Experimental and Numerical Studies of a Linear Synchronous Motor with the Secondary Made of Coated Superconductor

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Abstract—Thrust tests of a linear synchronous motor (LSM) with its secondary made of coated superconducting coils were conducted via the built prototype over the traditional copper windings. A numerical model of the superconducting LSM was made and the measured data of experiment validate its reliability. The nonlinear resistivity of coated superconductor was electromagnetically modeled by resorting to the power law in conjunction with the constitutive relationship of conductor. Based on the numerical model, we carried out a set of transient studies to make a forecast about the superiority of the proposed high temperature superconducting (HTS) LSM, such as magnetic field distribution and the time evolution of thrust together with the speed in different loads and frequencies. The achieved results clearly confirm that the proposed HTS LSM has the advantages to work as a candidate for developing the high-thrust LSM with a large air gap.

Index Terms—Air gap, high thrust, HTS, LSM.

I. INTRODUCTION

With the merit of converting electric power to the linear motion without gears [1], linear motor is very attractive in a wide range of industrial fields [2]. The linear synchronous motor shows many advantages for the application in high speed transportation. However, the limited current capacity of copper windings puts restrict on the efficiency and output power of traditional linear machines, especially in the operating condition of large air gap because the magnetic flux density in the air gap plays an important role on its performance. Substituting conventional copper coils with superconductor is a promising method to improve this unfavorable situation. Due to the high current density carrying ability and the little joule loss property in coated superconductor, the superconducting coils can produce intense magnetic flux [3] and thus grant the machine enough power even at large air gap, which is critical to rail transportation [4]. In addition, such increase of coil current can also reduce the volume and weight of the field magnet to make the traction system more compact.

A variety of concepts of superconducting linear machines have been proposed worldwide [5]-[7]. Among these efforts, much attentions were devoted to developing the superconducting bulk machines [8]-[10], in particular for the electromagnetic aircraft launch system [11]. The development of the linear motor using superconducting tapes has also showed good performance of improved efficiency and high power density [12]. Zhao et al manufactured a HTS linear induction motor (LIM) with the Bi-2223 superconducting tapes as the primary windings [13], but the actual performance of the HTS LIM is limited by the AC loss and weak superconductivity of Bi-2223 superconducting tapes at the temperature region of liquid nitrogen [14].

In view of the facts mentioned above and the development on the performance of YBCO coated superconductors, recent works focus on applying the YBCO tapes for field magnet to improve the performance of the linear motors. In 2009, Yen et al proposed a linear synchronous motor (LSM) with traditional copper windings as its primary and coated superconductor coils as secondary [15]. Because of the DC current injected in the coils, the coated superconductor can give full play to its superiority. The thrust and normal forces were studied by experiment [16, 17] and finally extended to cases of four connected coated superconducting coils [18]. More recently, De Bruyn et al presented a numerical modeling method based on the H-formulation for AC losses calculation in highly dynamic linear actuators with coated superconducting tapes [19]. In 2014, Martins et al fabricated a single pancake racetrack coil made of the coated superconducting tapes as field windings and the thrust against position under the quasi-static condition has been measured over a conventional copper stator [20]. These studies examined the basic characteristics of LSM with coated superconductor as a constituent and pointed us a promising way to upgrade the performance of LSM via replacing traditional field magnet mover with the coated superconducting coils. To explore the linear traction system with high-thrust and large air gap, this paper proposed a LSM with coated superconductor coils as the secondary. Static force-height relationship was tested based on the built prototype and a numerical model of the LSM was established to take further investigation of its performance. The dynamic properties of the LSM was also investigated with the model.
II. FABRICATION OF THE PROTOTYPE

A. Structure of the armature windings

The partial layout of armature windings of the LSM is shown in Fig. 1 and the parameters of the system are shown in Table 1. The number of the slots of per pole per phase is 2 with double cascade winding arrangement.

B. Coated superconducting coils

Fig. 2 (a) shows the single racetrack coil which was constructed of YBCO tapes (cross section: 4.75×0.25 mm) and there are totally four superconducting coils were used to work as double pairs of poles. The inner diameter $d_a=50$ mm, outer diameter $d_{oa}=60$ mm and the side length $l_s=170$ mm. The coil framework is made of epoxy resin, specially customized to protect the turns and ensure mechanical stiffness in liquid nitrogen with the advantage of light weight. The energized coated superconductor coils are embedded into a support made of epoxy glass cloth laminated sheet with pole pitch of 60 mm and the material of the support has the merits of non-magnetic, insulating and nice mechanical property at low temperature. One of the key point in assembling the secondary is to ensure the lowest possible terminal contact resistivity and avoid the mechanical stress in the strip, which is accomplished by the lap joint solder method with a joint resistance in the magnitude of $n\Omega$ [21], enabling the superconducting coil array to carry large current with less loss.

III. MODELING OF NONLINEAR BEHAVIOR OF SUPERCONDUCTOR

The superconductor has a nonlinear relationship between the electric field $E$ and the current density $J$ represented by an empirical equation (1),

$$E = E_c \left( \frac{|J|}{J_c} \right)^n \frac{J}{|J|}$$

where $E_c = 1 \mu\text{V/cm}$ is the criterion of critical electric field, $n$ is an creep index to indicate the nonlinearity of superconductor and $J_c$ is the critical current density determined in this paper by

$$J_c = \frac{I_c}{w(Ad)}$$

where $w$ is the width of the coated superconductor, $Ad$ is the average thickness of the superconducting tape with turn to turn insulation considered, and $I_c$ represents its critical current.

