Applied High-Tc Superconducting Electrical Machines

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Abstract – Superconductivity is key technology for 21st century. To suppress emission of green house effect gas, applied superconductivity is important. In this paper, the current status of superconducting power machines such as generatorand motor are described. Most of all studies are the step of demonstration of idea and possibility. There are large gap between physical idea and actual apparatus. Further collaboration between scientists and engineers has been required.

1. Introduction

Use of conventional energy fuels (such as oil, natural gas, and coal) leads to the green house effect that is responsible for global warming, and to the acid rains that greatly damage the agricultural lands. Emissions of different parts of the world to the successively increase in CO_2 concentrations are shown in Fig. 1. Some 160 nations adopted the historic Kyoto Protocol 11 December 1997 at the global warming conference formally known as the Third Conference of Parties to the United Nations Framework Convention on Climate Change (COP3). The draft agreement, which must be ratified by 55 countries, calls on industrialized nations to cut six greenhouse gases (carbon dioxide, methane, nitrous oxide and three fluorine compounds) by average of 5.2 percent between 2008 and 2012. Delegates will again take up the heavily debated issue of emissions trading at the 1998 Buenos Aires climate change conference. Under its terms, 38 developed nations agreed to reduce world-wide emissions. These countries are divided into eight groups, and their "targets" range from a reduction of 8 percent to and increase of 10 percent [1].

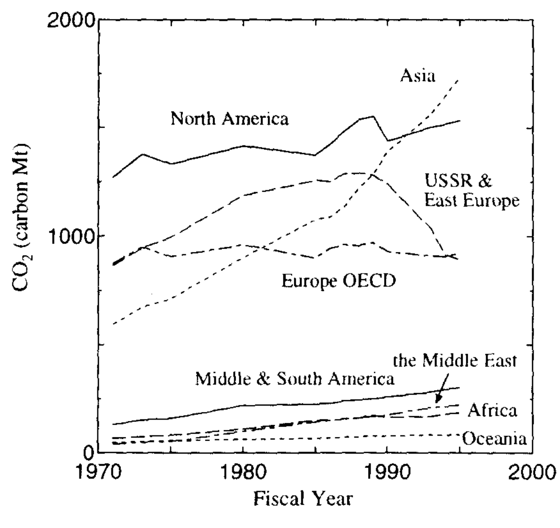

Fig. 1 CO_2 emission of different parts of the world [1].

Table 1 R & D Status of Superconducting Electrical Machines.

apparatus	type	status
generator	homopolar	L=C
	field superconducting	L=C, H=B
	fully superconducting	L=B, H=A
motor	synchronous machine	A∼B
	linear induction	A∼C
	linear synchronous	A∼C
	flux pump	A∼C
phase compensator	synchronous compensator	C

A: basic technology, B: feasibility study, C: practicability verification, L: low temperature superconductor, H: high temperature superconductor

Applied superconductivity is one of solutions to decrease such emissions. There are many applied superconducting apparatus, such as: generator, motor, rotating condenser, transformer, reactor, SMES, power transmission cable, current lead, current limiter, magnetic bearing, magnetic separation, magnetic stirrer, magnetic brake, MRI, magnetic levitation, digital information processing device, milli-submilli-meter wave sensor, magnetic measurement for living body. In this paper the current status of superconducting power machines are summarized as shown in Table 1 especially HTS application [2].

2. Generator

Superconducting AC generators which are being actively studied in various countries have many merits compared with conventional generators, e.g., improvement of efficiency, power system stability and operation performances, and reduction in size and weight, etc. First generator was developed by MIT. Furthermore, France, Russia, China, Japan, Korea and India are promoting the development. In Japan, it has been progressed as a project of the Agency of Instudrial Science and Technology of MITI and the demonstration test of 70 MW generator have been continued as the final stage of 12 years. In Korea, 3 year project of 1 MW geneator has been carred out by Korea Electrotechnology Research Institute. In these researches low temperature superconductor (LTS) was used. Available characteristics of LTS is

