Characteristic and magnetic field analysis of a high temperature superconductor axial-flux coreless induction maglev motor

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(Presented 31 October 2011; received 15 September 2011; accepted 20 October 2011; published online 15 February 2012)

A new high temperature superconductor axial-flux coreless maglev motor (HTS AFIM) is proposed, of which the primary windings are made of HTS tapes and the secondary is a non-magnetic conductor. The main works of this paper are the magnetic-field computation and characteristics analysis of HTS AFIM. For the first one, the reduction of magnetic fields near outer and inner radius of the HTS AFIM is solved by introducing the sub-loop electro-magnetic model along the radial position. For the second one, the AC losses of HTS coils are calculated. The relationships between the device's characteristics and device parameters are presented, and the results indicate that under certain frequency and current levitation device can output enough lift force. The conclusions are verified by finite element calculations. © 2012 American Institute of Physics. [doi:10.1063/1.3671783]

I. INTRODUCTION

AC applications, such as a power cable and a motor using Bi-2223 Ag-sheathed tape have been studied.¹ At present, the HTS motors are all focused on the DC motors and AC synchronous motors. The HTS linear induction motors (LIMs) are mainly focused on the bulk motors and permanent magnet synchronous motors.²⁻⁴ The HTS LIMs were conducted in Ref. 5.

The high temperature superconducting axial-flux coreless maglev motor (HTS AFIM), which is an electro-dynamic system (EDS), is presented in this paper.

The permanent magnets EDS have been studied by many researchers, such as Jonathan Bird and Thomas A. Lipo.⁶⁻⁸ However, the rapid translational motion of magnetic fields past conductors creates an unavoidable magnetic drag force, which tends to have a rather low levitation/drag ratio. The HTS AFIM, with rotating magnetic field (RMF) in its air-gap is generated by 3-phase AC current in the HTS primary coils. The interaction between the RMF and secondary eddy current induced by the RMF produces lift force, and stable electro-dynamic magnetic levitation can be realized while the device is static.^{5,9}

II. MACHINE CONSTRUCTION AND MODELING ANALYSIS

A. Machine construction

The machine is constructed of the coreless non-magnetic secondary and primary, as shown in Fig. 1. Three-phase HTS windings are placed in the slotted stator core to produce the time varying magnetic field.

B. AFIM modeling and analysis

The disk primary will be divided along the radial into the rings. We splice each ring model along the radial direc-

tion as shown in Fig. 2, and unfold it, which is similar to the long and narrow rectangular linear motor structure as shown in Fig. 3 below. The radial distribution of the air-gap magnetic field is converted to the horizontal distribution.

The geometry used to model the motor fields is shown in Fig. 3. Let the upper surface of the conducting plate coincide with the x-y plane ($y = 0$); the primary, which is located in a plane parallel to the surface of the conducting plate, at $y = g$, moves in the x direction.

To complete the problem definition and to get to a unique solution, the following boundary conditions are fixed:

First, the traveling wave excitation surface currents at the primary. The surface currents density caused by phase current A, B and C can be derived as¹⁰

$$J_a = \frac{4NI_1}{p\tau_n} \sin\left(\frac{b_n}{\tau_n}\right) \cos\left(\frac{\pi}{\tau_n}x\right). \quad (1)$$

$$J_b = \frac{4NI_1}{p\tau_n} \sin\left(\frac{b_n}{\tau_n}\right) \cos\left(\frac{\pi}{\tau_n}x - \frac{2\pi}{3}\right), \quad (2)$$

$$J_c = \frac{4NI_1}{p\tau_n} \sin\left(\frac{b_n}{\tau_n}\right) \cos\left(\frac{\pi}{\tau_n}x + \frac{2\pi}{3}\right). \quad (3)$$

Then, the excited surface currents density caused by the three phase ac currents can be obtained by taking the sum of Eqs. (1)–(3). This gives

FIG. 1. (Color online) HTS AFIM machines.

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FIG. 2. (Color online) Sub-loop model of the AFIM motor.

$$j_1 = J_a + J_b + J_c = 3\sqrt{2}NI_1 \sin(b_n/\tau_n) / p\tau_n \cdot e^{j(\omega t - kx)}, \quad (4)$$

$$j_1 = J_1 e^{j(\omega t - kx)},$$

where N is the coil number; $2b_n$ is the width of the E-type laminated thin steels; I_1 is the primary current, $\omega = 2\pi f$, $k = \pi/\tau_n \cdot \tau_n$ is the pole pitch of the n th ring; p is the number of pole pairs; f is the frequency of the primary current.

Second, the machine is assumed to be infinitely long and has a periodic construction. Third, the permeability of the stator core is assumed to be infinite, whereas the relative permeability of the winding, air gap as well as the shaft is assumed to be one.

