Development of an HTS motor with Ho-123 superconducting field coils at liquid nitrogen temperature

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Abstract. A 22kW, 360RPM, 8-pole high temperature superconducting (HTS) synchronous motor with Holmium (Ho)-123 field coils at liquid nitrogen temperature was designed, manufactured and tested. This motor employs an axial gap rotating-armature construction and consists of one field assembly and two armature assemblies. The field employs eight single pancake coils which are wound with the world’s first developed Ho-123 HTS wire. Ho-123 wire has potential high critical current density, which is expected to be as large as 100 times of BSCCO wire. Each coil is wound with 15m wire and the field can carry 75A current at liquid nitrogen temperature. We investigated coils AC behaviour and proposed a new way to minimize AC loss. A new method to suppress field current ripple is employed in this motor. A large variety of motor experiments were carried out and compared to the 3D model analysis that was conducted by Finite Element Method (FEM) showing the results met all its design goals. This paper provides the key designs of the motor, the analysis, tests of field coils and the motor.

1. Introduction

High temperature superconducting (HTS) machines are characterized by light weight, reduced size and high efficiency. Several years’ development on HTS rotating machine technology and the simplification of cooling system lead to reduced manufacturing costs on HTS machines. Except economic benefits, HTS machines also have environmental benefits. They are one of ideal candidates to solve problems such as global warming and energy crisis because they could contribute to save fuel and reduce greenhouse gas emissions. The benefits of HTS machines are due to low loss and high power density produced by HTS materials. There are several ways to apply HTS materials to machines. One way is to substitute copper wire by HTS wire in the field. HTS wire offers high current density and high efficiency compared to conventional copper wire. Equipped with Ho-123 HTS field coils making from Ho-123 thin film by Sumitomo Electric, we designed, built and tested an HTS motor at Liquid nitrogen temperature.

Ho-123 wire is a kind of rare earth element-123 HTS wire making of HoBa2Cu3Oy coated superconductor. Compared to the commercially available BSCCO wire, Ho-123 conductor offers about 100 times critical current density ($J_c$), which is in the $10^6$ A/cm² range at 77K and has high $J_c$ under high magnetic field. As the members of the 2G wire, HoBCO shows better environment
resistance than YBCO. Besides, Ho-123 layer deposition rate is about two to three times faster than that of YBCO, which means Ho-123 wire is suitable for mass production [1][2]. It is anticipated that this new wire could be applied to rotating machines.

We developed the Ho-123 HTS motor with the following goals:

- Validate technical feasibility of applying Ho-123 HTS coils to a motor field.
- Develop technologies to minimize AC loss of the HTS coils.
- Develop technologies to suppress field current ripple.

2. Ho-123 coils

Ho-123 wire is developed by pulsed laser deposition method and mainly consists of four layers: stabilization layer Ag for protection, superconducting layer Ho123 for electric conduction, buffer layer and substrate Ni-alloy for mechanical strength. The cross-section view of the wire is shown in figure 1. Each field coil is about 31.67 turns wound with 15m Ho-123 wire. The over view of coil is shown in figure 2. Specifications of the Ho-123 coil are shown in table 1. Concerning to field coils, there are two factors are vital to motor design: the critical current and AC loss. In this section, the characteristics of critical current and AC loss are described.

![Figure 1. The structure of Ho-123 wire.](image1)

![Figure 2. The over view of Ho-123 coil.](image2)

### Table 1. Specifications of Ho-123 coils.

| Specification               | Value          |
|----------------------------|----------------|
| Outer diameter             | 160mm          |
| Inner diameter             | 119.7mm        |
| Height (Including electrodes) | 36mm         |
| Wire width                 | 10mm           |
| Number of turns            | 31.67          |
| Length of wire             | 15m            |
| Inductance                 | 0.28mH         |

2.1. Characteristics of the critical current

Critical currents of eight coils in self-field at 77K range from 56A to 105A. The performances of Ho-123 wire short samples of each coil in applied fields at different temperatures are shown in figure 3.

