Conceptual Design of Superconducting Induction Motors Using REBa$_2$Cu$_3$O$_y$ Superconducting Tapes for Electric Aircraft

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Abstract—High power density motors are required for electric propulsion aircrafts. The highest power density of the conventional motor is reported as 5.2 kW/kg up to now. Superconducting rotating machines have a potential to realize higher power density due to its high current density and a large magnetic field property. In this study, the induction motor with air-cored superconducting armature windings was conceptually designed. The output power range was 3 to 6 MW and the output power density aimed to be over 20 kW/kg. The armature voltage should be below kV-class and joule loss below 122 kW. The target efficiency was over 95%. The electromagnetic design and analysis were carried out by JMAG Designer. The number of magnetic poles and operating temperatures were set as two poles and liquid hydrogen temperature of 20 K, respectively. The parameter was power frequency in the range of 100–250 Hz. As a result, all the requirements were satisfied when the power frequency was 130 Hz. The feasibility of the MW-class superconducting induction motor was investigated, and in conclusion, the superconducting induction motor can be applied to the aircraft propulsion system.

Index Terms—Superconducting coils, induction motors, aircraft.

I. INTRODUCTION

EMISSIONS of CO$_2$ of fuel combustion have been increasing year by year [1]. The traffic of aircraft is predicted to about 2.4 times in next the 20 years, so the CO$_2$ emissions will increase further [2]. However, the ICAO and IATA aim to a 50% reduction in total aircraft CO$_2$ emissions in 2005 by 2050 [3]. The automotive industry has been moving to electric vehicles to reduce the CO$_2$ emissions. Analysis and design optimization of a motor and performance analysis of torque for an electric vehicle have been studied by [4]–[6]. In addition, the aircraft industry will also become to be electrified. A distributed propulsion system with multiple fans is one of the promising solutions to reduce emissions by increasing efficiency. By the distributed propulsion, it is expected that the airframe can be designed as Blended Wing Body and then 72% of fuel can be reduced [7]. However, referring to NASA’s conceptual design, we can see that these systems require a high output power density, especially for propulsive motors (>20 kW/kg). The world-record power density of conventional motor is ~5.2 kW/kg [8], [9]. The distributed propulsion system requires about four times higher power density [10]. A superconducting technology has a potential to achieve such an extremely high power density requirement due to a capability of transporting a high current density and producing high magnetic field. In our previous studies, the synchronous fully superconducting rotating machines have been studied [11]–[13]. These machines need complicated structures as a rotating part with a slip ring for supplying electric power to field windings. From the viewpoint of dielectric strength and maintenance, the slip ring should be omitted. In this study, we studied superconducting induction motors for electric propulsion aircraft. The rotor is a cage rotor made of copper, and the stator is REBa$_2$Cu$_3$O$_y$ (REBCO) superconducting armature. Conventional motors usually use iron-core in the stators. Core losses are calculated by nonlinear lumped-parameter equivalent circuit model [14]. In this study, to achieve a high output power density, our induction motors employed air-core superconducting armature coils. The AC loss occurs in the superconducting armature windings due to AC magnetic field and current. Our research group has developed the laser-scribing technique and transposed parallel conductors to reduce the AC loss. These technologies were developed for superconducting transformers wherein the reduction of AC loss was successfully demonstrated [15], [16]. In addition, due to the strong magnetic field and high-speed rotation, a large Joule loss is expected to be produced in the copper rotor. The copper rotor is arranged outside the cryostat, with a fin cooled by outside air. Since the aircraft operates over 10 km above the sky, the air temperature is $-50 \, ^{\circ}$C and the speed over 800 km/h, so a high cooling effect is expected.

