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Development of superconducting generator having highly stabilized superconducting field winding—70 MW class superconducting generator ☆

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Abstract

The development of a practical superconducting generator has been carried out in Japan since 1988. The authors have developed a rotor with a highly stabilized superconducting field winding and a stator with an air gap winding composed of double transposed copper coils. A series of tests was completed at the end of 1997. The output of 78.8 MW was recorded, which was the highest value obtained to date worldwide. The development of the generator and the test results are described.

Keywords: Superconducting generator; Superconductivity; Superconducting field winding; Air gap armature winding; Load tests

1. Introduction

In 1988, the authors began to develop the rotor and stator of a 70 MW class superconducting generator in the New Sun-Shine Project of "Research and development on superconducting technology for electric power apparatus" [1]. During this time, the authors developed a rotor having a highly stabilized superconducting field winding [2] and a stator used for this rotor and the two other rotors. The development, fabrication and tests of the generator are explained here.

2. Gap winding armature winding

The main parts of the stator are the air gap armature winding, and the non-magnetic and non-conductive teeth which support the armature winding. Fig. 1 shows a longitudinal cross-section of the 70 MW class superconducting generator stator. For a superconducting generator, the air gap armature winding is adopted because it has no iron teeth. Then, the armature winding is directly exposed to the magnetic flux generated by the field winding and the armature winding. Fig. 2 shows the developed conductor which is doubly transposed for the armature winding. In order to reduce the losses owing to an alternative magnetic field, 21 insulated copper thin wires was made each with a cross-section of 2.5 mm × 0.9 mm, were transposed to form an insulated first transposed conductor. Next 14 first transposed conductors and four stainless steel cooling pipes were compacted and transposed again to give the doubly transposed conductor. After that the compacted conductor was insulated around the surface. The completed conductor insulation was tested and shown to have the same characteristics of dielectric breakdown and voltage aging as conventional machines. Conductors tests showed the conductor had a conducting ability of 5000 A and low eddy current loss performance.

As the armature winding is an air-gap winding structure, a large electromagnetic force acts on the winding directly, so the conductors are well insulated and supported firmly. For the supporting teeth, fiber reinforced plastics (FRP) non-conductive and non-magnetic materials were selected. The FRP teeth were analyzed to get

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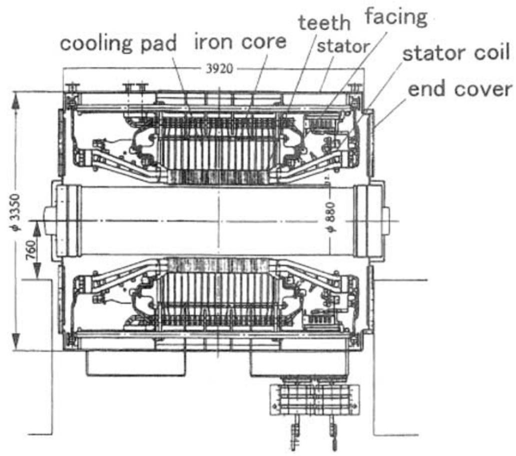

Fig. 1. Cross-section of a stator of 70 MW class superconducting generator.

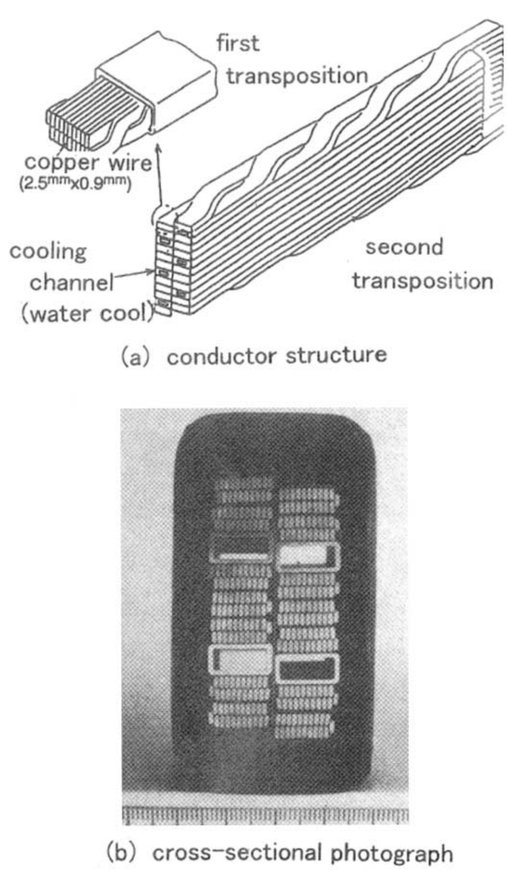

Fig. 2. Double-transposed armature conductor.

