

Analytical Modeling of High-Temperature Superconducting Single-Sided Linear Induction Motors for Rail Transportation Applications

Wei Qin¹, *Member, IEEE*, Lu Yujie¹, and Zou Duochang¹, Fang Jin¹,

¹ School of Electrical Engineering, Beijing Jiaotong University, Beijing, 100044, China

In this paper, an improved analytical model is presented for calculating the performance of a single-sided linear induction motor whose primary windings are made of high-temperature superconductors (HTS). The model is based on an accurate subdomain approach for predicting the magnetic field and structural parameters affecting the performance of the HTS SLIM with semi-closed slots. It considers the finite length of the primary iron core and the electromagnetic characteristics of the superconductor. Compared to conventional analytical models, the proposed model significantly improves accuracy by addressing the constraints related to the physical and mechanical properties of the HTS tape. Finally, finite element analysis (FEA) is employed to validate the proposed model, and the results are compared with experimental data from the HTS SLIM prototype.

Index Terms—HTS, SLIM, subdomain, Analytical Model, FEA.

I. INTRODUCTION

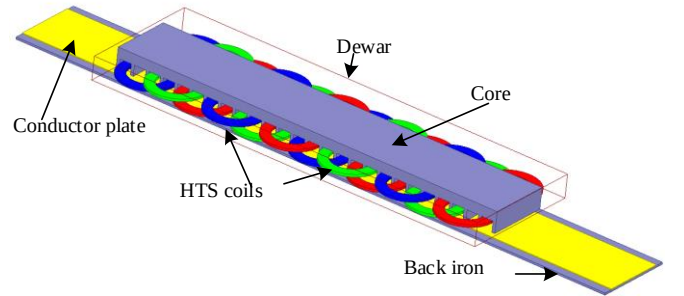
THE single-sided linear induction motors (SLIMs) are widely used in urban transportation systems due to their unique advantages, such as the absence of transmission gears and low vibration noise [1]. However, to ensure safe operation and manage initial capital costs, the air gap in LIMs is typically designed within a range of 10 to 100 mm. This design choice leads to higher leakage flux and lower efficiency, requiring larger excitation currents to maintain performance. HTS, with their characteristic high current densities and low power losses, offer the potential to increase linear current loading, thereby improving force density and overall efficiency compared to conventional machines. To enhance output power and reduce machine size, the HTS SLIM has been successfully developed. This configuration allows for a lighter, more compact motor while maintaining substantial thrust for propelling traditional trains or Maglev vehicles [2-3].

The structure of HTS SLIMs differs significantly from conventional LIMs, and the material properties, such as electrical conductivity and magnetic permeability, are more complex than those of conventional materials. Therefore, accurate and efficient design methods, along with reliable performance estimations, are essential for the study of HTS SLIMs. Zhao [3] and Li [2] investigated the influence of structural parameters, such as slot width, slot height, and winding turns, on performance using FEA. However, these methods are challenging to apply during the initial motor design, especially when multiple parameters vary over a wide range, and the state of the superconductor must be considered in superconducting motors.

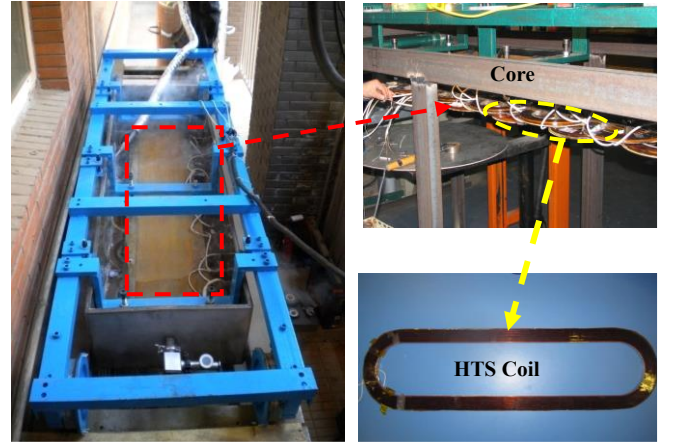
While analytical models are useful for the design and analysis of electromagnetic devices, the slotting effect significantly influencing the electromagnetic state of the superconductor is difficult to predict using traditional methods. The subdomain model, which divides the field domain into simpler subdomains, is effective for analyzing the slotting effect. In this approach, the vector potential in each subdomain is determined using the separation of variables method, and the field solution is obtained by applying appropriate boundary and interface conditions. Several studies have employed the

