Research on Highly Efficient Regenerative Characteristics of High Temperature Superconductor Induction/Synchronous Motor

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***Abstract*- In this paper discus about a high-temperature superconductor induction/synchronous machine. This motor has the same structure as a conventional induction motor. Replacing secondary windings with HTS windings, however, the HTS-ISM has several intrinsic features, i.e., high torque density and high efficiency. This paper presents regeneration characteristics of s high-temperature superconductor induction /synchronous motor (HTS-ISM) are discussed in this paper. HTS-ISM generates synchronous electric power at rated condition and the corresponding efficiency is more than 90%. It shows the possibility of highly efficient synchronous regeneration performance.**

Index Terms- High temperature superconductor induction/synchronous rotating machine, synchronous regeneration, transportation equipment, electric vehicle, induction motor.

I. INTRODUCTION

Efforts have been made for the development of High Temperature Superconductor (HTS) rotating machines. Transportation equipment is one of the most possible applications of the HTS motors, and recent advances in the HTS ship propulsion motors are really promising. As one of such transportation applications, our project group has carried out the research and development of so-called HTS Induction /Synchronous Motor (HTS-ISM). The motor has the construction of the conventional squirrel-cage induction motor, but the wire is replaced with the HTS wires. Fig. 1 shows the illustration of squirrel-cage secondary windings. In the figure, rotor bars are put in rotor slots and connected to end-rings. Electromotive force (e.m.f.) is induced in the rotor bars, and then the corresponding current is flowed through the end-rings. According to theoretical and experimental studies, the HTSISM has the excellent advantages: coexistence of slip rotation mode and synchronous rotation mode, high efficiency because of synchronous rotation, large starting as well as acceleration torque, high torque density, and robustness against overload .These characteristics are the novel advantages of the HTS-ISM compared with a conventional (normal conducting) motor. In this paper, we investigate the regeneration characteristics of the HTS-ISM under the braking mode.

II. BASIC PRINCIPLE OF HTS-ISM

A. Driving Mode

At one loop about the HTS squirrel-cage secondary windings, electromagnetic phenomenon is expressed by Kirchhoff's voltage law as follows;

$$d\varphi/dt - Ri = 0 \qquad (1)$$

where R is the resistance of the loop,
φ is interrupting magnetic flux, which come from the stator,
i is current flowing through the loop.

Firstly, in stationary state, even if applying the input voltage, the motor doesn't start though rotating magnetic flux will be shielded from the dissipation less rotor windings because of HTS zero resistivity ($R = 0$). Increasing the input voltage and e.m.f., the HTS rotor windings become flux flow (dissipative) state, and then the finite resistance arises. From eq. (1), magnetic flux interlink rotor bars and the driving torque generates due to cross product of the induced current. In this state, the HTS-ISM starts with a slip, s, that is defined as follows;

$$s = (N - Ns)/ Ns \qquad (2)$$

where Ns is synchronous rotation speed and N is rotor rotation speed. Accelerating the HTS-ISM, the induced electric field of the rotor bars is decreasing and then interlinked magnetic flux is trapped when induced current is lower than the critical current. At this stage, the magnetic poles are shaped in the HTS loops by persistent current, and then the motor behaves like a permanent magnet motor. Therefore, the synchronous rotation is realized by means of the interaction between the magnetic poles in the rotor windings and the rotating magnetic field in the air-gap. Actually, the persistent current will be dissipated slightly in the HTS rotor windings. However, our project group have reported that the slip by the dissipation is very small. We should consider this dissipating characteristic in synchronous regeneration.

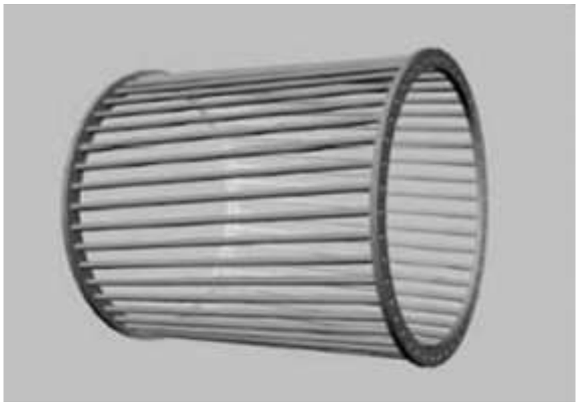

Fig.1.basic sketch of squirrel cage IM

B. Generator Mode

Fig. 2 shows schematic diagram of torque (τ) vs. slip (s) curve of the HTS-ISM, comparing with a conventional induction machine. Conventional induction motor has slip $0 < s < 1$ under driving mode, and slip $1 < s < 0$ under generator mode. In other words, the motor rotates over synchronous speed under generator mode.

