Design of an HTS motor

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Abstract. This paper gives a detailed description of the design of a high temperature superconducting (HTS) motor. The stator of the motor consists of six air cored HTS racetrack windings, together with an iron shield. The rotor is made of 80 superconducting YBCO pucks, which can be magnetized and equates to a four-pole permanent magnet. The whole HTS motor is cooled by liquid nitrogen to 77K, and acts as a permanent magnet synchronous motor with the power rate of 15.7 kW.

1. Introduction
In recent years, great interest has been aroused in the development of high temperature superconducting (HTS) technology. It has been proposed in a wide range of engineering applications, such as levitated transportation, flywheels, fault current limiters, and electrical machine. Up to now, considerable efforts have been made to design and develop the first prototype of second generation HTS motor in Cambridge University [1-3]. By using of second generation superconducting tape with high current density, the iron core can be removed, and the machine can be made smaller and lighter.

2. Structure of the HTS motor
A schematic cross-sectional view of the HTS motor is shown in figure 1. The stator consists of the air gap HTS armature windings, which are installed in the slots of the nonmagnetic and insulating material, and an iron shield. The rotor is made of superconducting pucks, which can be magnetized and equate to a four-pole permanent magnet. The HTS motor is cooled by liquid nitrogen to 77 K.

Figure 1. Cross-sectional view of HTS permanent magnet synchronous motor
3. Design of the motor stator

3.1. Choice of HTS tape

The HTS tape used for the armature winding is AMSC YBCO wire, type 344. The specification for this type of wire is listed in table 1.

| Table 1. Properties of AMSC YBCO 344 wire (*: 95% Ic retention) |
|---------------------------------------------------------------|
| Average thickness: 0.20 (+/- 0.02) mm                          |
| Width: 4.35 (+/- 0.05) mm                                     |
| Maximum width (bare): 4.4 mm                                  |
| Min. double bend diameter (RT): 30 mm*                        |
| Max. Rated tensile stress (RT): 150 MPa*                      |
| Max. rated tensile strain (77K): 0.3%*                       |
| Max. rated compressive strain (77K): 0.3%*                    |
| Single piece length of wires: 20 m available                  |
| Critical current at 77 K, 0 T: > 60 A                        |

3.2. Design of the HTS armature winding

The armature winding sees a rotating magnetic field so it has to be arranged to minimize the AC losses. In the design of the HTS armature winding, the face of the YBCO tape is aligned with the strongest component of the magnetic field of the rotor, since the AC losses at different angles are governed mainly by the perpendicular field component [4]. Meanwhile, the YBCO tape is rather brittle having a maximum strain of 0.3%. Consequently, the armature winding in the HTS motor is made of six single flat-loop coils which are wound as racetrack coils with a bend radius of several centimetres. Racetrack windings and the geometry are shown in figure 2.
Double layers of HTS windings are stacked together to make one racetrack winding, which doubles the number of turns of the winding, and maximises the inductance of the winding within the limited geometry. The total number of turns per phase for the stator windings is 200 turns, with 50 turns for each layer.

3.3. Construction of the stator
The construction of the motor stator can be seen in figure 3. The stator of the HTS motor consists of six pancake HTS armature windings (labeled 1), non-magnetic supporters (labeled 2) to fix the windings’ positions, and the non-magnetic outer rings (labeled 3). At the late stage, a machine shield will be applied to prevent the electromagnetic radiation.

4. Configuration of the rotor
HTS pucks, acting as permanent magnets when magnetised, are adopted to construct the rotor. The configuration of the rotor is shown in figure 4.

