Superconductivity and Cryogenics
Vol.11, No.2, (2009), pp.33~36

Test Result Analysis of a 1 MW HTS Motor for Industry Application

S. K. Baik[1,*], Y. K. Kwon[1], H. M. Kim[1], E. Y. Lee[1], Y. C. Kim[2], H. J. Park[2], W. S. Kwon[2], and G. S. Park[3]

[1]Superconductivity Research Center, KERI, P.O.BOX 20, Chang Won, Korea
[2]Doosan Heavy Industries & Construction, 555 Gwigok-Dong, Chang Won, Korea
[3]Pusan National University, 30 Jangjeon-Dong, Busan, Korea

Received 30 July 2008; accepted 7 May 2009

Abstract-- **A 1 MW class HTS (High-Temperature Superconducting) synchronous motor has been developed. This motor is aimed to be utilized for industrial application such as large motors operating in large plants. The HTS field coil of the developed motor is cooled by way of neon thermosiphon mechanism and the stator (armature) coil is cooled by water through hollow copper conductor. This paper also describes evaluation of some electrical parameters from performance test results of our motor, which was conducted at steady state in generator mode and motor mode. Open and short circuit tests were conducted in generator mode while a 1.1 MW rated induction machine was rotating the HTS machine. Electrical parameters such as mutual inductance and synchronous inductance are deduced from these tests. Load test was done upto rating torque during motor mode and efficiency was measured at each load torque.**

1. INTRODUCTION

A 1 MW class superconducting motor with HTS field coil is considered to design and analysis. This motor has the rotating speed with 3600 rpm, which is aimed for industrial applications such as blowers, pumps and compressors installed in large plants. The superconducting synchronous motor is over 2 times smaller than an ordinary induction motor even though it is constructed without iron-core. Therefore, it can have small synchronous reactance that results in higher steady-state stability. The developed HTS synchronous motor is composed of Bi-2223 HTS field coil and aimed for industrial application such as large motors in large plants. The major specification is shown in Table I and Fig. 1 shows the construction of the developed 1 MW HTS Synchronous Motor [1].

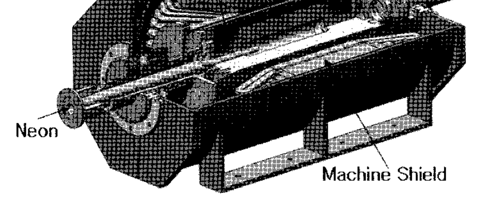

Fig. 1. Construction of the developed 1 MW HTS synchronous Motor.

TABLE I
SPECIFICATION OF 1 MW HTS MACHINE.

Rating Capacity	1 MW
Rotating Speed	3600 rpm
Frequency	60 Hz
Poles	2
Armature Terminal Voltage	3300 V
Power Factor	1.0
Synchronous Reactance	0.13 p.u
Field Coil Current	150 A
Field Coil Operating Temperature	30 ~ 35 K
Field Coil Turns	3348
Armature Slots	36
Armature Coil Turns	48 turns/phase
Axial Length × Height	2.4 × 1.2 m

2. PERFORMANCE TEST RESULTS OF A 1 MW HTS SYNCHRONOUS MOTOR

2.1. Cool-down and Excitation of HTS Field Coil

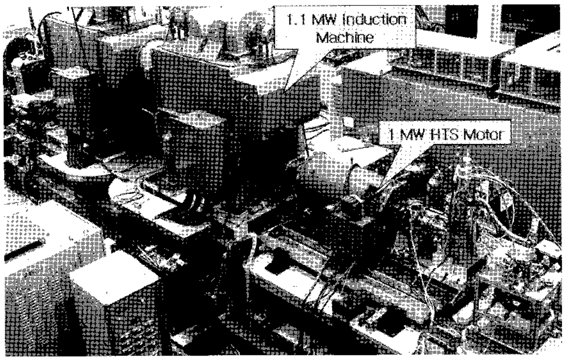

Fig. 2. The developed 1 MW HTS synchronous motor during load test.

Fig. 2 shows the developed 1 MW HTS Synchronous Motor coupled to 1.1 MW induction machine for load test. In order to cool HTS field coil down to 30 ~ 35 K operating temperature, neon gas is liquefied by cryo-cooling system coupled to rotor and flows down to inside of HTS field coil shaft via gravity [3]. The field coil is cooled not directly by liquid neon but indirectly by conduction cooling mechanism through coil shaft. At the first time it took 200 hours to cool down to operating temperature only with neon as a coolant. In order to reduce cooling time nitrogen was used at the first stage of cool-down.