the optimum configuration in which three teeth are connected tangentially. The complex teeth are shown in Fig. 3. The armature conductors and the complex teeth were tested in some models and the characteristics of vibration and fatigue, etc. were confirmed. Consequently the supporting method was judged to show good applicability. Other parts in the stator were tested

Fig. 3. Glass-fiber reinforced teeth.

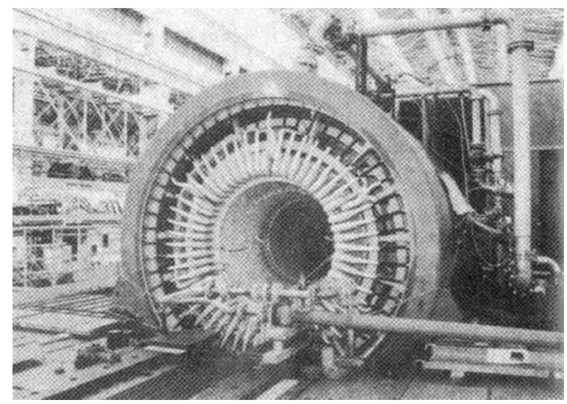

Fig. 4. Completed stator of a 70 MW machine.

in other models and the designed configuration, structures and materials were confirmed applicable. In consequence, the stator was manufactured. Fig. 4 shows an outer view of the completed stator.

3. Rotor and highly stabilized field winding

The developed rotor by has some special features as follows:

1. Highly stabilized field winding.
2. Single layer warm damper.
3. Double bearing system for thermal contraction of the rotor.
4. Three layer cold damper.

When the basic design was set, the rotor was given the same rotor outer diameter as, and one-third the rotor length of the 200 MW class machine that had been designed in a previous feasibility study. The basic design included the output power, electrical constants and dimensions and results are shown in Table 1. Fig. 5 shows a cross-sectional view of the rotor.

Both the rotor and the stator were combined in a superconducting generator which had a rating of 83 MVA, terminal voltage of 10 kV, armature current of 4792 A, power factor of 0.9 and speed of 3600 rpm.

The field winding consisted of the superconducting conductor including an aluminum stabilizer to get higher stability. The cold damper was made by the hot isostatic

Table 1
Specifications and dimensions of a 70 MW class superconducting generator

Item	Specification
Rating (MVA)	83
Voltage (kV)	10
Current (A)	4,792
Power factor	0.9
Number of poles	2
Speed (rpm)	3600
Synchronous reactance (pu)	0.35
Field current (rating/max. A)	3000/3600
Sweep rate of field current (A/s)	300
Rotor diameter (mm)	880

pressing (HIP) method and had a stainless steel–copper–stainless steel three-layer structure. The warm damper consisted of nickel–copper–aluminum alloy single layer. These dampers functioned well as the damper and shield for the invading alternating magnetic field from the armature winding. A double bearing system was adopted for the thermal contraction compensating structure.

3.1. Field winding

The field winding was a double transposed compacted strand including highly purified aluminum (99.999%) stabilizer. Following the Maddock theorem, the superconducting field winding was designed to be cryostable according to the higher heat transfer characteristics in the 3600 rpm rotating field in which the heat flux is ten times larger than that of the non-rotating static field. In the theorem, if the residual resistance is less than 12 μΩ/m, the field winding is able to be cryostabilized at 3600 rpm and 3000 A. Technological developments of superconducting wire allowed the authors to make a superconducting stranded conductor having the performance needed to meet the specifications. The conductor showed no aging in the test of repeated pressing during the life time cycle. The conductor is shown in Fig. 6.