subdomain model to predict the magnetic field distribution resulting from end and slotting effects [4]. However, these models typically neglect the constraints imposed by the electromagnetic properties of the HTS tape.

This paper focuses on developing an accurate analytical model for HTS SLIMs based on the subdomain method, integrating the physical and mechanical properties of the HTS tape as constraints. The model is used to analyze the impact of key parameters, such as end and slotting effects, on thrust force and efficiency. The results for thrust force and magnetic flux density are then compared with those obtained from 2-D FEA. Finally, to validate the calculated results, a prototype of the HTS SLIM is fabricated and experimentally tested.



(a) 3-D schematic of HTS SLIM



(b) The prototype of HTS SLIM

Fig. 1 The configuration of the HTS SLIM.

II. ANALYTICAL MODEL

A. Mathematical Model

Fig. 2 shows the analytical model of the HTS SLIM, with the following key parameters defined: L_p (length of the primary), h_p (height of the primary core), h_t (height of the HTS tapes), h_s (height of the slot), w_2 (width of the slot), w_l (width of the tooth), d (thickness of the conductor plate), and d_l (thickness of the back iron). The 2-D magnetic vector potential is decomposed into two components: A_{xz} for the x -edges and A_{yz} for the y -edges. The governing equations and undetermined constants will be solved in the full paper.

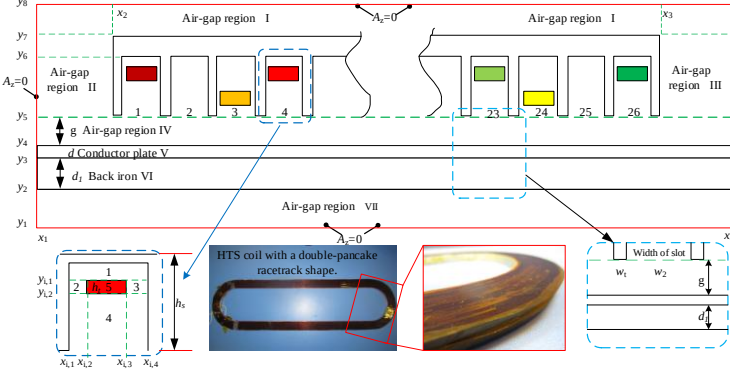


Fig. 2 The analytical model of the HTS SLIM

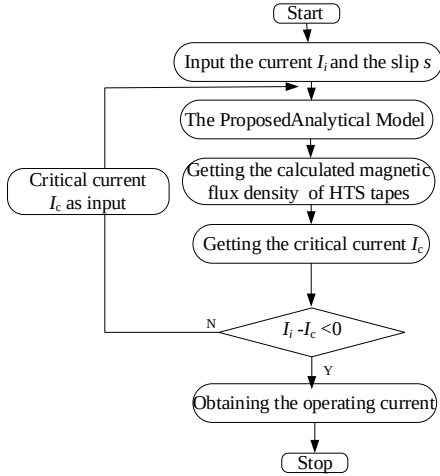


Fig. 3 The flow diagram for predicting the operating current of HTS.

B. Operating Current of the HTS Coils

The critical current density of an HTS coil depends not only on the temperature but also on the background magnetic field. Fig. 3 illustrates the flow diagram used to determine the operating current of HTS coils. Consequently, the analysis model developed in this paper enables the inclusion of the electromagnetic state of the superconductor in the performance evaluation of the HTS SLIM.