The purpose of this study is to conceptually design superconducting induction motors with output power of 3–6 MW with...
TABLE I
MAIN SPECIFICATIONS OF THE MODEL

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor diameter [mm]</td>
<td>256</td>
</tr>
<tr>
<td>Model diameter [mm]</td>
<td>370</td>
</tr>
<tr>
<td>Effective length [mm]</td>
<td>500</td>
</tr>
<tr>
<td>Winding configuration</td>
<td>Distributed winding and Full-pitch winding</td>
</tr>
<tr>
<td>Number of poles</td>
<td>2</td>
</tr>
<tr>
<td>Number of copper bars</td>
<td>20</td>
</tr>
<tr>
<td>Number of slots per phase</td>
<td>2</td>
</tr>
<tr>
<td>Number of slots / phase</td>
<td>8</td>
</tr>
<tr>
<td>Slot thickness [mm]</td>
<td>4.5</td>
</tr>
<tr>
<td>Yoke thickness [mm]</td>
<td>20 (JSOL-50A230)</td>
</tr>
<tr>
<td>Total weight [kg]</td>
<td>145.8</td>
</tr>
<tr>
<td>Yoke weight [kg]</td>
<td>83.6</td>
</tr>
<tr>
<td>Copper weight [kg]</td>
<td>36.7</td>
</tr>
<tr>
<td>GFRP weight [kg]</td>
<td>21.9</td>
</tr>
<tr>
<td>EuBCO weight [kg]</td>
<td>3.54</td>
</tr>
</tbody>
</table>

II. DESIGN OF SUPERCONDUCTING INDUCTION MOTOR

The REBCO superconducting tapes are developing by the National Institute of Advanced Industrial Science and Technology. The detailed electromagnetic properties were reported in the previous paper [11]. Here it is assumed that the REBCO superconducting wire will be laser-scribed into a 10-filament structure [17]. The AC loss of the REBCO tape was calculated by substituting the magnetic field amplitude penetrating vertically into the superconducting tapes into the approximate formula for the AC loss measured using a saddle-shaped pickup coil [18]. The magnetic field amplitude was analyzed using the finite element method. The refrigerant at the stator is assumed as liquid hydrogen at 20 K.

Table I shows the specifications of the induction motor. Fig. 1 shows a cross-sectional view in axis direction of the superconducting induction motor. The casing with a vacuum thermal insulation layer, bobbins for the superconducting windings and the shaft are made of GFRP. The GFRP wall of the casing was 4 mm in thickness and the vacuum layer of 6 mm in thickness. The electric gap between the inner diameter of stator and the outer diameter of rotor is 20 mm. The inset of Fig. 1 shows the size of copper rotor bars and copper fins for air cooling. The copper bar is 15 mm in height, 13.4 mm in innermost width, and 15.3 mm in outermost width. The number of copper bars was set as 20. The fin made of copper is attached to the copper bar, in order to increase cooling capacity. The length of the fin is 30 mm. Three fins are attached per a copper bar. The total weight was assumed as 145.8 kg. The heaviest part of the motor is the back iron yoke. It amounts to 57.3% (83.6 kg). The second heaviest part is copper rotor is 25.7% (36.7 kg).

The heat release was calculated using the convective heat transfer equation for a flat plate, for simplicity Ref. [19]. The copper bar and fin surfaces were assumed to be flat. Air at 800 km/h and $-50 \degree C$ cools the rotor by forced convection. The heat dissipation amount $Q$ from the surface of the flat plate is expressed by (1).

$$ Q = \overline{h}LW(T_w - T_e). \tag{1} $$

$\overline{h}$ is the average heat transfer coefficient. $L$ is the length of flat plate. $W$ is the width of flat plate. $T_w$ is the temperature of the flat plate. $T_w$ is 150 $\degree C$. $T_e$ is the temperature of the air. $T_e$ is $-50 \degree C$. $\overline{h}$ is expressed by (2).

$$ \overline{h} = \overline{Nu}L \frac{k}{L}. \tag{2} $$

$\overline{Nu}L$ is the Nusselt number that is a dimensionless number representing the ratio of heat transfer to heat transfer in a convective fluid. $k$ is the thermal conductivity. $k$ is 0.0276. $\overline{Nu}L$ is expressed by (3).

$$ \overline{Nu}L = P_r^{1/3} \left(0.037Re_L^{4/5} - 871\right). \tag{3} $$

$Re_L$ is the Reynolds number that is dimensionless quantity defined by the ratio of inertial force to viscous force. $Re_L$ is expressed by (4).

$$ Re_L = \frac{ueL}{v}. \tag{4} $$

$ue$ is the speed of air of 800 km/h in this study. $v$ is kinematic viscosity of air in this paper. $v$ is 0.00002976. $P_r$ is the Prandtl number that is ratio of thermal energy diffusion to kinetic energy diffusion. $P_r$ is expressed by (5).

$$ P_r = \frac{\mu C_p}{k}. \tag{5} $$
Fig. 2. Magnetic field distribution of the cross section of the induction motor when $T_{op} = 20$ K and $f = 130$ Hz. $T_{op}$ was set to the liquid hydrogen temperature of 20 K.