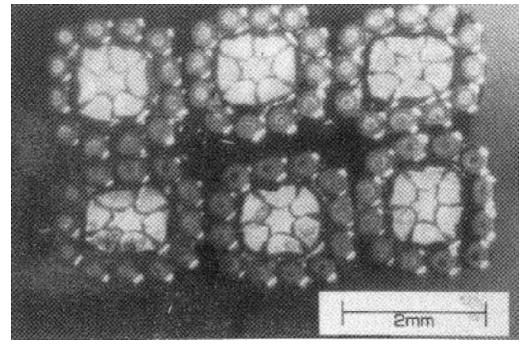

Fig. 6. Superconductor of field winding.

3.2. Structural materials and damper

A286 steel was applied for the field winding support shaft because its high strength and toughness were enough to meet the specifications for both cryogenic and normal temperature. The shaft was roughly machined in solid solution state and then machined completely after aging heat treatment. The material had 0.2% strength of 750 MPa at room temperature and 950 MPa at 4 K. When the shaft was machined with three-dimensional slots, a numerical controlled machine was used. Fig. 7 shows the shaft during the final machining. The helium vessel was also made of A286 steel because it is under high centrifugal stress and stress owing to possible high

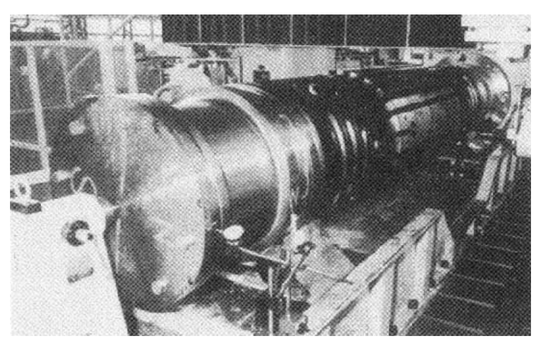

Fig. 7. Field winding support shaft in machining.

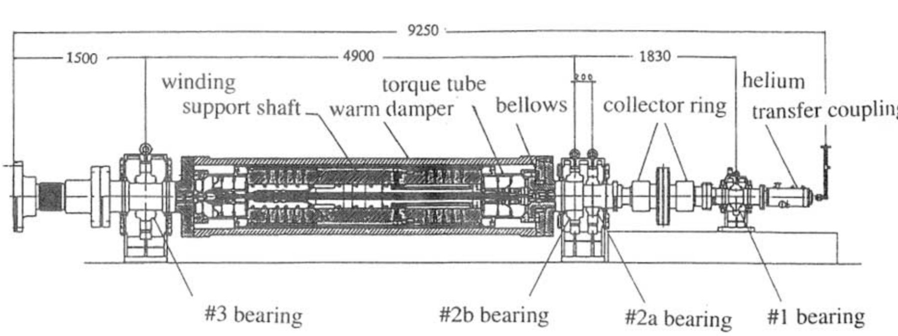

Fig. 5. Cross-section of rotor having highly stabilized field winding.

pressure when quenching the field winding. The damper system consisted of the warm damper and cold damper. The warm damper could shield 60 and 120 Hz magnetic fields and the cold damper could shield a field under 0.1 Hz. The warm damper was made of Ni–Cu–Al alloy that had have 0.2% strength of 760 MPa and resistivity of 50 μΩ cm. The highly pure copper cylinder of cold damper was reinforced by high strength stainless steel both inwardly and outwardly.

3.3. Thermal contraction compensation structure

The double bearing type rotor had two bearings on the non-driven end of the rotor, so the warm damper and the torque tube were supported by the bearings independently.

In both factory and site tests, rotor vibration at the journal sections and helium transfer coupling (HTC) were below the allowable value. The balancing method using balancing plane located at the end of the non-driven end of the torque tube, which was developed in the factory test, had an extension capability for large rating machines.

3.4. Field winding model

In order to develop a design method and fabrication technique for the complex saddle shape type field winding, a model winding and winding support shaft was manufactured and tested. The model had a short length in the straight section of the field winding. The excitation test was done for the model in a static state. The model showed good stability of excitation, so the supporting and cooling structure of the model were judged applicable to the 70 MW class model generator.

