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Comparison of Force Density of Various Superconducting Linear Motor Types Considering Numerically Evaluated AC Losses

B. J. H. de Bruyn, J. W. Jansen and E. A. Lomonova

Abstract—This paper presents a comparison of the force density of four types of superconducting linear motors, taking into account the AC losses. The losses are evaluated by finite element models in which several methods to reduce model complexity are combined to achieve a low computation time. A parametric search is performed to determine the maximum achievable force density of all motor types, in which the operating temperature, geometric parameters, and peak current through the superconducting coils are varied. Results show the optimum number of turns for each parameters, and peak current through the superconducting coils is performed to determine the maximum achievable force density combined to achieve a low computation time. A parametric search models in which several methods to reduce model complexity are account the AC losses. The losses are evaluated by finite element models which include the dependency of the critical current density on the magnetic flux density [6].

Keywords—superconducting coils, high-temperature superconductors, linear motor, design optimization

I. INTRODUCTION

LINEAR motors are applied in the semiconductor industry for dynamic positioning, for example in photolithographic equipment [1]. Motors incorporating superconducting tapes potentially achieve a higher force density than motors with conventional coils, which allows for an increase of throughput. A main concern for the design of highly dynamic superconducting motors are the AC losses in the superconducting tapes, which mainly consist of hysteresis losses [2]. Including these in the design is challenging, since the relation between AC losses and coil currents is highly nonlinear and depends on the geometry of the motor as well as the operating temperature. Although some implementations of linear motors incorporating superconducting materials are known [3, 4], no design method is available which takes into account the AC losses. Calculation of the AC losses by numerical methods is usually time consuming [5]. As a faster alternative analytical equations can be applied, but these cannot take into account all relevant phenomena, for example the dependency of the critical current density on the magnetic flux density [6].

In this paper, a design method for motors with superconducting coils is presented which takes into account the AC losses. The method is based on finite element method (FEM) models which include the dependency of the critical current on the temperature and magnetic flux density. The coils are YBCO superconducting tapes with a non-magnetic substrate. The method determines the parameters which maximize the force density of four linear motor types with superconducting coils. These parameters are the temperature, the number of turns of the superconducting coils, the tooth width of the core, and the peak value of the current through the superconducting coils. The results show the dependency of the maximum force density on the operating temperature and the number of turns.

II. MODELS AND METHODS

A. Motor geometries

Four types of double-sided linear motors with superconducting stator windings are analyzed. These are: coreless motor with moving permanent magnets, coreless motor with moving copper coils, iron core motor with moving permanent magnets, and iron core motor with moving copper coils. An example of the full iron core motor with moving copper coils, and one periodic section of each of the motors is shown in Fig. 1. The full motor with a double-sided stator is obtained by mirroring the periodic section in the Dirichlet boundary and by repetition.

![Fig. 1: Example of a full linear motor (a) and periodic sections of one side of the analyzed double-sided motors: (b) coreless with moving permanent magnets, (c) coreless with moving copper coils, (d) iron core with moving permanent magnets, and (e) iron core with moving copper coils.](image-url)
TABLE I: Parameters of motor geometries.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of turns superconducting coil</td>
<td>N</td>
<td>variable</td>
</tr>
<tr>
<td>Inner diameter superconducting coils</td>
<td>d_{in}</td>
<td>40 mm</td>
</tr>
<tr>
<td>Spacing between superconducting coils</td>
<td>d_{s}</td>
<td>10 mm</td>
</tr>
<tr>
<td>Thickness cryostat</td>
<td>d_{c}</td>
<td>10 mm</td>
</tr>
<tr>
<td>Height back-iron</td>
<td>h_{bi}</td>
<td>30 mm</td>
</tr>
<tr>
<td>Tooth width</td>
<td>w_{t}</td>
<td>variable</td>
</tr>
<tr>
<td>Height magnets</td>
<td>h_{m}</td>
<td>20 mm</td>
</tr>
<tr>
<td>Height coils</td>
<td>h_{c}</td>
<td>20 mm</td>
</tr>
<tr>
<td>Width superconducting coil bundle</td>
<td>w_{kb}</td>
<td>variable</td>
</tr>
</tbody>
</table>

Fig. 2: Motion profile of the motor.

of the resulting section at the periodic boundaries. All the motor types have superconducting coils in the stator. In the moving-magnet motors, currents in the superconducting coils are commutated. In the moving-coil motors, the superconducting coils carry DC currents, and produce a stator field, and the currents in the copper coils of the mover are commutated.

