Development of High Temperature Superconducting Machines

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Since 1990s, high temperature superconducting (HTS) machine techniques have been gradually developed. The developed HTS machines mainly include DC machines, synchronous machines, induction machines, linear machines, reluctance machines, hysteresis machines, and permanent machines. From the beginning of this century, the HTS machines have made rapid developments and significant achievements. HTS motors and generators are summarized in this paper with regard to their developments, advantages and prospect applications.

Key Words: High temperature superconductor, HTS machine, HTS motor, HTS generator.

1. Introduction

Since 1986, the discovery of high temperature superconductors (HTSs) has unfolded the new prospect for the HTS machine practical applications. Early 1987, as an example, American Electric Power Research Institute (EPRI) entrusted Reliance Electric Corp. (REC) to conduct feasibility study of the motors constructed with HTS materials [1]. At the beginning of 1990's, they had successively produced a small HTS DC motor and 2-5 horsepower (hp) HTS synchronous motors [2], [3]. So far, America has already developed a 5 MW (6,500 hp) HTS synchronous motor [4] and 100 MVA HTS synchronous generator [5]. Now, a 36.5 MW (49,000 hp) HTS synchronous motor is being fabricated [6]. Furthermore, a few countries also have developed various HTS machines, such as linear, reluctance, hysteresis, and permanent motors [7]-[19]. This paper introduces those developments respectively, and summarizes the merits and future application prospects of the HTS machines.

2. HTS Motors

2.1 HTS direct current motor

The research focus of HTS machines was on the HTS DC motor in early days, particularly was the homopolar DC motor used for ship propulsion which has the merits to build conventional electric propulsion ships having greater power, lighter weight, smaller size; and creates a solution for construction of a high speed and low noise warship.

Since 1992, EPRI cooperated with REC manufactured a small scale 25 W HTS DC motor [2], the HTS homopolar motor has generated 78 kW (104 hp) and 240 kW (167 hp) of output power with its HTS field winding operated in liquid nitrogen (77 K) and liquid helium (4.2 K), respectively [20].

In 2002, a program was underway at General Atomics (GA) for the Office of Naval Research where a 3.7 MW HTS homopolar DC motor was developed [21], and with projections for 19 MW level. The GA homopolar motor cross-sectional configuration is shown in Fig. 1.

2.2 HTS alternating current motor

With the development of HTS technology and the performance enhancement of HTS materials, as well as the maturity technology of high efficiency power electronics device and the AC speed-adjustment technology of machine, the AC superconducting electric propulsion also becomes attractive. The most common form of HTS AC machines is the HTS synchronous motor.

America, Germany, Korea, and some other countries have developed a series of HTS synchronous motors in different scales, and focused on the large-scale ship propulsion HTS motors. Currently, American Superconductor's 36.5 MW (49,000 hp), 120 rpm HTS ship propulsion motor is under initial component testing and final assembly [6]. In Korea and Japan, HTS squirrel cage induction motors also have been constructed with high starting torque and high efficiency at the same time [10]. Table 1 summarizes the main HTS AC motors developed.

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Table 1. HTS AC motors developed

Contribution	Rated power	Time	Type	Basic parameter	HTS material
America	1.5 kW(2 hp) [3]	1993	Synchronous	2-pole, 3,600 rpm	Multitilamentary BSCCO coil
	3.7 kW(5 hp) [3]	1993	Synchronous	4-pole, 1,800 rpm	Multitilamentary BSCCO coil
	92 kW(125 hp) [22]	1995	Synchronous	4-pole, 1,800 rpm	Multifilamentary Bi-2223/Ag coil
	735 kW(1,000 hp) [23]	2000	Synchronous	4-pole, 1,800 rpm	Multifilamentary BSCCO tape
	3.7 MW(5,000 hp) [24]	2001	Synchronous	4-pole, 1,800 rpm	Multifilamentary BSCCO wire
	5 MW(6,500 hp) [4]	2003	Synchronous	6-pole, 230 rpm	Multifilamentary BSCCO tape
Siemens	400 kW(550 hp) [7]	2001	Synchronous	4-pole, 1,800 rpm	Mg-reinforced Bi-2223/Ag tape
	4 MW(5,500 hp) [8]	2005	Synchronous	2-pole, 3,600 rpm	Bi-2223 tape
Korea	73.5 kW(100 hp) [25]	2002	Synchronous	4-pole, 1,800 rpm	Stainless steel-reinforced Bi-2223 tape
	3 kW(4 hp) [26]	2001	Synchronous	4-pole, 1,800 rpm	Bi-2223/Ag tape
	0.75 kW(1 hp) [10]	2005	Induction	4-pole, 1,710 rpm	Bi-2223 tape
Japan	3.1 kW(4 hp) [27]	2005	Synchronous	8-pole, 720 rpm	Gd-Ba-Cu-O bulk magnet
	1.5 kW (2 hp) [28]	2006	Induction	4-pole, 1,800 rpm	Multifilamentary Bi-2223/Ag tape
Finland	1.5 kW(2 hp) [29]	1997	Synchronous	4-pole, 1,500 rpm	Bi-2223/Ag coil