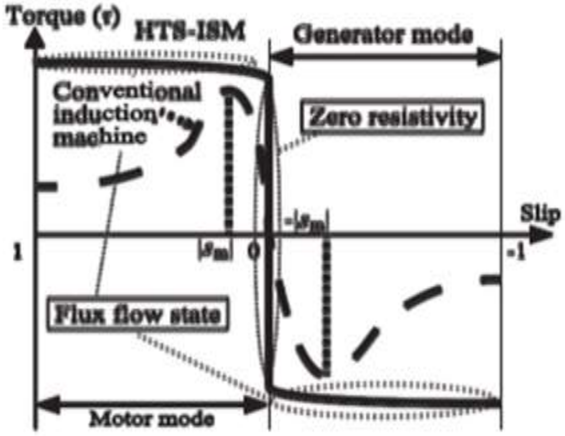

Fig.2. schematic diagram of torque vs slip.

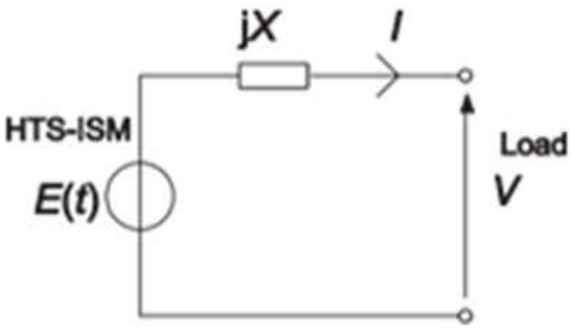

Fig.3. Thevenins equivalent circuit at synchronous mode

On the other hand, the HTS-ISM is operated in the motor and generator mode at synchronous speed ($s = 0$) on steady state. Namely, the HTS-ISM will be possible to generate negative torque and realize regeneration in the synchronous mode according to reversibility with driving mode. Fig. 3 illustrates Thevenin s equivalent circuit of the HTS-ISM in the synchronous rotation mode. E(t) in Fig. 3 is the equivalent voltage source by the equivalent pole obtained in the dissipation less HTS rotor windings. While the stator is fed, E(t) is constant be- cause the spatial distribution of the persistent current in the HTS rotor windings do not change. By contract, once not being fed, E(t) will decline due to the existing resistance in the windings. Therefore, the clarification of such decreasing characteristics is crucial in order to develop the regeneration control code.

III. STRUCTURE OF HTS-ISM

At this section. Fig. 4 shows a typical curve of the electric field (E) vs. current (I) property at 77 K (boiling point of atmospheric liquid nitrogen).

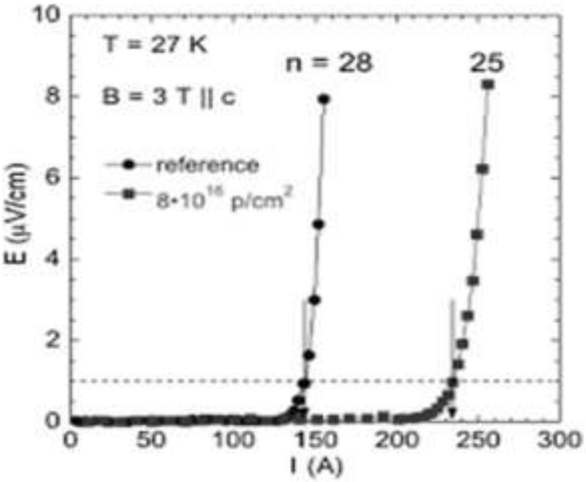

Fig.4. curve between electric field vs current.

Superconducting electric machines typically have the following advantages:

1. Reduced resistive losses but only in the rotor electromagnet.
2. Reduced size and weight per power capacity without considering the refrigeration equipment.

There are also the following disadvantages:

1. The cost, size, weight, and complications of the cooling system.
2. A sudden decrease or elimination of motor or generator action if the superconductors leave their superconductive state.
3. 3.A greater tendency for rotor speed instability. A superconducting rotor does not have the inherent damping of a conventional rotor. Its speed may hunt or oscillate around its synchronous speed.
4. Motor bearings need to be able to withstand cold or need to be insulated from the cold rotor.
5. As a synchronous motor, electronic control is essential for practical operation. Electronic control introduces expensive harmonic loss in the super cooled rotor electromagnet.

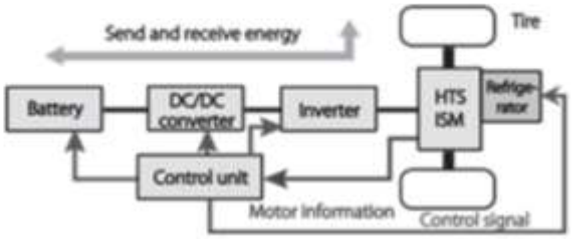

Fig.5. Concept diagram of direct drive electric vehicle equipped with the HTS-ISM.

