Coolant transfer coupling with integrated dynamo for rotor with HTS windings

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Abstract. Most superconducting synchronous machines employ HTS field excitation windings on the rotor operating at cryogenic temperature. These windings are usually cooled by coolant supplied from a stationary source to the rotor with rotary couplings. Closed loop gaseous helium couplings have been employed on mega-watt size machines operating at both low speed and high speed. However, these couplings were marred with leaking of cryogen out of the closed loop and needed periodic replenishment. This undesirable problem has been recognized long ago but no suitable solution has emerged in the open literature. Currently, the HTS machines are being considered for the aerospace applications, wherein leakage of cryogen from closed loop is highly undesirable. This paper presents a concept that prevents the cryogen leakage and/or its collections it for returning to the closed cooling loop. An option is also explored to include an HTS dynamo for providing the field excitation without current leads. This concept would need de-risking before using in the motors and generators for the aerospace applications. Possible cryogens for cooling include gaseous helium, Neon, H2 and N2.

1. Introduction

Superconducting machines have long been associated with characteristics like compactness, lightweight and high efficiency [1]. Most machines built to date have been synchronous type with DC excitation field windings on the rotor. In most cases, resistive losses in the field winding and stator AC winding are comparable. Superconducting field windings have been demonstrated to increase the magnetic field experienced by the stator winding, while reducing the field winding losses by nearly 80% as compared to copper equivalents. This has reduced the size and mass of machines used for industrial as well as ship propulsion applications [2,3]. Many such machines have been built, and all have been maintained at cryogenic temperatures during operation by transferring coolant from stationary coolers to the rotor through a rotary coupling [4,5,6,7].

Superconducting motors with further reduced mass may be suitable as propulsion motors for All Electric Aircraft. Electrically propelled aircraft have the potential to be more efficient, have reduced emissions, and operate with less noise both on the ground and in the cabin, as well as many other potential advantages as described in [3].

Figure 1 shows a concept AC synchronous machine [8] where both the DC rotor field winding and the AC stator armature winding are superconducting. The rotating magnetic field produced by physical rotation of a superconducting DC field winding is typically twice that produced in a machine built with conventional copper field windings.

The machine described in this paper has both stator and rotor windings requiring cryogenic cooling. Each winding has individual vacuum space for ease of construction, testing and maintenance during operation. In this concept the cooling for each winding is supplied from a non-rotating source. This paper presents a concept design for the transfer coupling to supply coolant to the rotor in a closed loop where the coolant warmed by the rotor losses is recovered. The recovered coolant may then be re-cooled and reused.

An HTS dynamo [9] is also integrated with the transfer coupling for wireless excitation of the field windings. This is intended to increase the efficiency of the motor by reducing the thermal conduction into the rotor cryogenic environment, and removing resistive components from the field winding supply circuit.

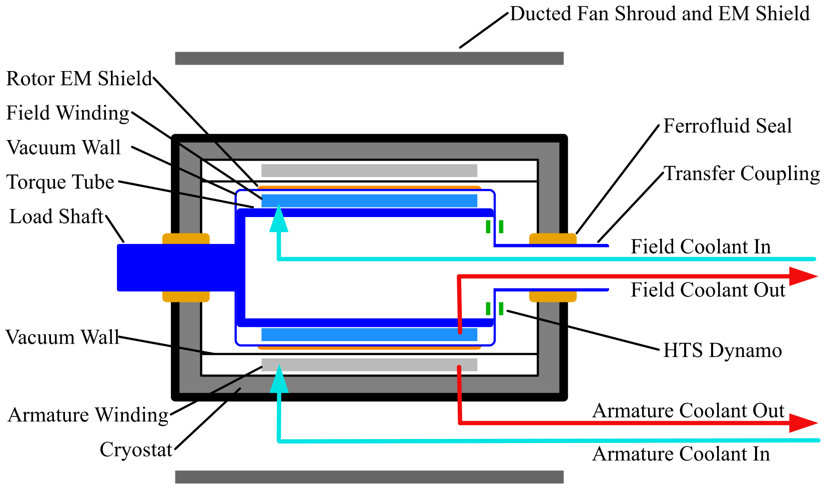

Figure 1. Superconducting motor concept with HTS field winding.

2. Transfer Coupling Concept Description

A coupling concept shown in Figure 2 uses a double walled bayonet to transfer cold coolant to the rotor and return warm coolant out of the rotor. This bayonet mates with the end of a second single walled bayonet fixed to the rotor. A Teflon cold slip seal separates the cryocooled coolant in stream from the warmer coolant out stream.

The warmed returning coolant enters the outer rotating tube through holes in the tube wall. This rotating tube is attached to the room temperature motor shaft. Thus, this coolant tube is cold at the slip seal, and at room temperature at the shaft end. On the warm end, stationary and rotary parts are supported with a room temperature ferrofluid seal. This seal can hold a small pressure difference across it, but the sealing action is not totally leak free. The bayonets serve as an interface between the cold rotating parts and stationary cooling system. Since a partial vacuum is required in the air gap of the high-speed machine, the motor shaft is supported with another set of ferrofluid seals at the load shaft end of the motor.