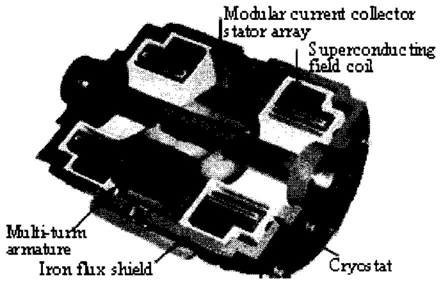

Fig. 1. GA homopolar motor concept model [21]

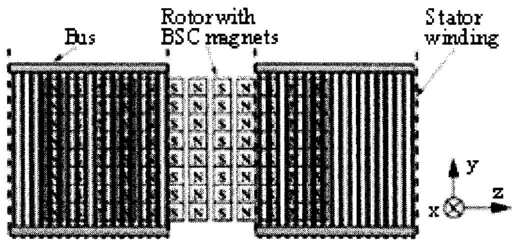

Fig. 2. One motor of the complete LBSCMM [18]

2.3 *HTS linear motor*

Linear motor is a kind of motor that transforms electric energy to mechanical energy directly, and does not need any converter mechanism. With development of HTS technology, HTS wires and bulk materials are gradually applied to the linear motors, and a series of products have been made.

Japan has contributed to the HTS linear motor technology. In 2000, Japanese Waseda University developed a HTS bulk linear synchronous actuator [16] with a single-sided primary and a HTS bulk secondary. Two years after, they fabricated a double-sided and short-secondary type of linear synchronous actuator [17] which has a field-cooled HTS YBCO bulk plate as its secondary.

In 2004, America designed and fabricated a linear bulk superconductor magnet synchronous motor (LBSCMM) with YBCO BSC secondary magnets for an electromagnetic aircraft launch system [18]. The complete motor consists of four independent motors, and each of four motors had closed-loop controlled and supplied by an independent converter. In the case of fault the motor associated with the fault is switched off, and the remaining three motors are sufficient to produce the required thrust of 2 MN to finish the launch process. One of the motors is shown in Fig. 2, where the coordinate z is assumed to be the motion direction.

In 2001, Korea designed a HTS linear synchronous motor with a HTS wire primary [19]. The inductance, the electromotive force constant, and the force constant of the HTS linear motor were much lower than those of the conventional ones, because of small number of turns and high current density of primary windings.

2.4 *Other types of HTS motors*

Other types of HTS motor contain hysteresis, reluctance, and permanent motors. These HTS motors are developed on the basis of the theoretical analysis of electrodynamic and hysteresis properties of the HTS YBCO bulk samples and tape shape Bi-2223/Ag elements. The construction scheme of these types of HTS motors is shown in Fig. 3.

In Russia, Moscow State Aviation Institute (MAI) has designed and built a series of HTS hysteresis, reluctance, and permanent (trapped field) motors [12], [13] with output power rating 5-150 kW by using HTS YBCO bulk and Bi-2223/Ag tape elements. These HTS motors have overall dimensions and specific power up to 3-6 times better compared with the traditional asynchronous motors, and have high power factor.

Other countries liked Japan and China also have designed and fabricated similar HTS motors [14], [15], [30].

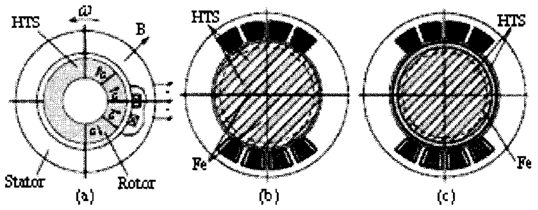

Fig. 3. Schematics of HTS motors [12]: (a) Hysteresis HTS motor, (b) Reluctance HTS motor with compound rotor, (c) Permanent (trapped field) HTS motor

3. HTS Generators

There are different kinds of HTS generators have been developed [5], [9], [11], [31]. In 2004, General Electric (GE), in conjunction with the US Department of Energy, has manufactured and tested of a 100 MVA class HTS demonstrator generator [5]. The rotor of the commercial HTS utility-size generator consists of a cold superconducting field coil, coil supports, and a warm iron core. The iron core concept has significant advantages over air core designs.

In 2003, Australia and New Zealand developed a 2 MW, 20 rpm low-speed and high-torque HTS turbine generator [9]. The design feature is a multi-pole permanent magnet rotor with a single global HTS stator coil having 4 and 6 m diameter for each phase. This concept minimizes the rotor and machine mass, avoids the need to refrigerate rotating HTS components and accommodates the limits in bending strain of HTS tapes.

4. Efficiencies and Applications of HTS Machines

Compared with the conventional machines, HTS machines have a number of advantages, such as smaller size, smaller synchronous reactance, and higher efficiency, especially at partial load, as shown in Fig. 4. The compact size and low weight are highly attractive for electric ship applications. There is a substantial focus worldwide to develop HTS-based synchronous machines for navy/marine applications, and prototypes have been built [4], [8]. Benefits of using HTS machines in ship propulsion systems include reduced weight, reduced volume, reduced noise, better dynamic characteristics, better efficiency, as well as feasibility of innovative sleek hull designs, and increased cargo space [6].

