Driving Characteristics of an HTS Linear Synchronous Motor for an HTS Magnetic Suspension and Propulsion System

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Abstract — In this paper, driving model of a high temperature superconducting (HTS) linear synchronous motor (HTSLSM) with HTS bulk magnet secondary for an HTS magnetic suspension propulsion system is introduced with numerical analysis results. Different magnetization methods are applied to obtain the HTS bulk magnets, and the HTS magnetization characteristics using those methods are identified. Comprehensive experiment has been conducted to the HTSLSM drive. The practical results obtained show that the HTSLSM developed has applicable thrust characteristics without the conventional friction, and a better practical performance can be achieved by using HTS bulk magnets having a higher trapped magnetic field.

I. INTRODUCTION

With the improvement of high temperature superconducting (HTS) material performance and application technologies, linear motor with HTS bulks or HTS coils have been developed. The developed linear motors to date based on their principles and structures mainly can be classified as: 1) HTS linear reluctance motor (LRM) with zero-field-cooling (ZFC) HTS bulk as secondary; 2) HTS linear synchronous motor (HTSLSM) with HTS bulk magnets or HTS coil magnets as secondary [1,2]; 3) HTSLSM with HTS coil winding as primary [3]. These HTS linear motors also can be further divided into: 1) single-sided type; 2) double-sided type, and 3) cylindrical in structures. Comparing to the conventional linear motors, HTS linear motors has many advantages like less weight, smaller size and higher efficiency etc. for using the resistance-less HTS wires or strong-pinning HTS bulks with high trapped magnetic field.

In this work, a single-sided HTSLSM with moving HTS bulk magnet secondary for an HTS magnetic suspension propulsion system has been proposed and developed. The numerical model of the HTSLSM will be given in the paper with the magnetization characteristics of HTS bulk magnets by different magnetization methods. Experimental results are presented to characterize the HTSLSM performances.

II. HTSLSM DRIVING MODEL FOR HTS MAGNETIC SUSPENSION PROPULSION

A new type HTSLSM model for HTS magnetic suspension driving has been proposed with the schematic as shown in Fig. 1. The HTSLSM is located in the middle of the propulsion system, and the HTS bulks-permanent magnet guideway (PMG) repulsion type magnetic suspension sub-systems are on both sides of the LSM. The HTS magnetic suspension sub-system can provide stability levitation force F_{Lev} and guidance force F_{Gui} on vertical and lateral directions at stationary or moving states without any active control system, so that the HTSLSM can run freely with the functions of self-levitation and self-guidance and without any sliding friction force.

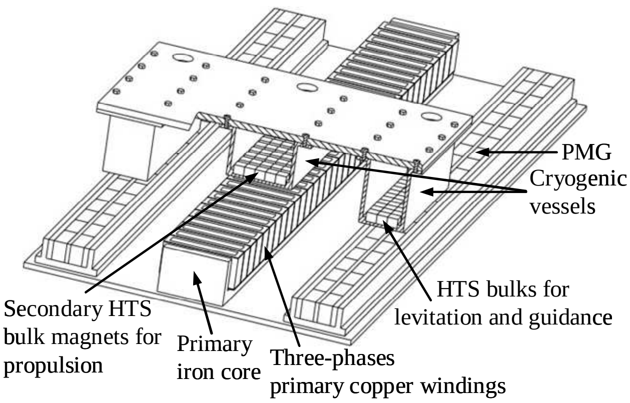

Fig. 1. Principle scheme of the HTS magnetic suspension propulsion system driven by HTSLSM.

III. NUMERICAL MODEL AND CHARACTERISTICS OF THE HTSLSM

The longitudinal section with magnetic circuit of the HTSLSM is shown in Fig. 2. According to the empirical value, the relative permeability of HTS bulk magnet μ_{r} is set to be 0.4. Neglecting the magnetic reluctance of primary iron-core and secondary back-iron, the magnetic flux linkage of one coil generated by one pole-pair HTS bulk magnets can be obtained approximately as

$$\psi_{\mathrm{SC}} = \frac{\mathscr{F}}{R_{\mathrm{tot}}} = \frac{2H_c \cdot h_s}{\dfrac{2h_s}{\mu_r \mu_0 l_s w_s} + \dfrac{2g}{\mu_0 \cdot (l_s + l_t)/2 \cdot (w_s + w_t)/2} + \dfrac{2\tau}{\mu_0 \cdot w_s \cdot h_s}}$$
$$= \frac{B \cdot h_s (l_s + l_t) \cdot (w_s + w_t) l_s w_s h_s}{h_s (l_s + l_t) \cdot (w_s + w_t) h_s + 4\mu_r g l_s w_s h_s + \mu_r \tau l_s (l_s + l_t) \cdot (w_s + w_t)} \quad (1)$$

where $\mathscr{F}$ is the magnetomotive force of magnetic circuit, R_{tot} the total magnetic reluctance, H_c the magnetic field intensity of HTS bulk magnet, μ_0 the permeability of vacuum; l_{s}, w_{s}, and h_{s} are the length, width and height of

HTS bulk magnet respectively; l_t, w_t are the length and width of stator-tooth respectively. When the parameters are substituted in (3), ψ_{sc} can be calculated out with the value of 0.42 mWb.