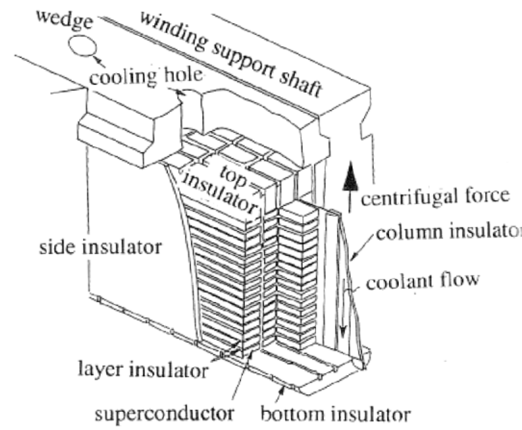

Fig. 8. Structure of field winding.

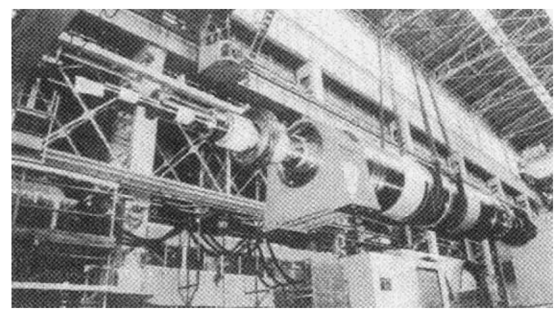
Fig. 9. Completed rotor.

4. Design and fabrication of the model generator rotor

The model generator rotor was designed and fabricated with the above-mentioned technology. For the design, the following were completed: superconducting field winding stability analysis; inner piping and its supporting interval to avoid harmonic vibration; multi-channel data acquisition systems; and other items. After machining the field winding support shaft, the superconducting conductor was directly wound to the shaft to make a field winding. Fig. 8 shows the inner structure of the field winding. In the field winding, conductors were wound edgewise and many insulation spacers were used to form the electric insulation and cooling duct. There were also supporting components to withstand centrifugal and electromagnetic forces.

After fabricating the winding, it was tested in a static cryostat filled with 4.2 K liquid helium and 1.8 K saturated superfluid helium. Excitation tests and heater tests were done and the soundness and stability of the field winding were confirmed. After that, cold damper was attached to the field winding support shaft. The inner piping and warm damper were attached to the shaft and the rotor was completed. Fig. 9 shows an outer view of the rotor.

5. Factory tests

The completed rotor and stator were combined and tested in the factory. The electrical constants, efficiency and other basic performance items were confirmed. Main results in the tests were mentioned as follows:

(a) Thermal insulation vacuum in the rotor reached 0.173 Pa 64 h after beginning operation.
(b) In low speed turning, the rotor could carry liquid helium.
(c) The heat load of the field winding part showed dependence of rotating speed. The heat load at the rated speed with no excitation was 53 W.
(d) The superconducting field winding could be excited to 2819 A which was equivalent to 1.2 pu of the no load excitation current of the generator. From the heater tests, it became clear that when the field current of 2783 A and heater input of 4.33 W produced

a normal state zone, the normal state zone was delayed. For less current and heater input than these, the normal state zone became the superconducting state and the field winding was stable.

(e) From the state of the excitation current of 1.2 pu, a shut down test was done at the rate of 0.65 pu/s and the winding showed no quench.

After the factory test, the rotor and stator were ready for the verification tests in the Super-GM test center.

6. Verification tests and other results

The rotor and the stator were set in the test center which had a refrigeration system and the verification tests were done from March to December 1997.

During the tests, basic performance items of the superconducting generator were obtained. The 78.7 MW output and 82.2 MVA leading power factor operation were verified.

Main results of the verification tests were summarized as follows:

1. Electrical basic performance and constants: The Dalton–Cameron method, slip method, no load saturation performance, three phase shortcircuit performance, three phase sudden short-circuit performance and other performance tests were carried out and many constants of the generator were acquired.

Fig. 10 shows the no load saturation curve and the three phase short-circuit curve. The field current of 2320 A produced terminal voltage of 10.0 kV in a no load test and a linear relation between field current and terminal voltage was obtained. In the three phase short-circuit test, field current of 942 A produced 4792 A of rating armature current. These results led to the synchronous reactance Xd of 0.41 pu.

Table 2 shows the constants of the generator obtained by different methods. Xd was calculated as 0.42 pu by the finite element method, and it was close to 0.41 pu of the test result.

