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OVERVIEW OF RESEARCH AND DEVELOPMENT OF SUPER-CONDUCTING AC GENERATORS IN JAPAN

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INTRODUCTION

The superconducting ac generator is expected to be the optimum among ac generation systems in future because of its reduced size,weight,high efficiency,and contribution to stability of power systems and higher generator terminal voltage.

Experimental superconducting ac generators with power ratings between 20 and 50 MVA have been developed throughout the world.

Japanese activities on the development of superconducting generators are briefly described here.

When high capacity niobium-titanium superconductors became commercially available at the end of the 1960's,works on superconducting machines were initiated over the world following the successful test of the first experimental synchronous 45 kVA generator at the MIT in 1969. Meanwhile a large number of small generator models has been built and successfully tested,indicating the worldwide interest in this development.

These small models are listed in Table 1, which have been built in the USA,USSR,China, Japan,France,Germany and Czechoslovakia.

Table 2 indicates larger experimental SCGs ranging from 10 to 50 MVA and full-scale but short superconducting rotor models. The first four machines in the upper column were successfully tested or under testing. The MIT generator is expected to go on tests until 1987. The large test rotors already built or still under construction are listed in the lower column. Only the Alsthom model has so far been tested over a long period.

The KWU rotor is being built, which in 1992 will be set up in the prototype generator of 850 MVA rating. Beyond the stage of experimental superconducting generators the first step in the world to a prototype generator of 300 MVA rating had been ever made in the USA with the EPRI-funded Westinghouse generator that would be expected to be completed in 1986. But this project was quitted in 1983 because of rising cost of R&D and slow-down of growth-rate in electricity demands.

JAPANESE ACTIVITIES

In Japan, the research on superconducting rotating machines has been initiated in the latter period of 1960's.

The development of ac machines was preceded by dc machines in the early stage and thus a 3,000 kW homopolar dc generator was built by Toshiba Corp. in 1974. In the early 1970's several small ac superconducting machines were built and tested; e.g. 30 kVA generator by Fuji Electric Co.,Ltd. in 1973.

Although such small machines might not simulate future practical machines,the experiences in manufacturing and operating such machines have been accumulated to get sufficient potentials for realization of practical machines.

Thereafter,a 6,250 kVA machine was completed in 1977 under the collaboration of Fuji Electric Co.,Ltd. and Mitsubishi Electric Corp. with financial support of MITI. Its successful operation as synchronous condenser has accelerated japanese activities to develop superconducting generators. They went on to develop another machine as a synchronous condenser with power rating 30 MVA over the range of leading and lagging phases. This machine was initiated in 1977 and completed in 1983 and is still under testing after setting up a closed cycle refrigeration system.

Hitachi,Ltd.made a program to a 50 MVA superconducting generator initiated in 1975, too. The rotor of this machine was constructed in 1982. Finishing the rotor, the machine was completed in 1983. Performance and improvement tests are being conducted at present.

Toshiba Corp.started the development of a superconducting ac generator in 1981,too, and has performed basic research for a 1,000 MVA class geenrator focusing on key design

Table 1. Superconducting generator models < 10 MVA

Manufacturer	Country	Rating	Test
MIT	USA	0.045 MVA	1969
All-Unions Institute	USSR	0.02 MVA	1971
MIT	USA	3 MVA	1972
WH	USA	5 MVA	1972
PERI,Shanghai	China	0.4 MVA	1974
All-Unions Institute	USSR	1.5 MW	1974
EMMW	China	0.4 MVA	1977
Fuji/Mitsubishi	Japan	6.25 MW	1977
Elektrosila	USSR	2 MW	1979
CRTBT,Grenoble	France	0.5 MW	1980
TU of München	FRG	0.3 MVA	1980
Fuji	Japan	0.02 MVA	1982
Skoda	Czechoslovakia	5 MVA	1984
ALSTHOM	France	0.02 MVA	1986

and manufacturing technology. On the basis of a conceptual design of a two-pole 1,000 MVA machine,a small unit of the generator with rating of 3 MVA was constructed in 1983. At present they are still conducting tests on it.

Another approach to practical use of superconducting generator in network is an experimental study conducted by University study group in which operational performance of the machine connected to actual network has been simulated with a 20 kVA machine and an equipment simulating a power network. The group composed of Kyoto,Saga and Seikei Universities is going on testing the 20 kVA built by Fuji Electric Co.,Ltd.

TECHNICAL FEATURES OF JAPANESE MACHINES

Four japanese superconducting machines are described here. Their specifications and technical features are summarized in Tables 3,4 and 5.