---

* Corresponding author: skbaik@keri.re.kr

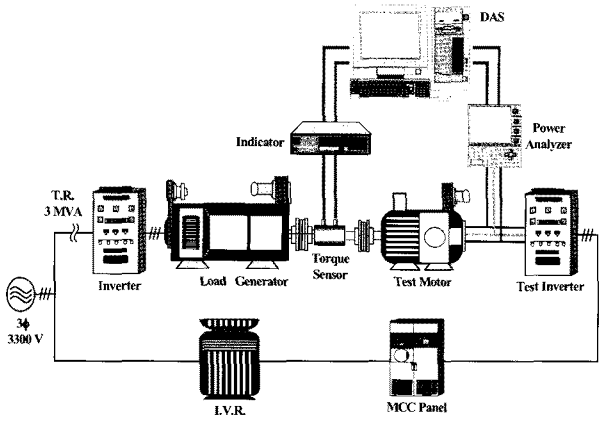

Fig. 3. Test setup of the developed 1 MW HTS synchronous motor.

Fig. 3 shows total test setup diagram of the developed 1 MW HTS synchronous motor (Test Motor). The load generator is an induction machine which acts as a driving motor while generated voltage measurement test and an induction generator while the HTS synchronous machine runs as a motor.

Fig. 4 shows the cool-down curves obtained from an experiment by using two kinds of gas. Until 55 hours from cool-down start, rotor had been cooled down to about 90 K by nitrogen and then nitrogen gas was evacuated out of the rotor by vacuum pump. After 56 hours had passed neon gas was used to cool down to HTS field coil operating temperature. It took about 78 hours totally with this two gas cooling method, so we could reduce the cooling time more than half compared with one gas cooling method.

Fig. 5 shows HTS field coil excitation and temperature variation profiles while it was excited up to 150 A operating current. After cool-down was completed upper part temperature of the field coil was 36 K and bottom part was 28 K. During 150 A excitation upper part temperature increased 1.5 K and bottom part 2.2 K. During each current steps of 30 A, 60 A, 90 A, 110 A, 130 A and 150 A, generated voltages were measured at 600 rpm, 1200 rpm and 1800 rpm rotating speeds while the HTS motor was being driven by the induction machine.

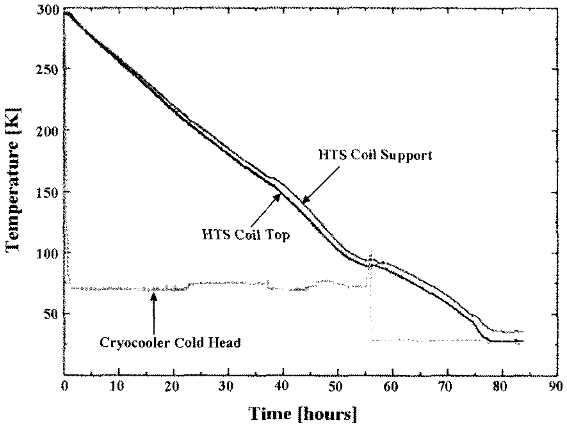

Fig. 4. Rotor cool-down curves of 1MW class HTS motor.

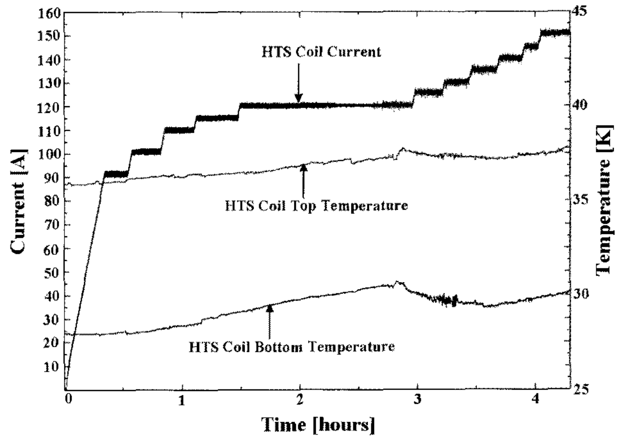

Fig. 5. Field coil current and temperature variation.

