 h, during which a voltage stabilization test and a branch reactor reduction test were conducted to grasp various events occurring in interconnection operation. The result of the interconnection tests demonstrated that the superconducting generator accurately responded to various disturbances encountered in actual system operation, and that it can operate stably. We also obtained informative technical data necessary to quantitatively identify the effect of the superconducting generator on actual systems.

8. Conclusion

The superconducting generator has excellent features that are never seen with the existing machines. It offers a new possibility of structuring a power system. After 12 years of R&D activity, we have developed a 70 MW class superconducting generator with quick-response excitation, and tested and verified the feasibility and applicability of the technology. We take pride in having successfully completed the first step of commercialization of superconducting generators.

This study is one of the study themes of Engineering Research Association for Superconductive Generation Equipment and Materials (Super-GM). It was conducted as part of the New Sunshine Program of the Agency of Industrial Science and Technology, Ministry of International Trade and Industry and under contract with the New Energy and Technology Development Organization (NEDO). Kansai Electric Power Company and Super-GM carried out the power system interconnection tests jointly.

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