![Figure 3. Ho-123 wire in-field performance at different temperatures—short samples of eight coils. The field direction is perpendicular to the wire face. (The measured data is supplied by wire developer).](image3)

It is safe to say that Ho-123 coils are able to carry larger current at 77K than other coils. However, the small volume makes it hard to produce reasonable field that a motor required. Besides, figure 3 shows they do not have uniform characteristics in presence of applied field, which set limitation on field rated current since the lowest critical current has to be taken into account.
2.2. AC loss of coils
AC loss is an important consideration for motor design. In order to understand Ho-123 coils AC behavior and develop the motor design, the tests that the coil conducting direct current (DC) in presence of AC field at 77K were carried out to evaluate its AC loss. A copper winding is employed to produce background AC field to HTS wire at different frequencies. Figure 4 shows the test arrangement. Reading is taken of loss power produced. Figure 5 shows the measured results. In spite of the differences of the field conditions between this test and the actual motor, the test results shown are clearly enough to explain the AC characteristics of Ho-123 coil. It is estimated that there will be a considerable amount loss generated when coils conducting 75A current under much stronger changing field at 24Hz in the trial motor.

Figure 4. The arrangement of AC loss tests.

Figure 5. AC loss of the Ho-123 coil.

3. Ho-123 Motor Characteristics

3.1. Configuration of Ho-123 HTS motor
Based on the features of Ho-123 coils, an axial-gap rotating- armature synchronous motor which employs an HTS field winding on the stator and two conventional copper armatures on the rotor was designed, built and tested. The stationary field is arranged between two rotating armatures. The photograph and the cross-sectional view of the motor are shown in figure 6 and figure 7 respectively.

Figure 6. Overview of Ho-123 HTS motor.

Figure 7. Structure of Ho-123 HTS motor.

3.1.1. Structure of the stator assembly. The stator assembly includes two parts: an HTS field winding and its cryostat. The field winding contains eight Ho-123 coils with central room-temperature laminated iron cores. Eight coils are connected in series with short copper strips maintaining at liquid nitrogen temperature inside the cryostat, while eight iron cores are located at the outside of cryostat. The cryostat is made of eddy current free Fiber Reinforced Plastics (FRP) and contains two layers: The inner vessel is full of cooled liquid nitrogen that supplied by Gifford McMahon refrigerator through insulated circulating pumps and the outer layer is used for vacuum insulation. Temperature sensors are installed at various places inside the cryostat to fully monitor the operating temperature of field coils. Because the field is used as a stator, all the cooling elements are fixed. The stationary
cooling equipments and liquid nitrogen coolant make the whole cooling system simple, cheap and easy to handle.

3.3.2. Structure of the rotor assembly. There are two armatures fixed on back yokes running with shaft. One armature consists of six copper laminated-iron-core concentrated windings. Two copper windings form one phase and three phases are arranged in a wye connection. A rotary encoder is mounted on the end of shaft to detect poles phase. The sine wave current, which is decided by the relation of poles phase and torque, is transferred from an inverter through slip ring and brush to armatures.

3.3.3. Motor’s parameters. The trial motor’s parameters are summarized in Table 2.

Table 2. Parameters for Ho-123 HTS motor.

| Parameter                      | Value       |
|--------------------------------|-------------|
| Rated power                    | 22kW        |
| Rated armature line voltage    | 120V(rms)   |
| Rated armature current         | 180A(rms)   |
| Rated field current            | 75A         |
| Rated speed                    | 360rpm      |
| Frequency at rated speed       | 24Hz        |
| Torque density                 | 3490 N•m/m³ |

3.2. Design conception

The electromotive force (EMF) induced in one armature coil by air gap flux \( \Phi \) produced by field can be expressed as:

\[
E_{\text{peak}} = \omega pN\Phi = 12\pi \times 4 \times 140 \times 0.007 \times 0.4 = 59V \quad (1)
\]

where \( \omega \) is the angular speed of the machine, \( p \) is the number of pole pairs, \( N \) is number of turns of each armature coil.

The output is:

\[
P_{\text{output}} = nE_{\text{rms}} I_{\text{rms}} = 12 \times \frac{59}{\sqrt{2}} \times \frac{180}{4} \approx 22kW \quad (2)
\]

where \( n \) is the number of armature coils.