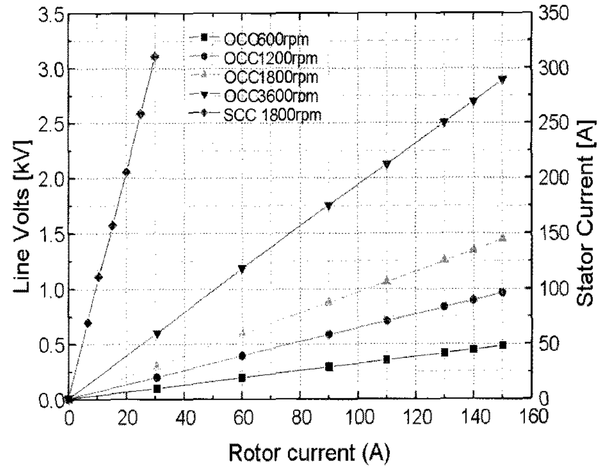

Fig. 6. Open and short circuit characteristics test result.

2.2. No Load Test Result

Fig. 6 shows generated voltage with the stator coil open-circuited (OCC) and current with the stator coil short-circuited (SCC) while the HTS motor was rotating. The OCC curve is straight due to air-cored structure of this HTS motor and the generated voltages are exactly proportional to rotating speed and excitation current of field coil. As shown in Fig. 8 the generated voltage wave forms are so sinusoidal originated from iron toothless structure.

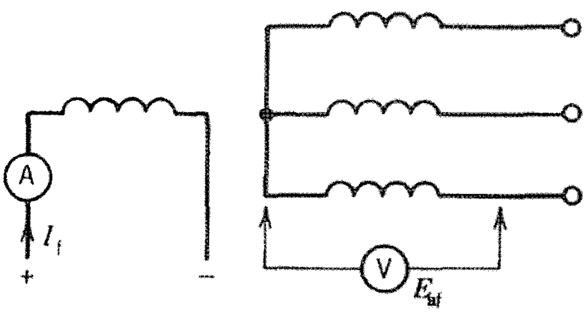

Fig. 7. Circuit for armature open circuit test.

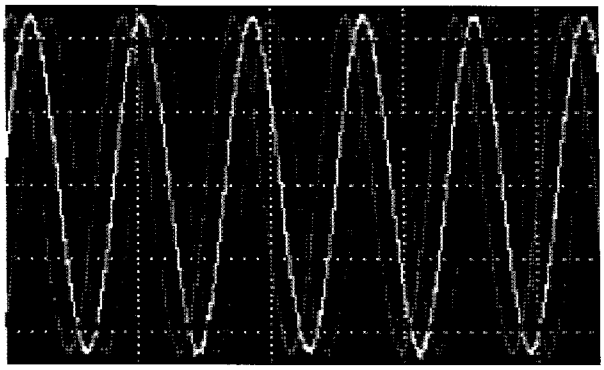

Fig. 8. Measured armature open circuit voltage waveforms.

$$E_{af} = \frac{\omega L_{af} I_f}{\sqrt{2}} \quad (1)$$

Where, E_{af} is generated(excitation) voltage per phase during OCC test.
ω is angular frequency.
L_{af} is peak value of stator and field coil mutual inductance.
I_f is field coil current.

The armature open circuit voltage was measured at several rotor speeds up to 1800 rpm, the half of 3600 rpm rating speed, and field currents up to the rating current of 150 A. Due to vibration problem of the dynamo system coupled to the HTS machine, it was not possible to do test at 3600 rpm rating speed. The results are shown as OCC (Open Circuit Characteristics) curves in Fig. 6 at each different field current and rotor speed. The open circuit voltages shown in Fig. 6 are three phase line-to-line terminal voltage (Root Mean Square(RMS) value) that is $\sqrt{3}$ times of the armature phase voltage (RMS value), E_{af}, shown in Fig. 7. This voltage is also called "excitation voltage" and directly proportional to the rotor speed (angular frequency, ω) because the time variation of the armature coil flux linkage by the field coil excitation is directly proportional to the rotor speed. Other parameters to decide the excitation voltage are mutual inductance between the field and the armature coils and the field current, I_f, by the relation of the equation (1). In case of the conventional iron-cored synchronous machine, the open circuit voltage is saturated due to magnetic saturation of iron-core as the field current increases. However, the developed 1 MW machine shows non-saturated (straight) OCC curves as shown in Fig. 6 because no ferro-magnetic material (iron) is used for the rotor and the armature teeth [4]. Moreover, the measured waveforms of open circuit voltages are sinusoidal as shown in Fig. 8 because there are non-magnetic FRP (Fiber Reinforced Plastic) armature teeth instead of iron teeth to support the armature coils.