III. RESULTS

The comparison between the analytical method and FEM results for the normal magnetic flux density distribution in the air-gap is shown in Fig. 4. As seen in Fig. 4, there is very good agreement between the proposed analytical model and the 2-D

FEM results. Additionally, the thrust force calculated by the proposed analytical model is compared with both FEM and experimental measurements, as shown in Table I. The three results are in close agreement, validating the accuracy of the analytical model. More in-depth analysis and results will be presented in the full paper.

TABLE I
FORCE COMPARISON BETWEEN ANALYTICAL, FEM AND EXPERIMENTAL

Phase Current	Frequency	Speed	FEA	Analytical	Test
13.7A	10Hz	0.968m/s	275N	272N	208N
18.0A	10Hz	0.671m/s	540N	533N	410N
22.0A	8Hz	0.597m/s	630N	627N	493N
25.7A	6Hz	0.254m/s	1080N	1090N	786N
28.6A	5Hz	0.246m/s	1130N	1117N	839N
33.1A	4Hz	0.287m/s	1156N	1140N	861N

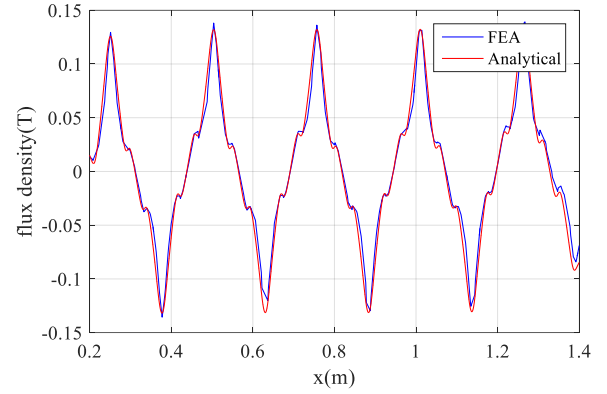


Fig. 4. FEM and analytically predicted flux density waveforms in air gap.

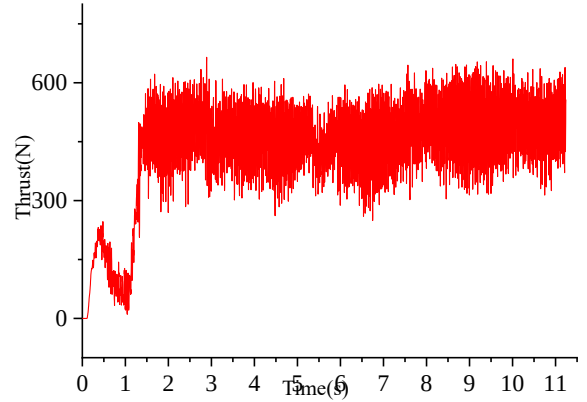


Fig. 5. Measured line for thrust at 10Hz and 18 A

REFERENCES

- [1] I. Boldea, "Linear Electric Machines, Drives, and MAGLEVs Handbook," *Linear Electric Machines Drives & Maglevs Handbook*, 2013.
- [2] D. Li, W. Li, J. Fang, X. Zhang, and J. Cao, "Performance Evaluation of a Low-Speed Single-Side HTS Linear Induction Motor Used for Subway System," *IEEE Transactions on Magnetics*, vol. 50, no. 5, pp. 1-9, 2014.
- [3] J. Zhao, T. Q. Zheng, W. Zhang, J. Fang, and Y. M. Liu, "Influence analysis of structural parameters on electromagnetic properties of HTS linear induction motor," *Physica C Superconductivity & Its Applications*, vol. 471, no. 21-22, pp. 1474-1478, 2011.
- [4] L. Roubache, K. Boughrara, F. Dubas, and R. Ibtouen, "New Subdomain Technique for Electromagnetic Performances Calculation in Radial-Flux Electrical Machines Considering Finite Soft-Magnetic Material Permeability," *IEEE Transactions on Magnetics*, vol. 54, no. 4, pp. 1-15, 2018.