The geometric parameters of the motors are shown in Table I. The inner diameter of the superconducting coils is limited by the minimum bending radius of the superconducting tapes [7]. The thickness of the superconducting coil bundle, w_{kb}, depends on the number of turns. For the iron-core motors, the tooth height is equal to 34 mm and the opening of the teeth is chosen such that force ripples are minimized. The width of the permanent magnets is equal to 0.8 times the magnet pitch, to reduce force ripples. In the moving-magnet motors, the air gap, h_{gap}, is equal to 1 mm, while in the moving-coil motors the air gap is equal to 2 mm, to allow room for the water cooling system of the copper coils. For the moving-coil motors, the width of the coil bundles equals 1/3 of the coil pitch. The peak current density in the copper coils is equal to 40 A/mm², which can be achieved with appropriate water cooling.

In the application, a highly dynamic motion profile is required. The motion profile used for the optimization procedure is shown in Fig. 2. A peak force of 10 kN is required at the maximum acceleration, and the maximum velocity is equal to 8 m/s. Furthermore, the input power of the cryocooler should not exceed 30 kW.

B. Material parameters

The magnetic materials in the motors include the permanent magnets, soft-magnetic back-iron, and the superconducting tape. The permanent magnets have a remanence of 1.3 T. For the back iron, a Cobalt-Iron alloy is modeled, which is a nonlinear soft-magnetic material with a saturation flux density of 2.2 T.

The resistivity of superconducting material is described by the macroscopic power law model

\[ \rho = \frac{E_c}{J_c} \left| \frac{1}{J_c} \right|^{n-1}. \]  (1)

A threshold voltage, \( E_c = 100\mu V/m \), and an \( n \)-value of 25 are used in the models. The dependency of the critical current density, \( J_c \), on the parallel and perpendicular components of the local magnetic flux density is described by the elliptic model

\[ J_c = \frac{J_{C0}}{\left(1 + \frac{\sqrt{k^2|B_{||}|^2 + B_{\perp}|^2}}{B_0}\right)^\alpha}, \]  (2)

which is an extension of the Kim model [8]. The parameters \( J_{C0}, k, B_0, \) and \( \alpha \) have been obtained by a least square error fit of the elliptic model to Superpower [9] measurement data for the considered temperatures. The critical current density \( J_{C0} \) and critical current \( I_c \) relate as

\[ I_c = 2adiJ_{C0}, \]  (3)

where the half-width superconducting tape, \( a_i \), is 2 mm, and the thickness of the superconducting layer, \( d_i \), is equal to 1 \( \mu m \). The critical current and other tape parameters are given in Table II. The thickness of the superconducting tape, including insulation \( L_{\mu} \), is 293 \( \mu m \), such that the coil bundle width is equal to \( NL_{\mu} \).

III. Finite element modeling

The generated force and AC losses in the superconducting tapes are calculated by 2D finite element models. Several methods are combined to reduce the computation time of the models, and are implemented in Comsol [10]. Two finite element models per motor type are used, as illustrated in Fig. 3. The first model calculates the magnetic flux density on a boundary around the superconducting coil and the force, the second model calculates the AC losses, taking into account the flux density on the boundary, as calculated by the first model.
This method neglects any coupling between the inhomogeneity of the current distribution in the superconducting coils and the magnetic flux density at the boundary.

The first model is a magnetostatic model based on the vector potential formulation, and consists of a single periodic section of the motor. In this model, a homogeneous current density is imposed on the superconducting tapes. The generated force and magnetic flux density are calculated at 1 ms time intervals of the motion profile. The mover is modeled as a single region and the magnetization or current density in this region is imposed as an analytic function of time. Therefore no remeshing is required in between time steps to include the motion of the mover.