From the OCC test result, the maximum mutual inductance between the armature and the field coils can be calculated from the equation (1), which is 41.74 mH and almost same with a calculated value, 43.24 mH, from 3 dimensional Finite Element Analysis [6].

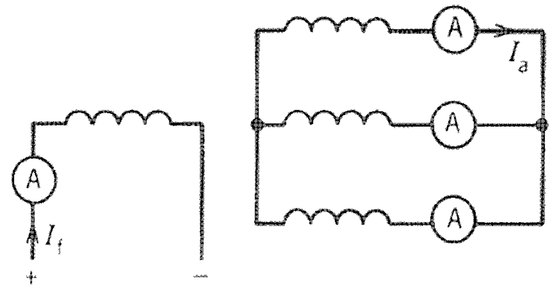

Fig. 9. Circuit for armature short circuit test.

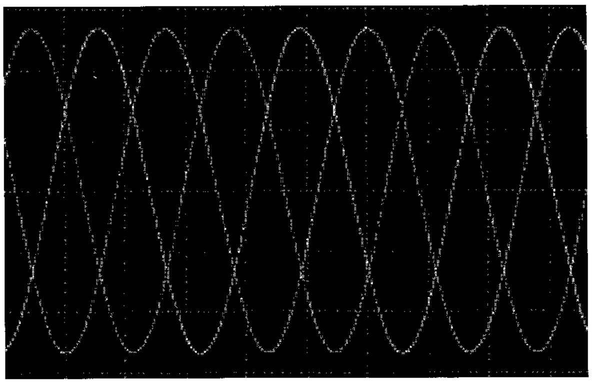

Fig. 10. Measured armature short circuit current waveforms.

$$I_a = \frac{E_{af}}{\sqrt{R_{ph}^2 + X_s^2}} \quad (2)$$

Where, I_a is the armature coil short circuit current during SCC test.
E_{af} is the excitation voltage per phase during SCC test.
R_{ph} is armature coil resistance per phase.
X_s is synchronous reactance.

The armature short circuit current was measured at 1800 rpm, the half of 3600 rpm rating speed, and several field currents up to 30 A. The result is also shown as SCC (Short Circuit Characteristics) curve in Fig. 6 at each different field current and very sinusoidal short circuit current waveforms are also measured by an oscilloscope as shown in Fig. 10. The armature short circuit current is related with other parameters as equation (2). The armature open circuit voltage, E_{af}, is 173.6 V per phase measured from OCC test and the short circuit current, I_a, is 310.8 A measured from the SCC test at the same field current of 30 A and rotor speed of 1800 rpm. The armature coil resistance per phase, R_{ph}, is 0.0965 Ω measured at 20℃. By using these parameters synchronous reactance, X_s, could be calculated to 0.5502 Ω at 1800 rpm from equation (2). As a result synchronous inductance, L_s, can be calculated from the equation (3), which is 2.92 mH. Therefore, synchronous reactance at the rating speed of 3600 rpm is 1.1008 Ω calculated from the equation (3) by substitution of 2 times of the angular frequency, ω, at 1800 rpm [4].

$$L_s = \frac{X_s}{\omega} \tag{3}$$

Where, L_s is synchronous inductance.

2.3. Load Test Result

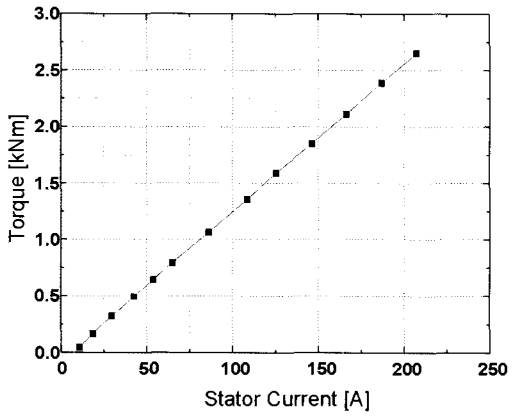

Fig. 11. Generated torque according to stator Current at 1800 rpm.