Fig. 5 shows our concept diagram of direct drive electric vehicle equipped with the HTS-ISM. We assume the HTS-ISM is fed by a battery through converter and inverter. On the other hand, the electric power at the braking mode is re-charged to the battery through inverter and converter, and then it will be possible to improve the efficiency of the power-train system.

Fig.6.Image of HTS rotor

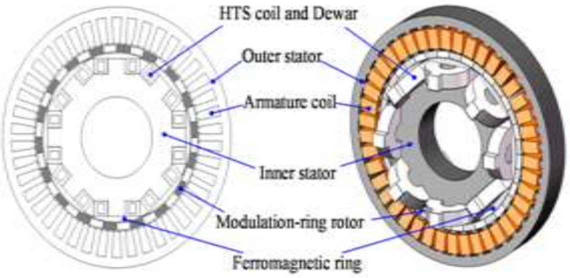

Fig.6.Stator of HTS

The structure of the rotor is the same as the conventional squirrel-cage windings, but the material are different. A rotor bar is made of eleven bundled BSCCO tapes and cupper bar for protection. A The stator windings are made of cupper, and so-called distributed winding technique is adopted to the stator in order to decrease spatial harmonics of magnetic flux in the air-gap.

Fig. 7 shows a wiring diagram of the HTS. Input power come from a step-up transformer (200 V/400 V), and is fed to the HTS-ISM through PWM (Pulse Width Modulation) inverter. The HTS-ISM is connected mechanically to the 30 kW class load motor. The load motor plays roles not only on applying mechanical load, but also on giving mechanical input, so the HTS-ISM can operate on regeneration mode. The HTS-ISM is located at a right far side and the load motor is located at a left near side. Measured values on primary circuit are obtained by 3-phase power-meter. Rotation speed and torque are measured by an optical tachometer and a contactless torque transducer, respectively. All tests are conducted on condition that the HTS- ISM is immersed in liquid nitrogen at 77 K.

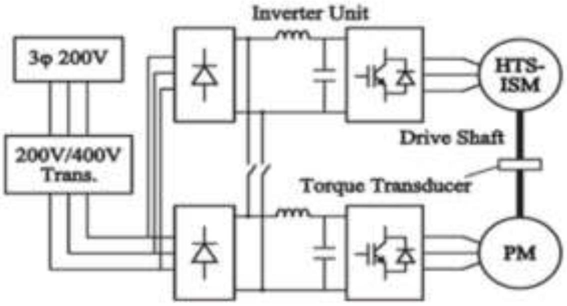

Fig.7.Wiring diagram of HTS

IV. RESULTS

Firstly, the load motor is operated at synchronous speed of the HTS-ISM, 1800 rpm, and then the HTS-

ISM is excited at rated voltage, 200 V & frequency, 60 Hz. After that, the input Firstly, the load motor is operated at synchronous speed of the HTS-ISM, 1800 rpm, and then the HTS-ISM is excited at rated voltage, 200 V & frequency, 60 Hz. After that, the input torque is given to the HTS-ISM by decreasing input frequency little by little. The same test is also conducted for different synchronous speeds, i.e., 1200 rpm and 600 rpm. Fig. 8 presents the efficiency vs. electrical output (generation) characteristics, of which include mechanical loss. The cycloid behavior in the figure shows the transient phenomenon by the discrete change of the input frequency. The regeneration efficiency reaches over 90% at wide output range. The highest efficiency is 94% at the rated output (20 kW@1800 rpm), and the corresponding slip is about 2* 10–3 Therefore, the HTS-ISM could regenerate efficiently with small slip. It should be noted that the efficiency has a tendency to improve as decreasing the rotational speed, especially in lower output region, and this is because of the smaller reactive power.

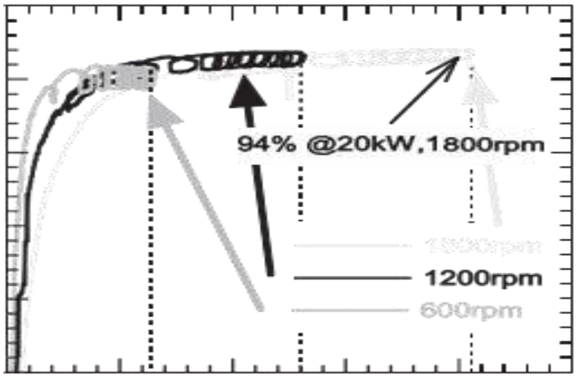

Fig.8.Efficiency vs electrical output

V.CONCLUSION

This paper presents the regeneration characteristics of High Temperature Superconducting Induction/Synchronous Motor, of which our project group has been researched and developed. On the steady state, it is possible to realize highly efficient synchronous regeneration according to experimental and analytical results.

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