Rotary seal concepts like this have been used by others [10]. However, the smaller ferrofluid seal between the rotating and stationary bayonets is not fully capable of stopping leakage of coolants such as gaseous helium to the environment. Closed loop cooling systems have been built [6] with room-temperature ferrofluidic seals. Currently no suitable solution is available in the published literature that prevents coolant leakage through the ferrofluid seals. The loss of coolant, however, is not acceptable in machines for airplanes and other applications.

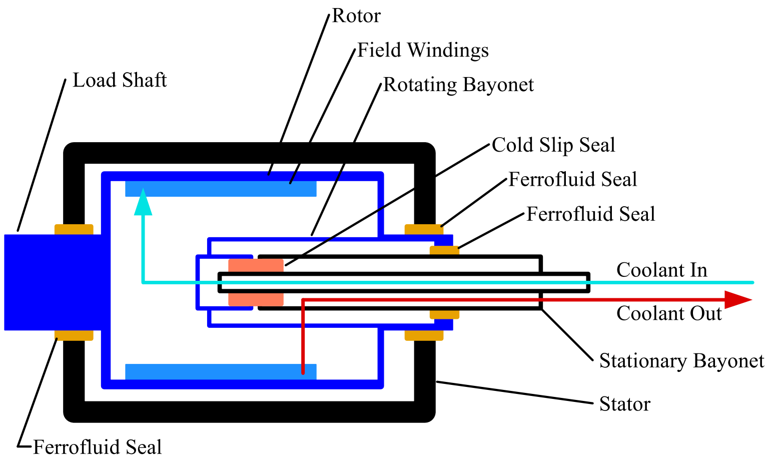

Figure 2. Coolant transfer coupling concept.

In order to fix the coolant loss, this paper presents a glove box type structure shown in Figure 3. This arrangement is expected to prevent leakage of the coolant from the machine by recovering the coolant that passes through the inter-bayonet ferrofluid seal. The glove box type structure encases all rotating parts against the motor wall and attaches to the stationary bayonet with a bolted flange. The pump out port in the glove box may be used for collecting the leaking coolant, or providing positive pressure to prevent the leakage.

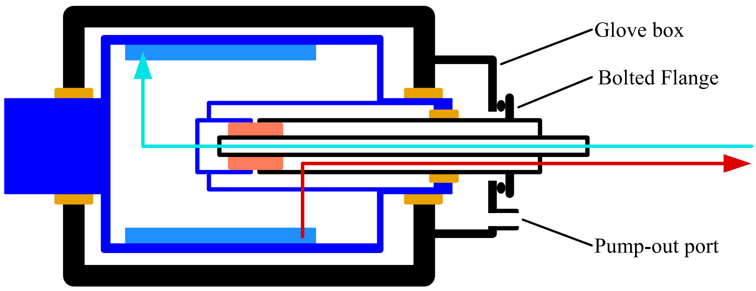

Figure 3. Leak-free coolant transfer coupling concept

Figure 4 shows the interface between the rotor and stationary cooling system. Coolant recovered via the pump out port is added to the closed loop gas circulating system. The coolant in the closed loop is circulated with a gas pump. Although this configuration has not yet been tried, almost all components needed for this cooling system are available off-the-shelf.

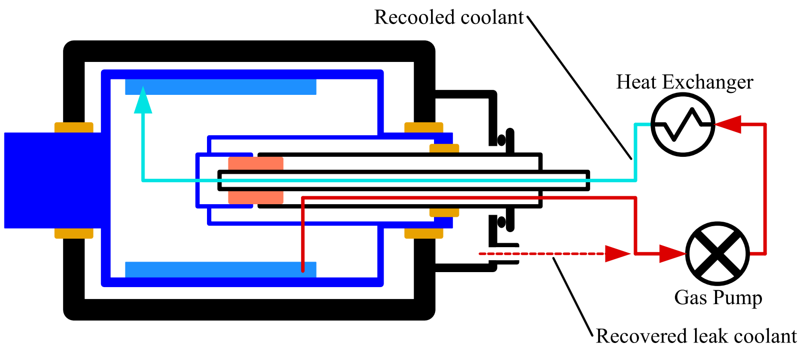

Figure 4. Rotor cooling system with stationary cooler

3. Integration of Dynamo for Field Winding Excitation

Field poles must be excited wirelessly without need for slip rings and brushes for avoiding reliability and maintenance issues for high-speed machines. In the past, brushless concepts based on magnetic iron core were used that employed current leads spanning room-temperature and cryogenic regions. These current leads created a large thermal load for the cryocooler. Moreover, such an exciter is too heavy for aerospace applications where high specific power is required. A possible option is to employ the HTS dynamo [9,11] developed by Victoria University of Wellington (VUW). Its weight is expected to be less than 10% of the weight of magnetic core exciter. Figure 5 illustrates the HTS dynamo concept that is capable of supplying more than a kA of current [12]. Figure 6 shows how such a dynamo may be integrated into the motor as a passive device for energising the field winding without current leads spanning crossing the cryostat wall.