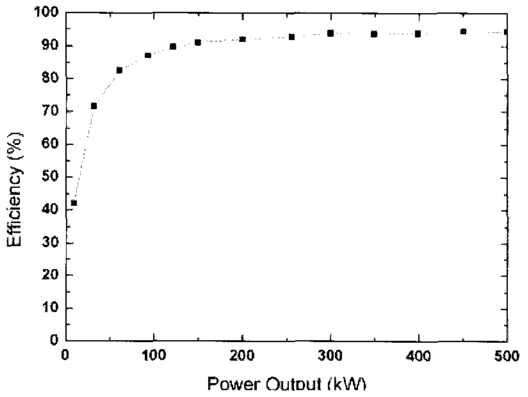

Fig. 12. Efficiency variation according to applied load at 1800 rpm.

Fig. 11 shows stator current versus generated torque when mechanical load is applied by the coupled induction machine. During this test HTS motor was rotating at 1800 rpm by an adjustable speed drive and generated rating torque of 2650 Nm. Fig. 12 shows efficiency variation at partial loads during load test at 1800 rpm. The output powers are calculated from the measured torques multiplied by the angular frequency, 188.5 rad/sec, at 1800 rpm rotating speed. It is confirmed that the HTS motor shows high efficiency even at small loads on the contrary of conventional motor having low efficiency at small load. This result comes from the fact that the conventional synchronous motor has the same field coil excitation I^2R loss regardless of power output, so this loss becomes relatively larger and reduces largely the efficiency of the conventional motor at small load situation. We could not test at 3600 rpm rating speed due to vibration problem, but it is expected that the developed HTS motor will show higher efficiency than 1800 rpm test result.

3. CONCLUSION

A 1 MW HTS synchronous motor has been developed. In this paper the influence of a major electrical parameter, synchronous reactance, was analyzed based on equivalent circuit model of synchronous machine. The developed HTS synchronous motor has small synchronous reactance, 0.13 p.u, so it can stand instant applied torque as large as 5 times of conventional synchronous with larger synchronous reactance. By using FEM tool inductance and Lorentz force were calculated 3 dimensionally. We figured out a support structure is necessary to endure strong magnetic stress generated at the HTS field coil.

The HTS field coil of the developed motor could be cooled down to 30~35 K by cryo-cooler with nitrogen and neon as coolant. The cooling time could be reduced to one third of only neon cooling method by using two kinds of gas. After cool-down the HTS field coil could be excited up to 150 A of rating current, which could be maintained during load test. Through OCC and SCC test synchronous reactance and mutual inductance could be calculated, which are close to the design data. Due to vibration problem we could not rotate the motor at 3600 rpm for load test, but could apply rated load torque and measure efficiency at 1800 rpm.

ACKNOWLEDGMENT

This research was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Education, Science and Technology, Republic of Korea.

REFERENCES

[1] Seung-Kyu Baik, Myung-Hwan Sohn, Eun-Yong Lee, Young-Kil Kwon, Tae-Sun Moon, Heui-Joo Park, Yeong-Chun Kim, “Design of Water-cooled 1MW HTS Synchronous Motor,” *Journal of the Korea Institute of Applied Superconductivity and Cryogenics*, vol. 3, pp. 21-28, 2005.

[2] Ji-Young Lee, Sung-Il Kim, Jung-Pyo Hong, Young-Sik Jo, Myung-Hwan Sohn, Seung-Kyu Baik, Young-Kil Kwon, “Optimal Design of Superconducting Motor to Improve Power Density Using 3D EMCN and Response Surface Methodology,” *IEEE Trans. on Appl. Supercond.*, vol. 2, pp. 1819-1822, 2006.

[3] M. Frank, J. Frauenhofer, P. van Hasselt, W. Nick, H.-W. Neumueller, G. Nerowski, “Long-Term Operational Experience With First Siemens 400 kW HTS Machine in Diverse Configurations,” *IEEE Trans. on Appl. Supercond.*, vol. 2, pp. 2120-2123, 2003.

[4] A. E. Fitzgerald, Charles Kingsley, Jr., Stephen D. Umans, *ELECTRIC MACHINERY*, McGRAW-HILL, pp. 216-259, 1991.

[5] The Institute of Electrical and Electronics Engineers, Inc., *IEEE Guide: Test Procedures for Synchronous Machines*, pp.27-38, 1995.

[6] S. K. Baik, Y. K. Kwon, H. M. Kim, E. Y. Lee, J. D. Lee, Y. C. Kim, T. S. Moon, H. J. Park, C. H. Lee, W. S. Kwon, “Excitation Voltage Estimation of HTS Motor via Magnetic Energy Calculation,” *Proceedings of the 39th Korean Institute of Electrical Engineers Summer Conference*, pp. 870–871, 2008.