The magnetic field produced by the primary current of the machine can be described by the scalar magnetic potential A_z ,

$$A_{n2z} = (c_1 e^{py} + c_2 e^{-py}) e^{i(\omega t - k_n x)} \quad \text{in region 2 (air space),} \\ 0 < y < g, \quad (5)$$

$$A_{n3z} = (c_3 e^{\beta_n y} + c_4 e^{-\beta_n y}) e^{i(\omega t - k_n x)} \quad \text{in region 3 (secondary),} \\ -d < y < 0, \quad (6)$$

$$A_{n4z} = (c_5 e^{py} + c_6 e^{-py}) e^{i(\omega t - k_n x)} \quad \text{in region 4 (air space),} \\ y < -d, \quad (7)$$

The boundary conditions to be satisfied are

$$B_{x2}(y=g) = \frac{\partial A_{2z}}{\partial y} \bigg|_{y=g} = \mu_0 J_1, \quad (8)$$

$$H_{x2}(y=0) = H_{x3}(y=0), \quad A_{2z}(y=0) = A_{3z}(y=0), \quad (9)$$

$$H_{x3}(y=-d) = H_{x4}(y=-d), \quad A_{3z}(y=-d) = A_{4z}(y=-d), \quad (10)$$

$$A_{4z}(y=-\infty) = 0. \quad (11)$$

FIG. 3. 2-D long and narrow rectangular linear motor.

FIG. 4. Measurement system scheme of AC losses.

Application of the boundary conditions the lift force can be written as

$$F_{lift} = \sum_{n=1,2,3,\dots,m} \frac{r_2 - r_1}{4m\mu_0} \int_0^{2\tau_n} \text{Re}(B_{y3n} \cdot B_{y3n}^* - B_{x3n} \cdot B_{x3n}^*) dx,$$

where r_2 is outer radius of the stator core, r_1 is inner radius of the stator core, m is the number of sub-loops.

III. AC LOSS OF THE HTS COIL

To estimate the ac loss caused by the transport current, we adapted an analytical model to give the prediction.^{11,12} This model starts as an infinitely long stack of tapes carrying the same current. The magnetic flux lines lie parallel to the tapes where the flux has not penetrated. In the penetrated part the critical current density $J_c(x, z)$ is low, while a much lower current density J_m flows in the middle un-penetrated region. Below, $J_c(x, z)$ is given by the expression (12),

$$J_y = f(B_z) \\ = \begin{cases} J_c = J_0 \frac{B_0}{B_0 + |B_z(x, z)|}, & \text{where } c(z) \angle |x| \angle a \\ J_m = \frac{I/D - 2 \int_{c(z)}^a J_0 \frac{B_0}{B_0 + |B_z(x, z)|} dx}{2c(z)}, & \text{where } |x| \angle c(z) \end{cases} \quad (12)$$

where B_0 is a material constant and $B_z(x, z)$ is magnetic field in the z axis direction; a , $c(z)$, and D have the same meaning

FIG. 5. (Color online) Photograph of prototype motor with copper coils.

FIG. 6. (Color online) Curve between lift force and primary phase current.

as Ref. 4, which is proposed the expression by W. J. Yuan and is shown below,^{4,5}

$$Q_0 = 2 \int_{-b}^b \int_{c(z)}^a J_c(x, z) |B_{zf}(x, z)| (a - x) dx dz. \quad (13)$$

The experimental establishment is as shown in Fig. 4. The process of experimental is shown in article of our team Ref. 13.

IV. RESULTS AND DISCUSSION

The computer-simulation model constructed by the FEM has been developed for software ANSOFT and the AFIM motor with copper coils as shown in Fig. 5 is tested to verify the analytical results. The AC losses calculated by the extended Clem are analyzed and compared with the measured results.

Figure 6 shows the lift force with different-current in the secondary region. The curve indicates that the larger input current will produce a larger lift force. Figure 7 shows the comparison among experimental, analytical, and FEA results for lift force with air-gap in the secondary region. The curve indicates that the lift force increases as the air-gap decreases.

The experiments were carried out on a No. 15 coil in different frequencies. Specifications of the coil are the same as Ref. 13. Both experimental and theoretical results are listed in Fig. 9. The curve shows that the AC losses increase as the

FIG. 7. (Color online) Curve between lift force and air-gap length.

FIG. 8. (Color online) Comparison results of experimental and theoretical AC losses with different frequencies.

frequencies increase and the larger current will produce a larger AC loss. Therefore, the maximum current is 20 A and the maximum frequency of 10 Hz are designed in the HTS coil.

V. CONCLUSIONS

Analytical models, formulated in Cartesian coordinates, have been developed for predicting the field distribution in HTS AFIM, and the AC losses in the HTS coil with transport currents were numerically evaluated by the extended Clem model and measured by the electrical method. The field distribution analysis and AC losses performed in this paper can provide very useful information of mechanical-structure design and control-strategy development for the HTS AFIM.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China Nos. 51077003 and 50807004, by the Doctoral Fund of Ministry of Education No. 20090009110025, and by the Fundamental Research Funds for the Central Universities of China Nos. 2011YJS277 and 2011YJS275.

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