6.25 MVA Superconducting Generator

Table 3. Major specifications of japanese machines

Rating(MVA)		6.25	30	50	3
Voltage	(kV)	2.64	11	16	2.4
Current	(A)	1,375	1,576	1,804	722
Frequency	(Hz)	60	60	60	60
Speed	(rpm)	3,600	3,600	3,600	3,600
Rotor outer dia.	(mm)	390	730	600	445
Bearing span	(mm)	1,920	3,300	3,900	2,075
Stator height	(mm)	1,330	1,700	2,000	1,180
Stator length	(mm)	1,620	2,600	2,600	1,600
Rotor weight	(t)	0.7	4	6	1.3
Stator weight	(t)	4.5	13	18	5.1
				0.35	0.48
X_d	(pu)	0.4	0.697	0.35	0.48
X_d'	(pu)	0.23	0.51	0.28	0.44
X_d''	(pu)	0.15	0.27	0.19	0.29
T_{do}'	(sec)	300	260	200	38
T_{do}''	(sec)	0.2	0.02	0.06	0.02

This is the first machine with rotating superconducting field winding in Japan. The electrical,mechanical and thermal characteristics of the generator were investigated by a series of tests.

The two-pole field coil of saddle shape was wound of copper-stabilized multifilamentary Nb-Ti-Ta and consist of nine epoxy-impregnated modular coils for each pole.

Liquid helium flows through the field winding without Liq.He reservoir inside the rotor.

Two kinds of damper are applied to the rotor; a room temperature damper (warm damper) which also serves as a vacuum vessel and a cryogenic temperature damper (cold damper) which serves as a thermal radiation and electromagnetic shield. Both of the dampers are mounted on inner and outer rotors,respectively.

Table 2. Development of superconducting generators in the world

Experimental generators with a capacity of 10 - 50 MVA

Manufacturer	Country	Rating(MVA)	State	Test
All-Unions Inst.	USSR	20	Rotor test 1980-81	Generator 1981
GE	USA	20	Rotor test 1981	Generator 1982-84
Fuji/Mitsubishi	Japan	30	Rotor finished 1981	Generator 1982-83-
Hitachi	Japan	50	Rotor finished 1982	Generator 1982-84-
MIT	USA	10	Under construction	Generator 1984-

Test rotors with large diameter

ALSTHOM	France	1060 mm	Rotor finished 1980	1980-
KWU	FRG	1170 mm	Under construction	1986-87-
Toshiba	Japan	>800 mm	Under construction	1985-86-
Ansaldo	Italy	1200 mm	Under construction	1984-85-

Table 4. Technical features of japanese machines

Rating (MVA)	6.25	30	50	3
Field Windings				
Superconductor	NbTi/NbTiTa	NbTi+Nb_3Sn	NbTi	NbTi
Shape	Saddle	Saddle	Saddle	Saddle
Inner/Outer dia.(m)	0.19/0.26	0.4/0.5	0.34/0.4	0.19/0.27
Straight length (m)	0.4	1.0	1.0	0.3
Impregnation	Epoxy resin	non	Epoxy resin	non
Support	Binding	Wedge	Binding	Wedge
Rotor Cylinders				
Inner rotor	Without He tank	With He tank	With He tank	With He tank
Damper	Double	Double	Double	Double
Material	Stainless Steel	Ti/Ti alloy	Stainless steel	StainlessSteel
Joint	Slide and bellows	Welding	Double bearing	Slide and diaph.
Sealing In He Trans. Coupl.	Magnetic fluid	Magnetic fluid	Magnetic fluid	Magnetic fluid
Armature Windings				
Winding type	Air gap	Air gap	Air gap	Air gap
Cooling	Oil	Oil	Water	Oil
Refrigeration				
He flow Rate (L/h)	30	30	45	20
Ref. cycle	non	Claude	Claude	non
Loop	Open	Close	Close	Open

As a countermeasure to reduce the thermal stress between the inner and outer rotors, a sliding mechanics with bellows was adopted at the collector-ring side end of the cold damper.

As for a sealing mechanism in the helium transfer coupling system, magnetic fluid seal was developed and used because of its advantages; a less contamination of the helium, a long life due to lack of solid contacts, a good sealing referance and less heat losses.

Main parts of the rotor were made of stainless steel.

30 MVA Superconducting Synchronous Condenser

The 30 MVA machine was developed as a synchronous condenser, intending to apply a high reactive power control ability to power network.

The outer rotor diameter was chosen 730 mm, which is relatively large to the rating of 30 MVA in order to study and verify the structure design for a pratical rotor.

In addition, the new approache was applied as follows:

1) Trial of the use of Nb_3Sn wire in a part of the field winding

2) Slot-wedge support system for the superconducting field winding was adopted, expelling epoxy-impregnation, composed of six NbTi and two Nb_3Sn coils, which is preferred over other methods because it is mechanically strong and well establised for conventional machines.

