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Progress of HTS rotating machine development in Japan

Taketsune Nakamura

Department of Electrical Engineering, Graduate School of Engineering, Kyoto University, Kyoto-Daigaku-Katsura, Nishikyo-Ku, Kyoto 615-8510, Japan

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Abstract-- **This paper describes current status of High Temperature Superconductor (HTS) rotating machinery development in Japan. Recent advances in production technology of HTS materials have continuously stimulated the development of high performance rotating machines. One of the most promising applications for such machines is the ship propulsion, and then some major projects have been underway. Also, energetic challenges for the HTS drive motor, e.g., automobile, have started. Furthermore, low speed and large capacity HTS generators are considered to be exciting candidates for wind turbines. The technology trends of the HTS rotating machines is introduced and discussed in this review paper.**

1. INTRODUCTION

Discovery of High Temperature Superconductor (HTS) has continuously stimulated the practical realization of high performance power application. Rotating machines are surely one of such target applications. Since more than 50% of power demands in Japan come from motor operations, and the efficiency improvement of such electric machines is of crucial issue for the energy-saving as well as the low-carbon society. However, the power of 80% commercialized motor is less than 100 kW. Then, Low Temperature Superconductor (LTS) motors, unfortunately, have been difficult to be realized, because percentage of the cooling cost is relatively large in total system. In other words, the cooling penalty of the refrigeration system for the superconducting motor is one of the most serious drawbacks for the practical realization. Recent advances in the HTS materials development, however, take us to the possible breakthrough for such cooling problems. That is, the large capacity rotating machines are possibly fabricated, and be operated at higher temperature. In this article, technology trends of the HTS rotating machine developments are to be reported and discussed.

2. MERIT OF HTS TECHNOLOGY TO ROTATING MACHINERY

2.1. Expression of power in rotating machine

Power of rotating machine, P, is generally expressed as follows.

$$P \propto AC \cdot B \cdot D^2 L \cdot N \qquad (1)$$

Where, AC and B denote the ampere turns (electric loading) and magnetic loading, respectively. D^2L shows the effective volume of the rotor (D: diameter of the rotor, L: effective length of the rotor), and the term N denotes the rotation speed. That is, if we would like to increase the power with the fixed rotor volume, AC, B, or N should be increased. Determination of AC and B is the key issue for the design of the electric machinery. By using the HTS field windings, we can drastically increase the value of B. Especially, when the value of B overcomes the saturation field of the silicon steel core; such core can be evacuated from the motor, i.e., so-called air-core structure. In this case, we can realize really light weight motor with really low synchronous reactance, except for the enlargement of the stray field. On the other hand, electric loading can also be increased by fabricating the armature windings with the use of HTS materials. It should be noted, however, that such windings experience the AC current and the field, and then the problems of the corresponding AC losses have to be considered.

Among various kinds of the rotating machine, AC synchronous machines have been commonly developed. The mainstream of such machine is the HTS field windings type with copper armature windings.

2.2. HTS materials development

The HTS materials include the structures of wires, bulks, and thin films. HTS wires and/or bulks are wholly introduced for the power applications. With regards to the HTS rotating machines, HTS wires are utilized for the field and/or armature windings, and the HTS bulks are for the field by trapping the interlinked magnetic fluxes in it. The HTS bulks are also introduced as a magnetic shield body in order to obtain the reluctance torque.

In Japan, long length and homogeneous BSCCO wires can easily be purchased from SUMITOMO. Some types of wires can be selected depending upon the application purposes. In Type HT, for instance, the critical current is more than 200 A at 77 K, self-field. Thermal stability of BSCCO wires is good against the overcurrent. Y-system coated conductors have also been started shipping by FUJIKURA, and the performance of such commercialized wires is under rapid improvement. The merits of Y-system wires are the magnetic field dependency of critical current at higher temperature and allowable bending radius. High quality ReBCO bulks can also be purchased in Japan (eg., Nippon Steel Co.).