Since the FEM method is allowable to create a new material whose conductivity $\sigma$ is determined by electric field $E$, we made a transformation of the (1) and the equivalent conductivity of superconductor was deduced as follows,

$$\sigma = J_c \left( \frac{E_c}{|E|} \right)^{n+1}$$

To simplify the form (3), we assume $n\rightarrow\infty$ where the power law is reduced to the Bean’s model of critical state [22]. Then we obtained a simple constitutive relation of HTS,

$$\sigma = J_c \frac{1}{|E|}$$

According to this simplified expression, we successfully introduced the HTS material into the FEM model [22-24].

IV. EXPERIMENTAL INVESTIGATION

To study the feasibility of the proposed LSM with secondary made of coated superconducting coils, we built a prototype and tested the static force over traditional copper windings. Besides, the dynamic experiment of the proposed HTS LSM was also achieved success based on this prototype, see Fig. 2 (b).
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Fig. 3. Static force tests of the proposed HTS LSM (a) Time evolution of the thrust at 2 Hz. (b) Maximum thrust curve against different air gap.

The static force of the proposed HTS LSM against time, obtained by experiment and finite-element analysis at a frequency of 2 Hz and voltage of 120 V in armature windings together with the superconducting coil current being 80 A, was showed in Fig. 3 (a). Their behaviors are similar that both experimental and simulation results are sine curve and main features of them fit very well with the peak value of 45 N. Fig. 3 (b) illustrates the maximum thrust of HTS LSM versus the mechanical air gap $h_g$ by means of experiment and simulation with $f$, primary voltage $V_p$ and superconducting current $I_s$ being 3 Hz, 150 V and 80 A respectively. The result shows that the thrust decreases as the air gap increases, of which the experimental and simulation results shared the same variation trend once again. The established numerical model has been confirmed by the result of the experiment, therefore, more works will be done by means of FEM in the following section to make further study of the proposed HTS LSM.

V. FURTHER INVESTIGATION VIA SIMULATION

In this section, the 2-D numerical model of the LSM which has been validated by experiment was used. The turns of superconducting coil is enlarged to 70 and the fundamental characteristics of superconducting LSM is compared with a traditional PM LSM, whose primary is the same as the superconducting LSM, width of PM is the same as the outer width of coated superconducting coil, length of PM equals to the straight section of the racetrack coil and the secondary core also made of epoxy reinforced glass fiber. Fig. 4 shows the magnetic flux density $B$ for the HTS LSM which says that the flux forms a large circle between primary and secondary which gives an intuitive feeling for their interactions. This figure also shows that parts of the primary core is subjected to a relatively high value of magnetic flux density, which prompts us to adopt high permeability alloys or optimize the primary core structure.

The flux distribution at the central line of the air gap in one pole pair at different instants (0, 83.3, 166.7 and 250 ms) within a time cycle was simulated, as shown in Fig. 5. The primary winding alternating current is 24 A in amplitude and DC current in secondary superconducting coil is 110 A. Generally, the field in the air gap displays good sine feature along the red arrow direction and travels smoothly along the stator position against time. Specially, the flux leakage in the air gap is about 12.5 mWb and the travelling speed is 0.36 m/s. As mentioned above, the working frequency is 3 Hz and pole pitch $= 60$ mm, so the synchronous speed is also 0.36 m/s, which equals to the speed of travelling-wave.

Fig. 4. 2-D model of HTS LSM and the value of magnetic flux density is indicated by color and its direction pointed by small arrow.

Fig. 5. Travelling flux distribution along the central line of the electromagnetic gap (10 mm) within one pole-pair pitch at the time instant of every 1/4 cycle with the working frequency being 3 Hz.

The thrust of the locked-mover against electric degree of the HTS LSM with the air gap of 20 mm was showed in Fig. 6. The thrust develops as a sine wave against electric degree, which is directly related to the forms of travelling flux, with the maximum values of 612 N. The inset shows the tendency of the peak value of the thrust when the air gap of the system changes. There is an obvious reduction of the peak thrust as the air gap
The speed curves of two kinds of motor with different loads are illustrated in Fig. 7 (a) and (b). The mover weight is 22.5 kg in both cases with 3 Hz being the operating frequency and air gap height being 20 mm. At the start, the mover travels in the opposite direction for an instant while because of the constant load. After that it keeps on moving in the forward direction due to the effect of electromagnetic force and finally reaches to the synchronous speed of 0.36 m/s. When the load beyond a specific value, the secondary will move in the opposite direction under the load force and can’t start properly. The maximum value of the load which the HTS LSM could suffer is much larger than the PM LSM. Besides, this graph also shows that when the HTS LSM could start properly, the motor reaches to the stable speed after identical time period, even though with different loads which means that the starting time of the speed line is independent of the loads, which is a great advantage for industrial application. Fig. 8 (a) and (b) demonstrate the thrust curve against time with different loads, which are corresponding to the speed curve in Fig. 7 (a) and (b) respectively. When the load force is less than the maximum load capacities of the linear motor, the electromagnetic force reaches to peak value rapidly. Mover keeps on accelerating and finally reaches to a steady state with its speed constant when the electromagnetic force is equal to the load force after a series of fluctuation.

VI. CONCLUSION

This paper reports the preliminary work of developing an HTS LSM with the secondary made of coated superconductor coils. The electromagnetic force is measured by experiments which shows an ideal result of thrust at large air gap. A numerical model of the LSM was established by finite element method, which was validated by the data obtained of the experiment. The effect caused by load and mover mass on the
performance, such as thrust and speed, has been examined for further investigation based on the numerical method. The results of both experiment and simulation confirm the feasibility of HTS LSM which could keep available output with a large air gap.

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