Loss analysis of a 1 MW class HTS synchronous motor

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Abstract. The HTS (High-Temperature Superconducting) synchronous motor has advantages over the conventional synchronous motor such as smaller size and higher efficiency. Higher efficiency is due to smaller loss than the conventional motor, so it is important to do loss analysis in order to develop a machine with higher efficiency. This paper deals with machine losses those are dissipated in each part of a HTS synchronous motor. These losses are analyzed theoretically and compared with loss data obtained from experimental results of a 1 MW class HTS synchronous motor. Each machine loss is measured based on IEEE 115 standard and the results are analyzed and considered based on the manufacturing of the test machine.

1. Introduction
A 1 MW class superconducting synchronous rotating machine with HTS field coil is considered for test and analysis. This machine was designed to have the rotating speed with 3600 rpm that is the ordinary speed of turbine generator and industrial motors applied to blowers, pumps and compressors installed in large plants. The developed HTS synchronous machine has been tested while connected to a driving and load induction machine with 1.1 MW rating. As the first step to a synchronous rotating machine test, the object 1 MW HTS motor has been rotated by the driving induction motor while the three phase armature (stator) coils are open-circuited and short-circuited at the terminal. Through armature open circuit test, excitation voltage was measured at different field current and rotor speed. This excitation voltage is induced at the armature coils of a synchronous rotating machine by rotating magnetic field of the field coil and does an important role in output characteristics of a synchronous rotating machine. During this test open-circuit losses had been measured at each test condition and open-circuit core losses were derived from them. Through armature short circuit test, short-circuit losses had been measured at each test condition and stray load loss was derived from them. These two tests are basic tests as generator operation of a synchronous machine without any connected electrical load. After these two tests, the object HTS machine was driven by an inverter and the efficiency as a motor was measured under several load conditions applied by the 1.1 MW induction machine operated as a generator.
2. The object 1 MW class HTS synchronous motor
The developed HTS synchronous machine is composed of Bi-2223 HTS field coils cooled by conduction heat transfer of liquid neon and copper armature coils cooled by water passing through them. The Figure 1 shows the construction of the developed 1 MW HTS synchronous machine and the Table 1 shows the major specifications.

![Construction of the developed 1 MW HTS synchronous machine](image)

Liquid neon is supplied from outside of the rotor through a long stainless steel pipe connected to a cold head of a GM cryocooler which liquefies gas neon evaporated from inside of the rotor. This 2 phase closed loop cooling mechanism is called thermosiphon that has been applied to several HTS motors developed worldwide [1] [2].

Table 1. Major specifications of the object 1 MW HTS synchronous motor

|                            |       |
|-----------------------------|-------|
| 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 |
3. Armature open and short circuit test
As a basic test of a synchronous machine, the object 1 MW HTS machine has been rotated by a 1.1 MW induction machine shown in Figure 2 while the three phase armature coils open- and short-circuited as shown in Figure 3 and Figure 4. During these two tests called “Armature Open Circuit Test” and “Armature Short Circuit Test”, the open circuit voltage, $E_{af}$, and the short circuit current, $I_a$, were measured while the 1 MW HTS machine was operating as a generator driven by the dynamo 1.1 MW induction machine [3].

The armature open circuit voltage was measured at various 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 impossible to do tests at 3600 rpm rating speed. The results are shown as OCC (Open Circuit Characteristics) curves in Figure 5 at each different field current and rotor speed. The open circuit voltage in Figure 5 is 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 Figure 3. This voltage is also called “excitation voltage” and directly proportional to the rotor speed (angular frequency, $\omega$) 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 Figure 5 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 Figure 6 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 [5].

\[ E_{af} = \frac{\omega L_{af} I_f}{\sqrt{2}} \]  

(1)

Where, \( \omega \) is the angular frequency in rad/sec  
\( I_f \) is field coil current  
\( L_{af} \) is maximum mutual inductance between field and armature coils

**Figure 5.** Armature open circuit (OCC) and short circuit (SCC) test result

**Figure 6.** Measured armature open circuit voltage waveforms

**Figure 7.** Measured armature short circuit current waveforms
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 Figure 5 at each different field current and very sinusoidal short circuit current waveforms are also measured by an oscilloscope as shown in Figure 7. The armature short circuit current is related with other parameters as the 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 with the same field current of 30 A and rotor speed of 1800 rpm and the armature coil resistance per phase, $R_{ph}$, is 0.0965 Ω measured at 20°C. By using these parameters the synchronous reactance, $X_s$, is 0.5502 Ω at 1800 rpm, so the synchronous inductance, $L_s$, can be calculated from the equation (3), which is 2.92 mH and the 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, $\omega$, at 1800 rpm [4].