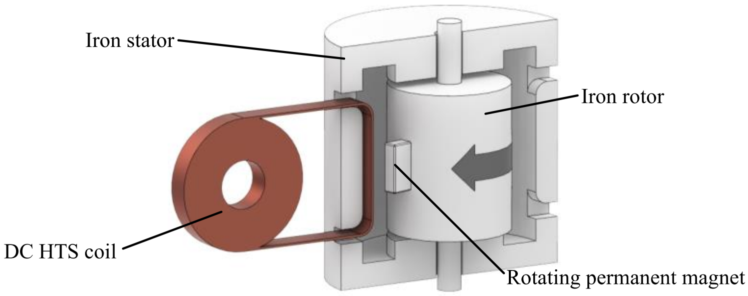

Figure 5. Brushless HTS dynamo concept.

The permanent magnets (PM) for excitation are attached to the outer wall of the stationary bayonet within the air core of the motor. The superconducting elements in which DC voltage is induced is attached to the outer wall of the rotating bayonet. To prevent the rotating magnets acting as a magnetic brake the rotating bayonet must be manufactured from a non-metallic material such as carbon fiber composite.

The field windings may be energized to high DC currents over many rotations of the magnets relative to the superconducting elements. Energization will occur continuously provided there is relative movement between these components, thereby providing the current to make up any losses caused by losses due to non-superconducting joints in the HTS circuit, or AC effects. The HTS dynamo enables all components of the field winding circuit to be superconducting, and high currents may be supported with little loss. A high circuit current within the field windings allows large magnetic output coils to be produced with relatively few windings. In addition to being lighter and cheaper to produce, low turn coils have smaller inductance and are faster to charge.

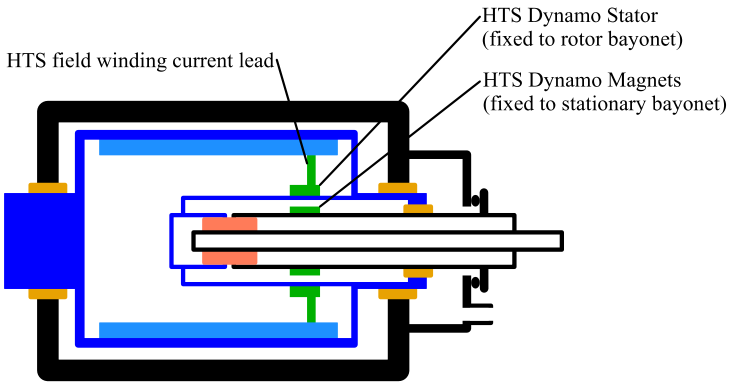

Figure 6. HTS Dynamo integrated with transfer coupling for rotor field excitation

It may be necessary in some cases to charge the rotor poles before a synchronous machine is started. This would require the PMs to rotate when the rotor is stationary. This could be accomplished by rotating the outer tube of bayonet using external means on the room-temperature end. However, Figure 7 shows an additional tube carrying PMs that could be rotated independent of the rotor. This will require an additional ferrofluid seal on the room temperature end. This tube is rotated with a small motor located within the glove box. Once the field windings are energized, the small motor may be disengaged so the dynamo may operate in passive mode as in figure 6. Alternatively, the motor may be used to vary the current in the field windings throughout their operation as desired.

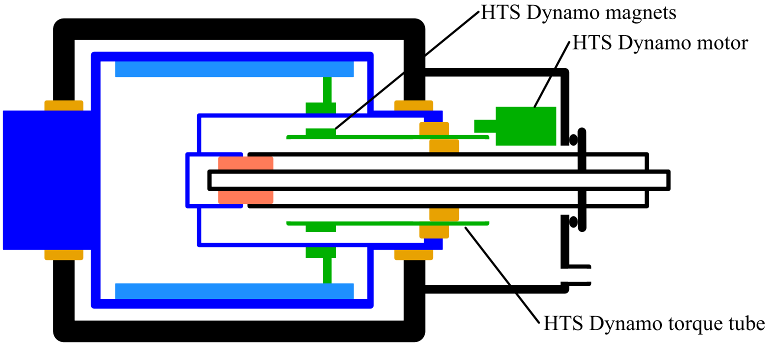

Figure 7. HTS Dynamo integrated with independent HTS dynamo drive tube

4. Conclusions

A rotary seal concept is presented to facilitate transfer of coolant from stationary source to the rotor for cooling the field winding poles. This rotary seal is expected to capture coolant leaking through the room-temperature Ferro-Magnetic seals. The rotary coupling also incorporates DC dynamo for charging the field coils without current leads spanning room-temperatures and cold environment. Leak-free transfer coupling with dynamo is highly essential for achieving highest possible power densities (kW/kg) for airplane applications.

Acknowledgments

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