The second model is a transient magnetic model, based on the H-formulation implemented with edge-elements. This finite element model includes one coil side, and a bounded air region around the coil side. On the boundary of the air region, the time dependent flux density calculated by first model is imposed [11]. A total current per tape is imposed, such that the current density in the superconducting coil can be non-homogeneous. The macroscopic power law model is applied to model the superconducting material. A homogenization approach is used to model the coil sides [12]. This approach assumes an equal current density distribution in groups of adjacent tapes, and therefore greatly reduces the number of required mesh elements. Only one coil side is included in the model, since the losses in each coil side are approximately equal. Losses in the coil side are multiplied by the number of coil sides per segment to obtain the total loss per section. Dependent on the model and its parameters, the calculation time of the force and the AC losses ranges from 3 to 15 minutes.

IV. DESIGN METHOD

The design method, illustrated in Fig. 4, determines the parameter values which maximize the force density of the four motor types for a given cryocooler input power and a given required peak force. For each motor type, the operating temperature $T$, number of turns, and tooth width (if applicable) are varied over a pre-determined range. The superconducting tape parameters are set dependent on the temperature. The peak current of the moving-magnet motors is the maximum value of the phase currents which are commutated for maximum propulsion force (q-axis). In the moving-coil motors, the peak current is the value of the DC current in the superconducting coil. For each combination of parameters the peak current is increased in steps of 10% of the critical current, and the force and AC losses in the superconducting coil per section (as shown in Fig. 1) are calculated. Losses in the copper coils are not taken into account. If the losses per section exceed a limit much higher than the available cooling power, the geometry is not evaluated at higher currents by the design method.

Given the calculated peak force per periodic section, $F_{pk}$, multiple periodic sections are required to achieve the required peak force of the full motor, $F_{req}$, of 10 kN. The time averaged AC losses of the full motor, $P_{full}$, are calculated from the AC losses per section, $P_{sec}$, as

$$P_{full} = \frac{F_{req}}{F_{pk}}P_{sec}. \tag{4}$$

The AC losses should be compensated by a cryocooler. The input cooling power $P_{in}$ is chosen as 30 kW. GM cryocoolers achieve an efficiency of approximately 10% of the Carnot limit [13]. Therefore, the available cooling power of the full motor, $P_{cool}$, is given by

$$P_{cool} = P_{in} \frac{T}{T_h - 0.1}, \tag{5}$$

where the temperature of the environment $T_h$ is 300 K. Finally, the maximum force density of a motor geometry is determined at the highest superconductor peak current for which the losses of the full motor are lower than the available cooling power.

V. RESULTS AND ANALYSIS

To validate the accuracy of the calculated AC losses of the reduced model as described in the previous section, it is compared to a model fully implemented in the H-formulation, where each turn of the superconducting coils is represented by a separate region. The losses calculated by both models, for the iron core moving-magnet motor, with 100 turns and 3 cm wide teeth, at a temperature of 40 K, and a peak current of 20% of the critical current, are shown in Fig. 5. The calculated losses of the models are similar, and their average value differs by only 8.6%. However, the calculation time of the full model is 24 hours, while the reduced model requires 18 minutes, which is a factor 80 faster.

![Diagram](image-url)
The design method is applied to the four given motor types. The resulting maximum force density of all motor types for four different temperatures, as a function of number of turns and tooth width is shown in Fig. 6. The results show that all motor types can achieve a force density close to 2500 N/dm$^3$ at 20 Kelvin. The force density for all motor types decreases with an increase in temperature as a result of the decrease in critical current density, although the available cooling power increases. For some combinations of geometry and temperatures the required force cannot be produced, since the total AC losses in the required number of sections are higher than the available cooling power for any value of the peak current. For both moving-magnet type motors, the highest force density is achieved for coils with approximately 100 turns, because for these coil widths the magnet pitch is favorable. For the moving-coil type motors, the force density increases for coils with a higher number of turns. The evaluation of the force density for peak currents in steps of 10% of the critical current does result in some irregularities in the results of Fig. 6.

VI. Conclusions

This paper presented a design method for linear motors with high-temperature-superconducting tapes. The method includes several model simplifications to decrease the computation time of the finite element models. The method was applied to four different motor types, and it was shown that all types can reach a maximum force density of around 2500 N/dm$^3$. For the moving-magnet type motors, the optimum number of turns lies between 50-100, while for the moving-coil type motors the force density increases with the number of turns. The force density of all motor types increases with decreasing operating temperature.
REFERENCES