With the development of HTS technology, the costs of HTS wires and cryocoolers will drop significantly, and the HTS current carrying capacity and efficiency of refrigeration will be increased. Consequently the HTS machines will be more attractive and accelerate market penetration; and will be applied to more fields.

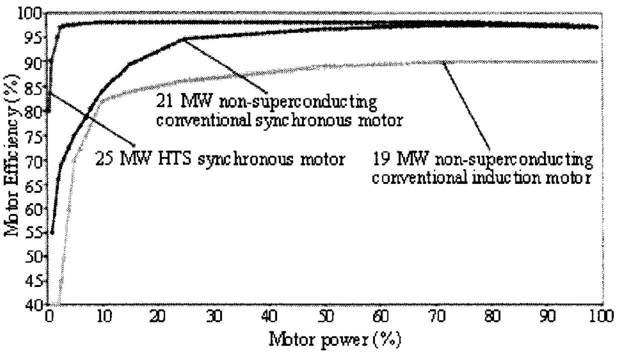

Fig. 4. Higher efficiency at partial load operation [32]

5. Conclusion

Progress on HTS development has opened the door to develop HTS motors and generators with potential competitive cost, high efficiency and reliability, and high probability of acceptance by the end user. The key technologies for development of HTS machines have been essentially proven, and to be sufficiently robust and affordable. With the development and progress of HTS material technology, as well as the realization industrial production of second generation of HTS wires, HTS machines can be more compact, lighter, and efficient than the conventional machines, and will replace the conventional machines in more areas.

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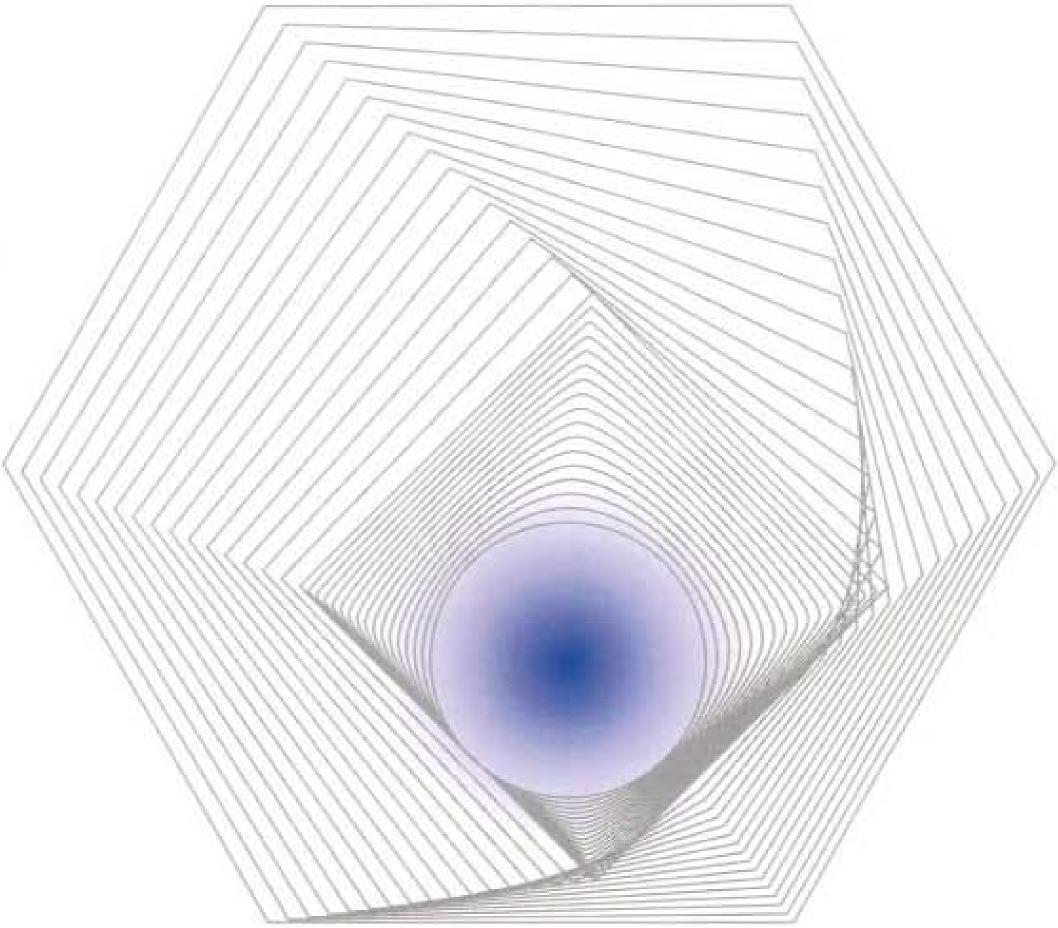

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