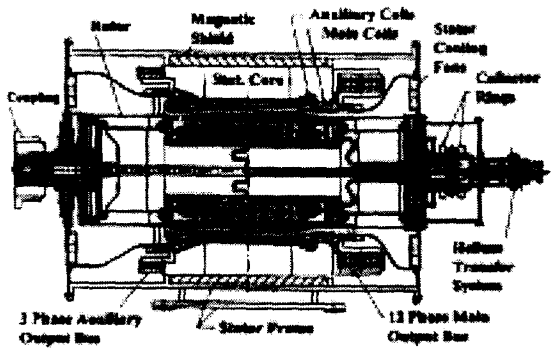

Fig. 2 HTS rotor and stator assembly [3].

not enough to introduce these generators.

GE Corporate Research (U.S.A.) started 100 MVA HTS rotating field winding type synchronous generator, which operated at 16 ~ 25 K from 1993. Its purpose was (1) generator design, element development and evaluation of energy and economics, (2) HTS wire development, prototype saddle shape coil fabrication. This project quitted until development of proper HTS wire.

Westinghouse Science & Technology Center and American Superconductor Corporation present conceptual design of 1 MW generator for Mobile Radar (MR) applications as shown in Fig. 2 [3]. The field winding of generator consists of HTS coils. The cooling of the field winding is provided by heat exchange with helium gas cooled by a Gifford-McMahon cryocooler. Total losses are estimated as 10343 W. This work was supported by the Ballistic Missile Defense Organization and the Air Force Research Laboratory Propulsion Directorate.

Kovalev et al. reported two types of alternators [4]. The first is a synchronous machine containing a stationary field winding made from HTS Bi-based were placed into a cryostat, which is cooled by liquid hydrogen. it may be seen that critical current becomes 10 times higher at LH_2 temperature. This machine provides the output power 3 kVA for rotating speed 12000 rpm. The second alternator is an electrical machine consisting of a conventional three phase stator winding and the rotor is constructed from bulk YBCO elements.

3. Motor

60 % of power demand is from the motor load. The 70 % of motor demand is occupied by large scale motor such as over 350 kW. If one to two percent of the efficiency is increased, it is great energy save for human. The development of small sized motor using bulk material has been domestically progressed by private companies for the golf-cart use. The R&D activities of it have been progressed in Germany, Russia and England.

3.1 Synchronous Motor

There are several type synchronous motor such as HTS field winding, HTS permanent magnet type, reluctance type, and hysterisis type motor.

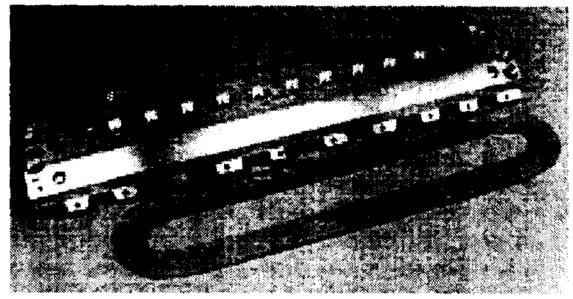

Fig. 3 Photograph of completed subset along with individual subcoil [5].

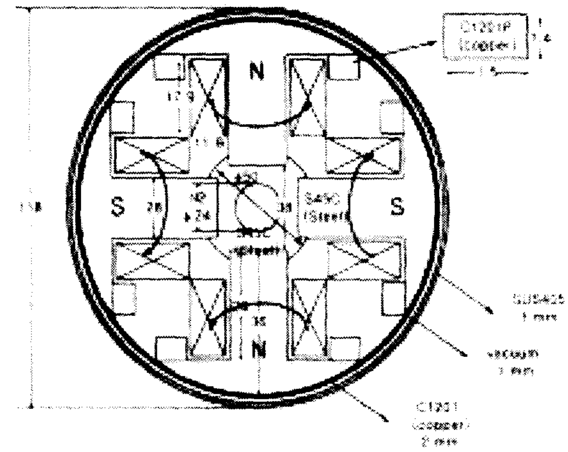

Fig. 4 Cross section of the rotor [7].