3.3. Features of Ho-123 HTS motor

3.3.1. Field iron core. In this motor, we applied eight central iron cores to every coil. There are intense debates between iron core and air core in an HTS motor. Iron saturation is a serious problem to many HTS machines design. But when the flux density in air-gap is below 1.8T, utilization of iron cores will be a better choice to build a cost-effective and compact HTS machine. The advantages of iron core in this motor are described as follow:

- Increase flux linkage with armatures. According to the analysis, carrying 75A current, eight 15m Ho-123 coils can only produce an average 0.05T air-gap flux density while iron cored coils can produce 0.4T field. Air cored field means more field ampere-turns and current are required to drive the desired flux to armatures. With the help of iron core, it is possible to employ minimum wire to obtain intense field, which also reduce cost of the field winding.
- Minimize AC loss of HTS coils. AC loss is a big obstacle to HTS wire’s AC application. Each watt of AC loss deposited as heat in wire requires many watts of cooling power for its removal. It is well known that changing flux is the main reason caused AC loss, so prevent time-varying flux that produced by rotating armatures to penetrate field coil will be the most direct way to reduce loss generated. Compare to high resistance air, magnetic materials are apparent better paths for magnetic flux. When iron core is arranged in the middle of HTS coil, the
majority of the flux produced by armatures will be applied to iron core rather than coil, thus prevent varying flux to penetrate wire. The 3D FEM analysis of motor models with iron cores and air cores were carried out respectively to compare the AC behaviours. The air cored model has a total 29mm air gap from Ho-123 coil to armature cores, which is equal to the 28mm-thickness of the cryostat with cooling and insulation layer plus 1mm essential air gap separating from armatures. The iron cored model has 1mm nonmagnetic air gap from field iron cores to armature cores. Figure 8 shows the flux distribution of one of field coils.

![Flux distribution of the iron-cored field coil when motor is operated at rated conditions.](image)

In 10mm width coil, flux density changes from one end to another end as the order of strong(0.07T)-weak(0T)- strong(0.07T). Figure 9 (a) and (b) show the penetrating flux analysis results of one coil from air-cored field and iron-cored field when motor is operated at rated conditions through one electrical cycle. In this plot, the strong field of two ends and the weak field are presented. The calculation is taken every 12 electrical degree. It is noted that in the iron cored model, the penetrating flux almost keeps constant.

![Perpendicular field distribution on field coil.](image)

3.3.2. **Field current control.** The field current ripple is another source that contributes to field loss since HTS wire is loss free only when it conducts DC. In this motor, we proposed to employ field current control loop by a chopper instead of the conventional way that applies the stabilized power supply and large volume capacitors to suppress current ripple. Figure 10 and figure 11 show the field current waveforms when the current supplied by a stabilized power and a control loop.

![Field current that supplied by a stabilized power when motor is operated at 360rpm under 2.7kW load.](image)

![Field current that supplied by a chopper when motor is operated at 360rpm under 3.5kW load. (Gain=10).](image)
3.3.3 Axial-gap configuration. It causes extra eddy current loss and cooling loss when iron cores are cooled, so field cores are arranged at outside of the cryostat to be kept at room temperature. The axial-gap configuration is proven to be more compact and easier to arrange iron cores at the outside of cryostat than radial-gap motors.

4. Motor test
A range of experiments were carried out to demonstrate motor basic performances and decide motor parameters. All the tests were performed when field temperature is 69k ~77k. Field is powered by a chopper and armatures are powered by an inverter. The typical test results are described as follow.

4.1. Locked rotor test
The test was performed when armatures are locked at proper position that average torque can be obtained when torque ripples under full load are taken into count. The result is shown in figure 12. Because of the limitation on measure equipments, the data was observed when rotor current reached about 90A. According to the test results, 290N·m was observed at 90A and the relation of current and torque kept in a line, so that 580N·m at 180 A can be derived which is 22kW output.

4.2. Four-quadrant operation
Four-quadrant operation showed in figure 13 was conducted when speed varied as 0~360rpm~360rpm~0. Identity of speed detection and command shows the motor can be accelerated and decelerated smoothly. The torque corresponds well with speed change showing this motor can successfully work at motoring and regenerating modes.

5. Conclusion
The Ho-123 wire’s application to rotating machine was successful demonstrated. In this motor, we employed iron cores to overcome the issues caused by small volume wire. Employing iron cores in the motor not only can produce an intense field, but also can minimize AC loss, which is an effective way to build a cost-efficiency machine. Dealing with the current ripple of the field, which is a common but serious problem of HTS motor, the current control loop was proposed. The measured results show effect of employing control. The 3490 N·m torque per m³ shows the sufficient performance of motor technology. It is expected that with larger Ho-123 coil volumes, a compact, high efficiency and low cost HTS motor can be constructed.

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