The rotor consists of a shaft in the middle made of nonmagnetic material, a shallow space to fill in liquid nitrogen to cool the superconducting pucks, and 80 round superconducting pucks which are attached on the copper wall by a 1 mm low temperature adhesive layer. The copper wall conducts the heat from superconducting pucks to liquid nitrogen. The rim of the rotor is made of thermo-insulated material. The total diameter of the rotor is roughly 180 mm.
At the beginning of the machine operation, the armature HTS windings are used to generate the magnetization field for the rotor. Each one of the armature phases is supplied with a DC current in order to generate a static field, emulating the magnetic field produced by an alternating three-phase current system balanced at a given time. Then the rotor will be cooled by liquid nitrogen, and the pucks will become superconducting, which will hold the flux within. Afterwards, three-phase AC currents will apply to the stator, and the machine will act as a permanent magnet synchronous motor.

5. Testing of the HTS windings
The armature windings are reinforced by the second Generation (2G) Yttrium barium copper oxide (YBCO) tapes manufactured in Trithor GmbH. The configuration of the winding is shown in figure 5.

According to figure 5, the coil consists of a stainless steel former, which is slit at one place to avoid a closed current loop. At the slit the former is stabilized by means of a G10 piece. The former was
bandaged by glass fabric as a base insulation. The coil contains two halves of HTS wires, internally connected. At both ends of the HTS windings, copper contacts are integrated for current connections by screws. Three voltage leads (blue) are integrated – one at each end, one in the middle of the coil. Two thermocouples (thin red/yellow) wire are placed between the two halves of the coil. Two Pt100 sensors are integrated (4 wire connection, red wires). The coil was completely impregnated with epoxy resin.

The critical current of both the YBCO coated thin film tape sample of and the whole coil were measured by DC pulse current measurement technique and the results are shown in figure 6 and 7.

![I-V curve for YBCO sample](image1)

**Figure 6.** The critical current of YBCO sample

The critical current criteria used is based on electric field $E_C = 1 \mu \text{V/cm}$. For the YBCO tape sample, the length between the voltage taps is 2 cm, so the measured critical current is 106 A. On the other hand, the total length of the HTS coil is 60 m, so the measured critical current of the coil is 51 A. The decrease of the critical current is due to several factors. One is the self magnetic field generated by the HTS coil itself. The other, which we believe is more significant, is the fact that the single piece length of wires is 20 m, while the whole length of the coil is 60 m. This leads to at least two wire joints which reduce the critical current of the whole coil.

6. **Machine equations and power rate estimation**

The stator flux linkage and electromagnetic torque equations in dq-reference frame are shown as follows:

\[
\lambda_d = L_d i_d + \lambda_f \\
\lambda_q = L_q i_q \\
T = \frac{3}{2} p (\lambda_d i_q - \lambda_q i_d)
\]

where $\lambda_f$, $L_d$, and $L_q$ are the armature back emf constant and inductance, and $p$ is the number of pole pairs.

The machine was modeled in Femlab. The estimated magnetic field produced by the magnetised superconducting pucks is roughly 0.3 T. As a result, the calculated values of armature back emf constant $\lambda_f$ and synchronous inductances $L_d$ and $L_q$ are show as below:

$\lambda_f = 0.675 \ Wb$

$L_d = L_q = 0.8052 \ mH$
If a control algorithm is applied that keeps the torque angle at 90 degrees, then the value of $i_d$ is zero, and $i_q$ equals to the total current which is 50 A, the electromagnetic torque can be estimated as 100 Nm. And the power rate can be calculated as:

$$ P = T \omega = 100 \times 50 \pi = 15.7 \ kW $$ \hspace{1cm} (4)

7. Conclusion
This paper gives a detailed description of the design of a HTS motor developed in Cambridge University. The stator of the motor consists of six pancake HTS windings, made of second generation YBCO tapes, while the rotor was constructed by 80 round superconducting pucks, which will be magnetised and act as a four-pole permanent magnet. The critical currents of the YBCO tape sample and the whole HTS winding have been measured, the values of which are 100 A and 50 A, respectively. The reduction of the critical current in the HTS coil is due to its self-field and the wire joints due to the limited length of single piece wire. The maximum electrical torque the motor can generate is estimated as 100 Nm, which results in the total power rate of 15.7 kW.

References
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