Rockwell Automation and Reliance Electric (U. S. A.) studies air core AC synchronous machine with Bi-2223 wire from 1994. It operates at 20 ~ 40 K cooled by closed Brayton cycle cryocooler. In phase II stage, R&D of HTS wire and coil, development of cooling system and verification of 1,000 hp HTS motor [5]. In Fig. 3 the final coil-set is shown. Its operating temperature is 33 K and field winding current is 134 A.

Tampere University of Technology built a HTS synchronous machine of 1.5 kW and 1500 rpm as a first step in an attempt to develop electric machinery for special purposes such as ship propulsion [6]. The working temperature of the SC coils is chosen to 20 K, liquid hydrogen will be used for cooling.

From May 1996, Yonsei University (Korea) performs project of rotating field winding synchronous motor with BSCCO tape rated 220 V and 25 A [7, 8]. The rotor includes liquid nitrogen cryostat. The cross section of the rotor is shown in Fig. 4. Its operating condition were 1800 rpm, 77 ~ 85 K, DC 4 A field current. Its output was 450 W.

The team; Technical University Budapest and University of the Negev reported an experimental HTS synchronous machine [9]. The machine is excited with NdFeB rare-earth permanent magnets on the rotor and BSCCO rod-shaped armature conductors on the stator. The operating temperature is 60 ~ 64 K. The cross-section of the machine is shown in

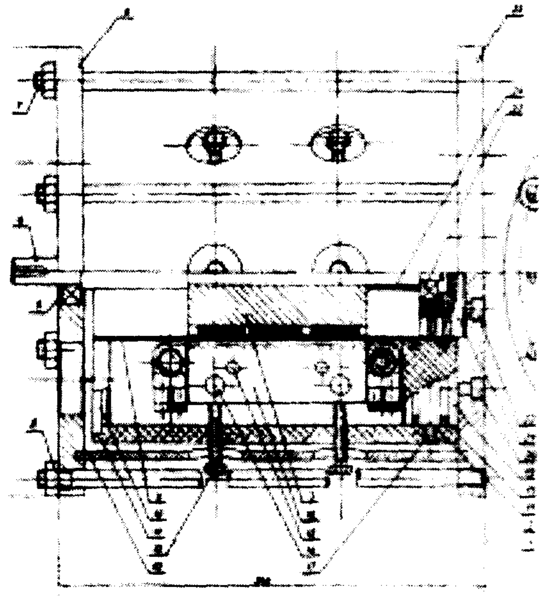

Fig. 5 Longitudinal view of the model machine [9].

Fig. 6 Superconducting 2 pole reluctance motor [10].

Fig. 5, which has 4 poles and 2 symmetrical phases.

Superconducting reluctance motors (2 poles and 4 poles) with YBCO bulk material have been built and tested up to more than 10 kW at 77 K by Oswald Electromotoren GmbH et al. [10] as shown in Fig. 6. Obtained maximum force density of 6 N/cm^2 exceeds the values of conventional asynchronus machines by a factor of four.

A series of two pole hysteresis HTS motors with output power rating from 1 kW (50 Hz) yo 4 kW (400 Hz) was constructed and successfully tested by the cooperation of Moscow State Aviation Institute and Institut für Physikalische Hochtechnologie [11].

A new class of motor/generator utilizes the magnetic flux trapping capability of HTS by J. R. Hull et al. [12]. The rotor consists of a cylindrical shell composed of HTS segments that act as trapped-field magnets, magnetized in such a way that a dipole magnetic filed is produced in the interior of the shell as shown in Fig. 7. The motor is constructed from 32 rectangular Y-Ba-Cu-O parallelepipeds measuring 32 mm × 32 mm × 13 mm and the c-axis in the short dimension. The operating temperature is not fixed.