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

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

$$L_s = \frac{X_s}{\omega} \quad (3)$$

4. Open circuit core loss

| Field Current [A] | Open Circuit Loss (HTS Machine Input Power) [kW] | Core Loss [kW] |
|-------------------|----------------------------------------------|----------------|
|                   | 600 rpm 1200 rpm 1800 rpm                   | 600 rpm 1200 rpm 1800 rpm |
| 0                 | 0.346   0.702   1.027                      | 0   0   0 |
| 30                | 0.348   0.856   1.491                      | 0.002 0.154 0.464 |
| 60                | 0.614   1.656   3.114                      | 0.268 0.954 2.087 |
| 90                | 0.908   2.708   5.414                      | 0.562 2.006 4.387 |
| 110               | 1.12    3.638   7.344                      | 0.774 2.936 6.317 |
| 130               | 1.419   4.714   9.6                        | 1.073 4.012 8.573 |
| 140               | 1.597   5.329   10.916                     | 1.251 4.627 9.889 |
| 150               | 1.817   6.107   12.492                     | 1.471 5.405 11.465 |
During the open circuit test, input power to the HTS machine was measured at each field current and rotating speed as shown in Table 2. Core loss of a synchronous machine is generated at armature iron core by alternating magnetic field due to rotating magnetic field of rotor, which consists of hysteresis and eddy-current losses. In case of superconducting synchronous machine, core loss is generated at the machine shield stacked with silicon steel sheet. The open circuit loss at 0 A field current (with zero excitation) is generated by windage and friction loss due to rotation, so the core loss shown in Table 2 is calculated by subtracting this loss at 0 A field current from the open circuit loss. Figure 8 shows the core loss according to line-to-line armature terminal voltage [3].

![Figure 8. Core loss curves from open circuit test](image)

5. Short circuit loss and stray load loss

| Field Current [A] | Armature Current [A] | Armature Coil Temperature (Coil Center) [°C] | HTS Machine Input Power [kW] | Short Circuit Loss [kW] |
|-------------------|----------------------|---------------------------------------------|-----------------------------|------------------------|
|                   |                      | R   | S   | T   |                       |                        |
| 0                 | 0.432                | 23.8| 23.4| 23.9| 1.163                 | 0.136                  |
| 6.5               | 69.76                | 25.5| 25.2| 25.7| 2.569                 | 1.542                  |
| 10.5              | 111.19               | 26.6| 26.0| 26.5| 4.807                 | 3.78                   |
| 15.3              | 157.52               | 28.1| 27.8| 28.2| 8.569                 | 7.542                  |
| 20                | 205.41               | 31.4| 31.1| 31.5| 14.058                | 13.031                 |
| 25                | 258.62               | 37.4| 37.2| 37.6| 22.131                | 21.104                 |
| 30                | 310.76               | 45.3| 45.6| 45.9| 32.402                | 31.375                 |

During the short circuit test, input power to the HTS machine was also measured at each field current and 1800 rpm rotating speed as shown in Table 3. The short circuit loss is calculated by subtraction of windage and friction loss, which is 1.027 kW at 1800 rpm and zero excitation from Table 2, from the
HTS machine input in Table 3. Stray load loss consists of the losses arising from non-uniform current distribution in copper and the additional core losses produced in the iron by distortion of the magnetic flux by the load current. Stray load loss during the short circuit test can be calculated from the equation (4) with the data in Table 2 and Table 3. The core loss is 0.464 kW from Table 2 of the open circuit test result and the armature $I^2R$ loss is calculated to 27.958 kW with the armature coil resistance per phase of 0.0965 $\Omega$ measured at 20°C and the armature short circuit current of 310.76 A at 1800 rpm and 30 A field current. So the stray load loss, 2.935 kW, is calculated by subtracting the core loss and the armature $I^2R$ loss from the short circuit loss, 31.375 kW, at this condition. Figure 9 shows the short circuit loss and the stray load loss curves obtained from the test [3].