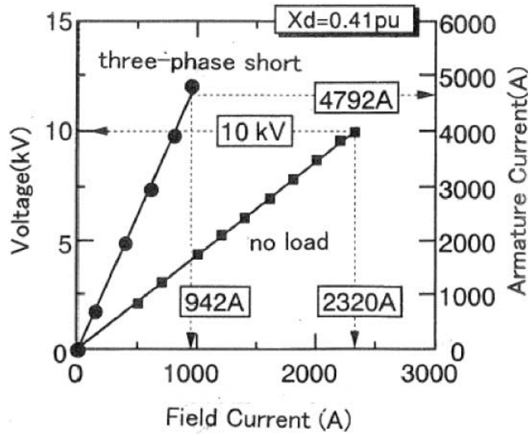

Fig. 10. Characteristics of no-load and three-phase short circuit.

2. Efficiency: Commercial efficiency of 98.15 % was obtained in the efficiency test. The efficiency of the 200 MW superconducting generator was calculated as more 0.6% that of a conventional generator (0.5% if refrigeration power were considered).

3. Stability of the field winding: The heater quench test was done to verify the stability of the field winding. The cryogenic stabilized limit of the field winding had been around 2700 A in the factory test and this was down to about 2100 A in the verification tests. For the load test, the quench detector was in action during the increase of the field current equivalent from 0.95 pu of the rated voltage to 1.05 pu. Fig. 11 shows the field winding performance in the verification tests.

A primary factor analysis was carried out, using the results of the dismantling inspection and factory and verification tests. Consequently, the drop of the cryogenic stability of the field winding was caused by a combination of the factors mentioned below and other factors.

(a) A large temperature difference which occupied when the normal transition occurred might be generated in the conductor. According to analysis results by the finite element method, the maximum temperature

Table 2
Measured machine constants

	X_d	X'_d	X''_d	X'''_d	X_q	X''_q	X'''_q	X_2	X_0
Reactance (pu)									
Measured	0.406	0.34	0.23	0.23	0.406	[a]	0.193	0.187	0.07
Designed	0.42	0.25	0.21	0.18	0.42	0.21	0.18	0.18	–
	T'_d	T''_d	T'''_d	T'_{do}	T''_{do}	T'''_{do}	T''_{qo}	T'''_{qo}	T_a
Time constant (s)									
Measured	11.8	0.06	0.02	[a]	[a]	[a]	[a]	[a]	0.1
Designed	186[b]	0.92	0.03	260[b]	1.1	0.04	1.1	0.04	0.11

[a] Have not been measured.
[b] If the inner resistance of the current source is taken into consideration, the measured value becomes equal to the designed value.

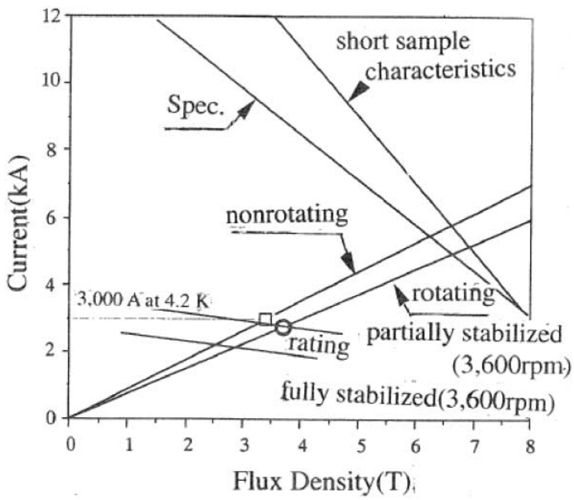

Fig. 11. Characteristics of field winding.

difference was 5.0 K. This large temperature difference indicated poor cooling performance of the superconductor and decline of cryogenic stability.

(b) The residual resistance of the aluminum stabilizer might increase owing to its mechanical strain susceptibility. In the factory test, the field winding was operated at the cryogenic temperature and at speeds above 3000 rpm about 20 times, and in the verification tests, it was operated over 40 times.

7. Summary

The rotor with a highly stabilized field winding was combined with the stator with an air gap armature winding and tested at the Super-GM test center. During the verification tests, 70 MW class electric generation was achieved. Leading power factor operation equivalent to the rating power was obtained. Lower reactance and other merits of the superconducting generator were verified.

In order to increase the cryogenic stability of the field winding, it was determined that higher rigidity and simplification of the superconductor were needed. Development of the essential elements and model generator technology have shown it possible to establish a design and fabrication method for the 200 MW class superconducting pilot generator.

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