3) Titanium and Titanium alloys are used in almost all parts of the rotor because of its higher mechanical strength, low thermal conductivity and light weight.

4) Rigid structure without any flexible joints in order to atain an overall rotor simplicity and to eliminate balancing problems.

5) As to the cooling circuits in the rotor,the method using self-pumping effect to reduce the vapour pressure and thus to limit the temperature rise in the rotor was adopted.

6) Double damper system (ambient and intermediate temperature) each of which is made of two layers (outer-support and inner -damper structure)

7) Air-gap winding which is made of diamond-shaped pancake coils and is immersed in silicon oil for cooling and insulation.

This machine has been cooled by a highly-automated closed refrigeration system with the liquid helium supplying capacity of 30 liters/hour, and has been successfully operated more than 2,000 hours totally.

50 MVA Superconducting Synchronous Generator

In 1982 Hitachi,Ltd. completed the rotor for the 50 MVA machine and succeeded in generating power with the generator built in a small stator of 4 MVA rating. Therafter, they built the stator for the 50 MVA machine.

The saddle-shaped field winding wound with NbTiZr ternary superconductor are impregnated with epoxy resin and installed in the wide grooves on the inner rotor surface and bound with non-magnetic steel girdle.

Composite double damper is adopted. In order to prevent the thermal stress between the inner and outer rotors, a double bearing method was developed: i.e. supporting them independently at undriven end of the rotor.

Another major difference between the 30 MVA and 50 MVA machines is in cooling method for stators and in the scheme of an air-gap armature winding.

In the 50 MVA machine, a water-cooled diamond-shaped winding is used as in conventional machines.

3 MVA Superconducting Synchronous Generator

Major features of the Toshiba's 3 MVA machine are as follows:

The saddle-shaped field winding which is made of NbTi wire, is fixed by slot-wedge method on the inner rotor.

The thermal contraction between the inner and outer rotors is absorbed by flexible support system at the turbine side end.

The air-gap armature winding is of conventional diamond-shape and is cooled by forced oil. Up to the present they have finished almost all of tests except actual loading.

20 kVA Superconducting Synchronous Generator

In 1982 the author's study group built a small superconducting generator for full-load test study, and has been running various tests.

Major specifications of the 20 kVA machine are listed in Table 5. Major features are as follows:

The machine is four poles and is of a vertical shaft type for easy mechanical balancing and low manufacturing cost.

The field winding of race-track shape is made of multifilamentary NbTi wire.

The vapored helium gas is sealed with magnetic fluid sealing system. The dual environmental shield comprises an inner laminated iron shield and outer aluminium eddy-current shield, intending to reduce the machine weight.

CONCLUSIONS

Remarkable progress has been made all over the world in the development of superconducting generator. As a result, its technical feasibility and several distinctive adv advantages over the conventional machines become more clear. However, an exceptionally large amount of development work has still to be done to establish a fully developed and highly reliable technology for utility operation.

Recently, main japanese electric power companies along with manufacturers seem to become enthusiastic for the development of superconducting generators.

Japanese government is showing a tendency toward the development of the superconducting generators with capacity of several hundred megawatts, although a national program is not yet clearly announced at present.

The two-years investigation committee to study on the feasibility of superconducting generators, their systems and superconducting materials technology has been started last year, supported by the MITI (The Ministry of International Trade and Industry).

Next year, such a national project would be expected to be initiated.

REFERENCES

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2) D.Lambrecht: Cryogenics, 25,619(Nov. 1985)

Table 5. Major specifications of the 20 kVA superconducting generator

Dimension	Total height 2,674 mm Maximum diameter 732 mm Weight 2.5 t
Field winding	No. of poles 4 No. of turns 455/pole Conductor NbTi/Cu 1.1 mmϕ Winding racetrack Length straight section 255 mm total 358 mm Exciting current no-load 207 A full-load 225 A (PF=0.8 lag)
Cold damper	Material Cu Outer diameter 251 mm Thickness 5 mm Length 568 mm Cooling by vapored He gas at the top end
Warm damper	Material Cu Outer diameter 293 mm Thickness 6 mm Length 513 mm
Armature winding	Inner diameter 336 mm Outer diameter 432 mm Length straight section 250 mm total 600 mm Conductor GLBI glass covered wire 2.7×1.5 mm^2 Widning double layer and lap No. of slots 60 No. of conductor/slot 3×12 No. of serial coils 60 Phase connection $4 \times Y$ Coil pitch $s/t = 12/15$ Cooling forced air