$\mu$ is viscosity coefficient. $\mu$ is 0.00001457. $C_p$ is specific heat. $C_p$ is 1005.

The calculated heat dissipation was 122.4 kW. In other words, the joule loss must be less than this heat dissipation amount.

### III. Numerical Simulation of Superconducting Induction Motor

Fig. 2 shows the magnetic field distribution of the cross section of the induction motor at power frequency 130 Hz. The maximum magnetic field applied to the superconducting tape face in perpendicular was 0.1 T. The critical current at 20 K and 0.1 T-field was 1711 A. The stator current is 800 $A_{peak}$, so the load factor was 46.8%.

Fig. 3 shows the output power vs slip frequency with various power frequencies. The range of the power frequency was 100–250 Hz. The slip frequency is expressed by (6).

$$f_s = Sf.$$  \hspace{1cm} (6)

Where $f_s$ is the slip frequency, $S$ is the slippage, $f$ is the power frequency. The solid lines show the output power properties. The dot lines show the torque properties. The maximum torque is 4671 Nm. All of the maximal output power is around the $f_s \sim 26$ Hz since the torque is maximum when the slip frequency is 32 Hz.

Fig. 4 shows joule loss (red line) and AC loss (blue line) for various power frequencies. These plots show the maximum output power for each power frequency indicated by the arrows in Fig. 3. The black dashed line is constraint condition of joule loss. Both joule loss and AC loss are roughly proportional to the power frequency. When the power frequency is less than 140 Hz, the induction motor can satisfy the required condition of the joule loss. For the power frequency of 150 and 200 Hz, the joule losses are almost the same values due to the same slip frequency as 26 Hz.

The voltage in armature windings is also proportional to the power frequency as shown in Fig. 5, since the impedance of the coil increases in proportion to the power frequency. When the power frequency is 100–150 Hz, the induction motor can satisfy the required condition of the armature voltage.

The efficiency was calculated by (7).

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Output power} + \text{AC loss} + \text{Iron loss} + \text{Joule loss}}$$  \hspace{1cm} (7)
After the use of the liquid hydrogen as a refrigerant, the hydrogen gas is used for fuel to the gas turbines. Therefore, the cooling penalty of cryocooler isn’t included the efficiency calculation. The efficiency is also proportional to the power frequency as shown in Fig. 6. Table II shows the electromagnetic properties for the power frequency of 100–250 Hz. When the power frequency is 130, 150, 200 and 250 Hz, the induction motor achieved the output power density over 20 kW/kg. The efficiency of the designed motor achieved over 95% under all power frequency. When the power frequency is 100–150 Hz, the armature voltage was below 1 kV. The joule loss satisfied the heat dissipation requirement when power frequency are 100 Hz and 130 Hz.

IV. CONCLUSION

We conceptually designed 3 to 6 MW superconducting induction motor for electric aircraft and investigated the various properties for the frequency range of 100–250 Hz by numerical simulation. At the frequency of 130 Hz, the power density over 20 kW/kg, armature voltage less than 1 kV, efficiency over 95% and joule loss less than 122.4 kW were satisfied. As a result, the feasibility of MW-class superconducting induction motor was demonstrated. The output power and efficiency increased with power frequency.

In this study, the heat release from the copper rotor was calculated by the simple turbulent heat transfer equation assumed as a flat plate. In fact, more detailed heat calculations are required. For rotor rotational motion with respect to air convection, a two-dimensional model is not sufficient to obtain more accurate results. Therefore, three-dimensional thermal analysis is required to design an accurate ventilation system for an air-cooled induction motor [20].

The most of the weight was iron yoke (57%). One of the attractive solutions is using superconducting magnetic shield instead of iron yoke. The superconducting induction motors are expected to be drastically reduced the weight. However, the permeance of the magnetic path might decrease. Therefore, the generated torque might decrease, so it is necessary to investigate the superconducting magnetic shield in detail. Our research group has started to develop the superconducting shields.

REFERENCES