* Corresponding author: tk_naka@kuee.kyoto-u.ac.jp

3. FUNDAMENTAL STUDY OF HTS ROTATING MACHINERY

3.1. HTS field-windings type

Preliminary design of the HTS generator was firstly reported by Maki and his co-workers [1]. They have shown the potential merit of HTS machines based on the design code of the LTS technology. Followed by their study, Han et al. reported the optimal design results of 70 MW class HTS generator by means of the genetic algorithm and the simulated annealing [2]. Jo et al. analyzed the HTS synchronous machine based on the FEM analysis [3]. Tangible developments of such machines, however, had not been realized.

Recently, ISTEC's project group has developed and tested the HTS motor, 400 V, 6-pole, 7.5 kW, 360 rpm, which introduces the rotating ReBCO field windings [4]. Each field coil is made of 400 m ReBCO tapes, and can generate maximum magnetic field of 0.67 T at 40 K. The cryogenic operation temperature is realized by use of the forced-flow helium gas. They have also started designing the 500 kW class ReBCO motor [5]. Watanabe's group (Central Japan Railway Co.) developed the small-scale claw-pole type HTS motor with the use of Bi-2223 field coils (stator) [6].

3.2. HTS bulks type

HTS bulk can generate large magnetic fluxes in a compact space, and also become an ideal magnetic-shield body. Further, intrinsically persistent current flows in such a bulk body. Then, high performance rotating machines are possibly realized with the aid of the aforementioned property.

With the stimulation of active reports from collaborative research group of Russia and Germany [7, 8], some groups in Japan have carried out the fundamental study on the HTS bulk motor. Ohsaki's group (Univ. of Tokyo) has studied the fractional horsepower HTS synchronous bulk motor by means of experiment and FEM analysis [9-10]. Muta&Nakamura's group (Kyoto Univ.) has also reported the fundamental study results of the HTS bulk motor [11-13]. Hirakawa's group (Central Japan Railway Co.) developed the trapped-flux type 1.5 kW-class HTS bulk motor (600 rpm, 8-pole) [14]. The bulks are cooled to around 30 K by a refrigerator, and the rotation tests were successfully carried out.

4. SHIP PROPULSION

One of the most promising applications of the HTS rotating machine is the ship propulsion. Izumi's joint industry-university research group (Tokyo Univ. of Mar. Sci. Technol., KITANO Seiki Co., etc) has carried out the pioneer works of the HTS bulk propulsion motor. The HTS bulk fields are indirectly cooled by means of condensed neon with a helium GM refrigerator. The structure of their motor is so-called axial-gap type (8-pole, concentrated copper windings), and the target specification is 30 kW at 720 rpm [15]. They have already succeeded in testing at the output power of 25 kW, by enhancing the trapped magnetic flux density at 1.3 T@38 K.

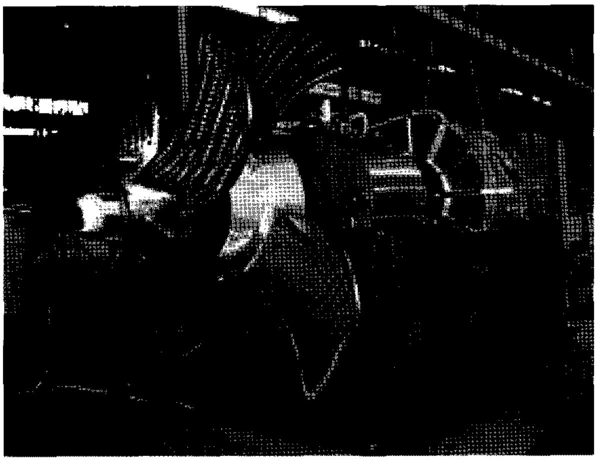

Fig. 1. IHI propulsion system by use of 365 kW class axial-gap type HTS motor (courtesy of IHI Co.).