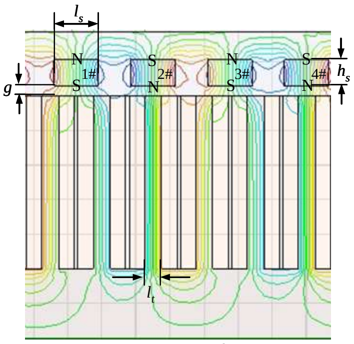

Fig. 2. Magnetic circuit of the HTSLSM.

The back EMF is determined with an rms value as $E_0 = \pi N_1 k_N \psi_{SC} v_s / \sqrt{2}\,\tau$, and then the electromagnetic thrust F_{em} is

$$F_{em} = \frac{P_{em}}{v_s} = \frac{3pE_0\left[U\left(X_t \sin\theta + R_1\cos\theta\right) - E_0 R_1\right]}{2\tau f\left(R_1^2 + X_t^2\right)} \\ = 3pE_0\left[U\sqrt{R_1^2 + X_t^2}\sin\left(\theta + \phi\right) - E_0 R_1\right] \Big/ 2\tau f\left(R_1^2 + X_t^2\right) \tag{2}$$

where P_{em} is the electromagnetic power, v_s the synchronous velocity, and $v_s = 2\tau f$, τ is the pole pitch and f is the frequency; N_1 is the number of turns of winding, k_N the winding factor, R_1 the phase resistance, X_t the synchronous reactance, p the pole pairs, U the phase voltage; ϕ is the load shift angle, and $\phi = \arctan R_1/X_t$. When load angle $\theta = 90° - \phi$, the maximum thrust F_{em_max} can be obtained.

When the f = 5 Hz, the results of F_{em_max} versus the trapped magnetic field B_{trap} of the HTS bulk magnets for different values of U/f are obtained as shown in Fig. 3, which shows that the F_{em_max} can reach a value of 3.8 kN with the B_{trap} = 3 T, U/f=40.

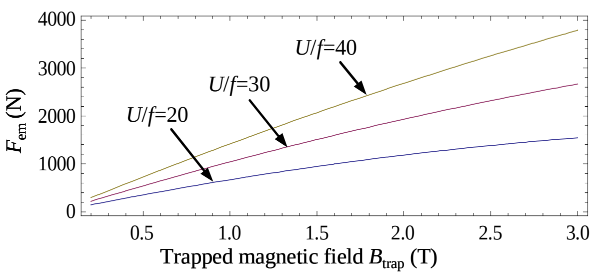

Fig. 3. F_{em} versus B_{trap} for different U/f.

IV. Magnetization Characteristics of HTS Bulk Magnet

The magnetic field trapping characteristics of HTS bulk by field-cooling (FC) and ZFC magnetization using a D.C. magnet, ZFC pulse magnetization using a pulse magnetizer are tested with the results as shown in Fig. 4. As it can be seen from the graph, the trapped magnetic field B_{trap} of HTS bulk magnet increases with the external magnetic field B_{ext} linearly, and then reaches saturation. The amplitude of B_{ext} for saturation magnetization using ZFC pulse magnetization is about double that for the ZFC D.C. magnetization, and four times that for the FC D.C. magnetization. The results have reference meanings to select appropriate methods to obtain HTS bulk magnets. For the low-field magnetization, using the FC D.C. magnetization is appropriate; however, ZFC pulse magnetization would be a better choice for the high-field magnetization for its lower cost and easier way to realize.

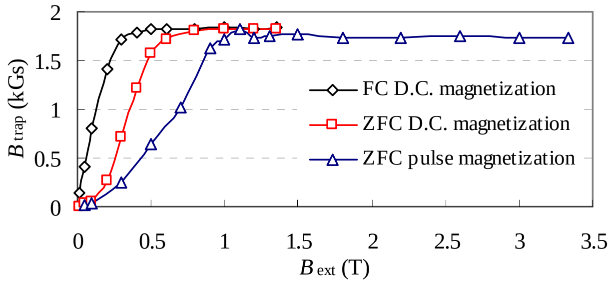

Fig. 4. HTS bulk magnetic field trapping characteristics comparison within the different magnetization methods.

V. Testing Results and Conclusions

HTSLSM with HTS bulk magnet secondary has been verified and tested with a practical prototype. The amplitude of the locked-mover thrust is the peak thrust force F_{em_max}. The locked-mover thrusts of the HTSLSM have been measured under working current for different frequencies with the results shown in Fig. 5.

From the results of running testing, the HTSLSM has a good thrust characteristic, and can move with stable levitation force and guidance force at various states without any guidance control system. A bigger thrust force of the HTSLSMs can be readily realized than conventional linear motors by using HTS bulks with higher trapped magnetic field, when the air-core stator used could escape magnetic saturation.

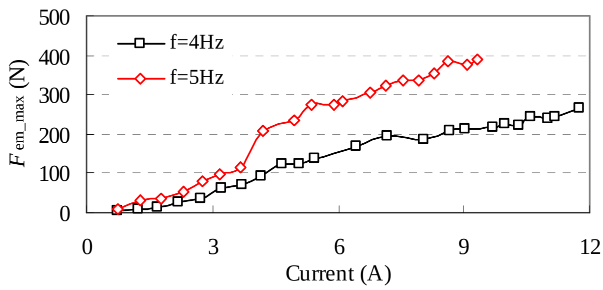

Fig. 5. F_{em_max} versus current for different f.

VI. References

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