\[
\text{Stray load Loss} = \text{Short circuit Loss} - \text{Core Loss} - \text{Armature } I^2R \text{ Loss} \tag{4}
\]

![Figure 9. Short circuit loss and stray load loss curves](image)

6. Efficiency measurement at load test as a motor

![Efficiency measurement graph](image)
Figure 10 shows test result of generated torque according to armature current at 1800 rpm as a motor operation. Due to vibration problem this test could not be done at the rating speed of 3600 rpm, but the test machine generated rating torque, 2650 Nm, with 207.2 A armature current and 1475 V armature line-to-line voltage at 1800 rpm. Based on these values, per unit synchronous reactance is 0.13 p.u., which is the same with the design value. At this load torque condition, losses can be summarized as Table 4. During this test HTS motor was rotating at 1800 rpm by an adjustable speed drive. Figure 11 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. The overall efficiency including a cryocooler power consumption is 93.17 % at 1800 rpm and 2650 Nm during motor operation. 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 at 3600 rpm rating speed.

Table 4. Loss analysis at 1800 rpm and 2650 Nm during motor operation

| Losses                  | [kW]   | Percentage |
|-------------------------|--------|------------|
| Core loss               | 11.465 | 31.26 %    |
| Armature $I^2R$ loss    | 12.429 | 33.89 %    |
| Stray load loss         | 1.305  | 3.56 %     |
| Windage and friction loss| 1.027  | 2.80 %     |
| Field coil cooling loss | 7.5    | 20.45 %    |
| Etc                     | 2.953  | 8.04 %     |
| total                   | 36.679 | 100 %      |
7. Conclusion
The generated losses of the developed 1 MW class HTS machine were calculated from the basic tests of a synchronous machine based on the IEEE standard 115. Although the HTS machine could not be tested at 3600 rpm rating speed, efficiency was measured at each applied load condition up to the full load torque during synchronous motor operation. In this full torque condition, the generated losses were analyzed based on the results obtained from the basic tests such as OCC and SCC tests. The core loss among the generated losses is too high to bring a test result showing distinguished high efficiency compared with a conventional synchronous machine with the same specification. It is estimated that this high core loss even in the armature open circuit condition is due to single-stranded armature coil made of hollow conductor applied for a purpose of water-cooling. Too large eddy current might be induced in this single-stranded copper conductor. Another reason to decrease efficiency is et cetera (Etc) loss shown in Table 4, which might come from large armature current harmonics generated from the driving inverter.

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8. References

[1] Kalsi S S, Weeber K, Takesue H, Lewis C, Neumueller H –W and Blaugher R D 2004 Development Status of Rotating Machines Employing Superconducting Field Windings Proc. IEEE vol 92, NO 10 p 1688–1704
[2] Frank M, Frauenhofer J, Hasselt P van, Nick W, Neumueller H –W and Nerowski G 2003 Long-Term Operational Experience with First Siemens 400 kW HTS Machine in Diverse Configurations IEEE Trans. Applied Superconductivity vol 13 p 2120–2123
[3] The Institute of Electrical and Electronics Engineers Inc. 1995 IEEE Guide: Test Procedures for Synchronous Machines (IEEE Std 115-1995) p 27–38
[4] Fitzgerald A E, Kingsley Charles Jr. and Umans Stephen D Electric Machinery McGRAW-HILL International Editions 5th Edition p 114–229
[5] Baik S K, Kwon Y K, Kim H M, Lee E Y, Lee J D, Kim Y C, Moon T S, Park H J, Lee C H and Kwon W S 2008 Excitation Voltage Estimation of HTS Motor via Magnetic Energy Calculation Proceedings of the 39th Korean Institute of Electrical Engineers Summer Conference p 870–871