After that, some groups have energetically started the development of ship propulsion motor with the use of HTS windings. IHI's joint industry-university research group has firstly developed the axial-flux type ship propulsion motor. They have succeeded in development and rotation test of the fully superconducting motor, which has been realized as an HTS motor for the first time in the world [16]. Both of armature and field windings are fabricated by using the DI-BSCCO® pancake coils, and cooled by means of circulated liquid nitrogen. Electromagnetic energy conversion is executed at so-called rotating flux-collector (iron core). This motor is categorized as an inductor-type synchronous motor, and all the HTS components are situated at the stationary part. Followed by the successful rotation test of the above-mentioned motor, the second generation motor (365 kW class) has been developed (Fig. 1) [17]. It should be noted that such motor introduces the permanent magnet field, and only the armature windings are made of DI-BSCCO® windings. Actually, this structure is unique from the point of view of the motor design. That is, the motivation of the development of typical HTS motors is the maximization of the magnetic loading. On the other hand, the motivation of the IHI's motor is the enlargement of the electric loading. Further development has actively been underway.

The joint industry-university research group with the leader of Kawasaki heavy industries has developed the ship propulsion motor system [18]. The project has been supported from New Energy Development Organization (NEDO), and successfully developed 600 kW class ship propulsion motor. Air-core HTS windings were introduced, and copper armature windings was utilized. HTS windings were cooled by the use of the circulated liquid neon, and the rated efficiency at 98.5 % was attained with the inclusion of the cooling penalty of the cryocooler. Kawasaki's group has then updated their contract of NEDO, and further development is underway. Fig. 2 shows a photograph of the developed HTS propulsion motor.

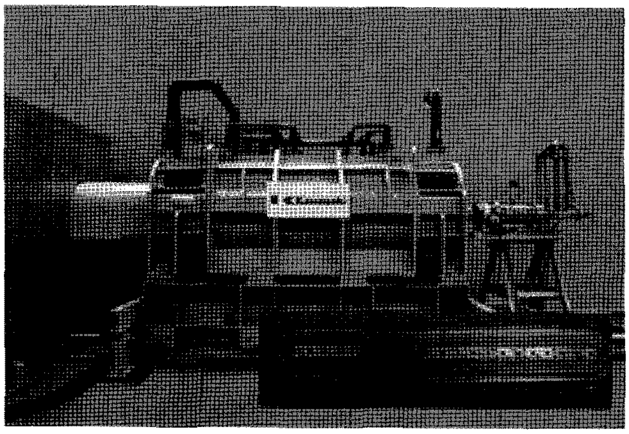

Fig. 2. Kawasaki propulsion system (courtesy of Kawasaki Heavy Industries).

5. OTHER TRANSPORTATION SYSTEMS

One of the major transportation systems is the automobile. Especially, recent advances in hybrid systems in Japan have stimulated the major introduction of the electricity driven automobile. Of course, power capacity of the battery is a big issue for the practical introduction of the Electric Vehicle (EV). Then, the efficient drive motor for the specific variable-speed mode is really important in a limited electric energy of the battery. Although there exists cooling problems, the HTS drive motors for the aforementioned applications are surely one of the possible candidates.

IMRA MATERIAL R&D Co.&Nagoya Univ,'s Research group has developed the DC motor that includes the trapped-flux type HTS bulk field, and incorporated in the golf cart [19]. They could succeed in driving the cart by means of liquid nitrogen as a coolant. Unfortunately, further developments had not been carried out.

Sumitomo Electric Industries has developed the claw-pole type series-connected DC motor, in which the DI-BSCCO® pancake coils are utilized as the fields [20]. Such fields are cooled by use of liquid nitrogen, and the maximum magnetic flux density of the coil is about 2 T. They have been carrying out further development. Fig. 3 shows a photograph of the Sumitomo superconductor car.