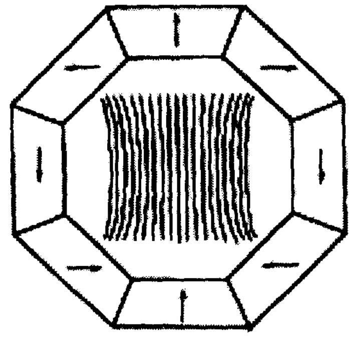

Fig. 7 Calculated flux lines for infinitely long prism of HTS array [12].

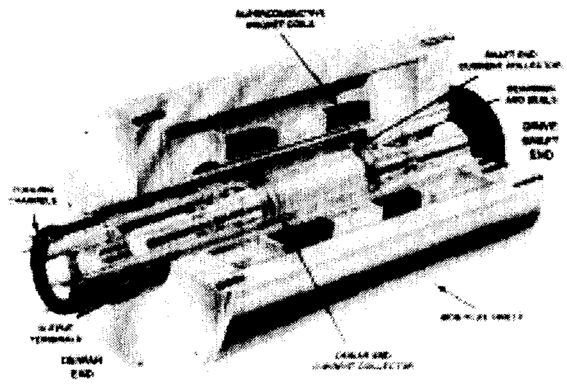

Fig. 8 An illustration of the CD/NSWC motor with a cutaway view of its internal components [14].

3.2 Homopolar Motor

Naval Surface Warfare Center (U.S.A.) started homopolar DC motor project in 1992 [13]. The output power were 122 hp at 28 K (liquid neon) and 320 hp at 4.2 K (liquid helium) with Bi-2223 and Bi-2212. With Bi 2223 HTS wire, the shaft power developed by the dc homopolar motor with its HTS field magnet operating at a temperature of 4.2 K and a current of 120 A was 125 kW as shwon in Fi. 8 [14]. This power was produced with an armature current of 30 kA and a rotational speed of 11700 rpm.

3.3 Brushless DC Motor

There were many prototype reports as shown in Fig. 9 [13]. IRC in Superconductivity starts bulk YBCO permanent magnet type motor project at October 1996. The project purpose is to find the design rule with bulk HTS magnet at 77 K.

4. Superconducting Wire

The specifications of available HTS wire are not enough to apply the system as shown in Table 2 ~ 3. Many effort to develop HTS wire should be done simultaneously with system study. If the J_e = 200 kA/cm^2 (overall J_c) is achieved, the system design will be changed. Y-123 PVD method samples show

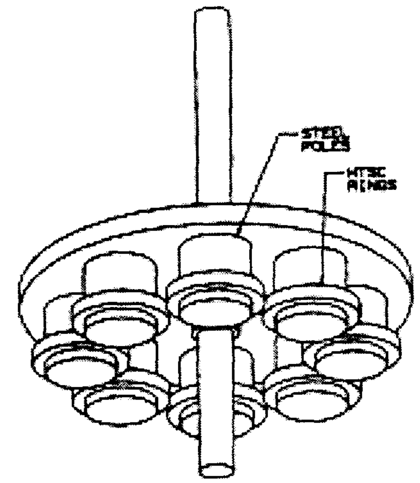

Fig. 9 Rotor of brushless DC trapped flux motor [13].

high J_c such as $J_c = 3,000$ kA/cm^2 for short sample and $J_c = 300$ kA/cm^2 for 1 m length sample.

5. Conclusion

The novel projects on HTS power machine are described. Many projects started in 90th. Almost idea to apply superconducting machines was proposed and demonstrated. It is required a long period to develop system under proper pilots with feasibility study. The collaboration between different field scientists and engineers such as physicist, electric engineer, mechanical engineer and cryogenic engineer has been required.

Table 2 Critical current density J_c of Bi system wire (PIT method).

year	1992	1995	1998
short sample	53.7	69	73.8
100 m class	6.6	27.8	27.8
1000 m class	—	17.7	23.3

unit: kA/cm^2, at 77 K, self field

Table 3 Critical current density J_c of Y system wire (metallic base).

year	1992	1995	1998
short sample	130	1,130	3,000
1 m class	45	160	300

unit: kA/cm^2, at 77 K, self field

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