Kyoto University & AISIN Seiki's joint industry -university research group has developed the HTS Induction/Synchronous Machine (HTS-ISM) for the purpose of direct drive automobile. Although basic structure of the HTS-ISM is the same as that of the conventional induction motor, not only slip mode but also high efficiency synchronous mode rotation is possible by trapping the interlinked magnetic fluxes in the HTS (zero resistance) cage windings. The existence of the synchronous torque was firstly reported by Cha et al. from the experimental results [21, 22]. And then, Nakamura's group has shown the rotating mechanism based on the analysis and the experiments [23-27]. With this research results, Kyoto&AISIN's group was supported by NEDO, and developed the 20 kW class HTS-ISM drive system, which is directly coupled with the stirling-type refrigerator. AISIN has already succeeded in reaching the cooling penalty (COP) of such refrigerator at 0.075@77 K [28], and then aiming at 0.1. Fig. 4 shows a photograph of the experimental system, in which the fabricated HTS-ISM is cooled in liquid nitrogen as a first step. They have succeeded in rotating the fully superconducting HTS-ISM at 1800 rpm in liquid nitrogen [29].

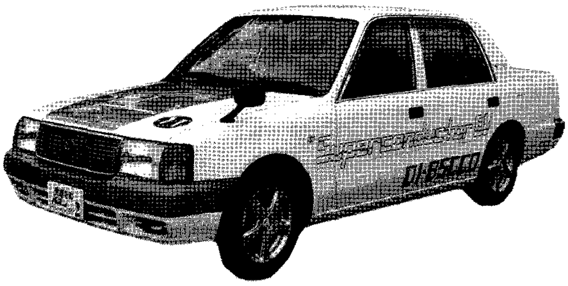

Fig. 3. Trial electric vehicle (EV) having DI-BSCCO® field windings (courtesy of Sumitomo Electric Industries).

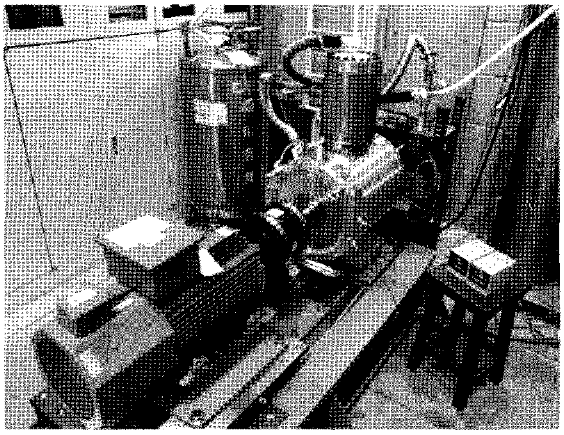

Fig. 4. Experimental system of 20 kW class HTS-ISM drive motor developed by Kyoto Univ.&AISIN SEIKI's joint industry-university research group.

With respect to the HTS electric trains, there are few research reports so far. Konishi and Nakamura's group has studied the effectiveness of introduction of HTS-ISM in DC electric rolling stock [30, 31].

6. WIND GENERATION

The development of HTS machine for the wind generation has just begun. Tsukamoto's group has designed the 10 MW-class wind turbine synchronous generators with HTS field windings [32]. Ohsaki's group has also analyzed the unique structure of the 10 MW class HTS wind turbine generators [33].

7. OTHER APPLICATIONS

Research group of Kyushu Univ., Kyoto Univ., and Hitachi Research Lab. has been developing the superconducting induction/synchronous motor with the use of MgB_2 monofilamentary wires for the liquid hydrogen circulation pump [34]. The MgB_2 wires are supplied from Hitachi, and the MgB_2 motor has mainly been developed at

Kyoto Univ. Kyushu Univ. will develop the MgB_2 liquid hydrogen level meter, and eventually plans to complete the circulation system. This project has been funded by NEDO. Komori's group (Kyushu Inst. of Technol.) has also developed the HTS motor for the purpose of the liquid nitrogen circulation pump [35].

8. SUMMARY

In this article, current status of HTS rotating machine developments is reviewed. Active research projects have also been carried out at Korea, and so the author hopes the effective collaborations between Korea and Japan for the acceleration of practical commercialization.

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