http://dx.doi.org/10.11142/jicems.2013.2.4.394

Output Characteristics of Linear Switched Reluctance Motor with YBCO Tape Conductors

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Abstract – This paper presents output characteristics of a linear switched reluctance motor (LSRM) with excitation windings wound by using high-temperature superconducting (HTS) tapes. In a double-sided LSRM, Bi-2223 or YBCO tape conductors are used for the excitation windings. The characteristics of the LSRM are obtained by a finite element method analysis. We can obtain large thrust compared with a conventional LSRM by using YBCO tape conductors. Also, the effect of a configuration of the YBCO coil on the thrust is calculated. We discuss a suitable coil configuration for the average thrust upgrading.

Keywords: Linear switched reluctance motor, High-temperature superconducting tape, Bi-2223, YBCO, Finite element method

1. Introduction

Linear motor drives have been widely used in industry applications such as transportation systems, conveyance systems, machine tools, home applications, and so on. In particular, a permanent magnet type linear synchronous motor (PM-LSRM) has been mainly used because the efficiency is high. However, there is a problem that a rare earth permanent magnet is expensive and difficult stable procurement. Recently, a research and development of a linear switched reluctance motor (LSRM) has been carried out all over the world [1]-[4]. The LSRM has distinctive merits of simple and robust structure, high-speed driving and is economical as compared with a PM-LSM. Furthermore, the LSRM has no problem of performance deterioration due to increased temperature and demagnetization of a permanent magnet because of without the permanent magnet for the field excitation. The efficiency of the LSRM is higher than a linear induction motor. However, the LSRM has problem of low thrust / volume ratio. In order to solve this problem, we proposed a new type LSRM in which high-temperature superconducting (HTS) tapes are used for excitation winding [5]. In the previous paper, we proposed the HTS-LSRM with excitation windings wound Bi-2223 tape conductors, the basic characteristics of the HTS-LSRM with the Bi-2223 coil are also verified by performing an analysis and experiments [5] [6].

This paper describes the performances of the LSRM with excitation windings wound by using YBCO tape conductors. The characteristics of the LSRM with the YBCO coil are calculated by the finite element method analysis. Also, the effects of a configuration of the YBCO coil on the thrust are investigated by performing the analysis in order to improve output characteristics. From these results, we discuss a suitable configuration for the average thrust upgrading.

2. HTS-LSRM

2.1 Structure of the HTS-LSRM

The structure of the HTS-LSRM is shown in Fig. 1. In this paper, the HTS-LSRM is a double-sided linear motor. This linear motor consists of two stators with HTS coils and a mover iron core. Two stators are set on both sides of the mover. The HTS coils are wound on each salient pole of stators. The excitation winding consists of A-phase, B-phase, and C-phase and four windings of each phase are connected in series. The mover consists of only an iron core of salient pole structure.

2.2 Operating Principle

In the HTS-LSRM, a thrust in which the excited stator magnetic pole pulls the mover salient pole is used. This force is called a reluctance thrust. Therefore, in order to generate the thrust continuously, the excited phase needs to

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Received 12 October 2013; Accepted 31 October 2013

be changed according to positional relationship between the stator pole and the mover pole.

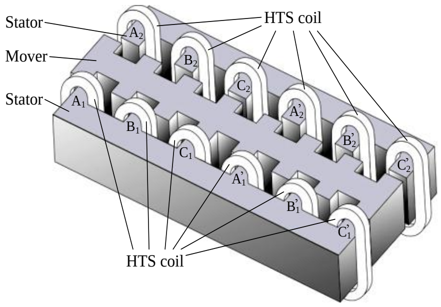

Fig. 1. Structure of the double-sided HTS-LSRM

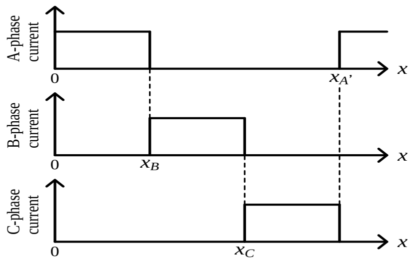

Fig. 2. The supplied current waveform

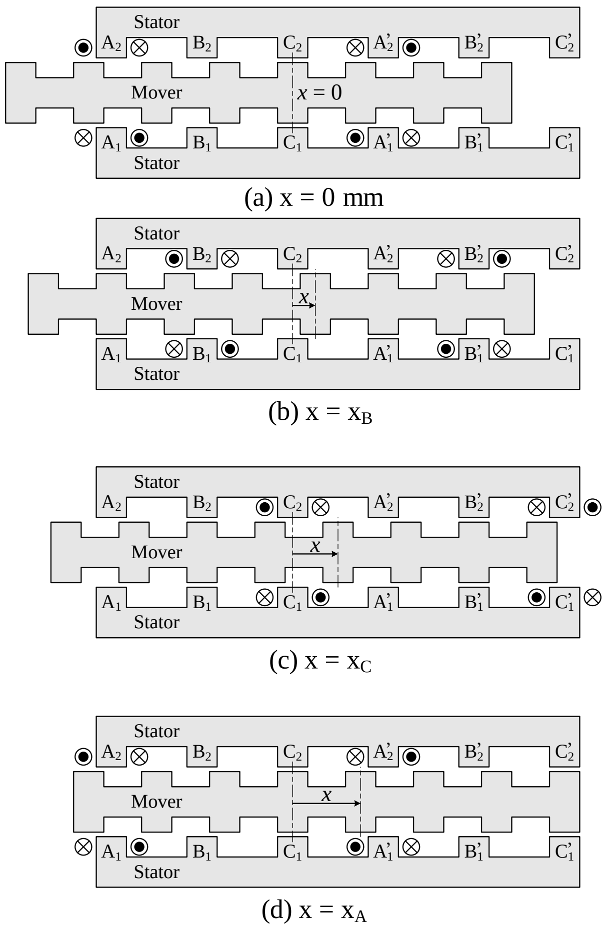

Fig. 3. Positional relationship between the mover position and excited stator coils

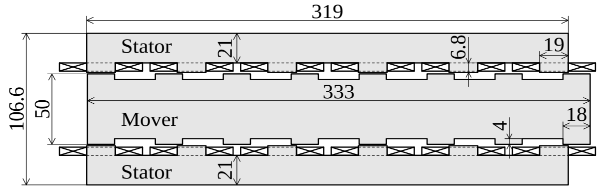

Fig. 4. Cross-section view of the analytical model for the HTS-LSRM

Table 1. Dimensions and specifications of the HTS-LSRM

Stator pole pitch	60 mm
Mover pole pitch	45 mm
Air gap	0.5 mm
Stack height	100 mm
Number of poles: Stator	6 (only one side)
Mover	8 (only one side)
Core material	35JN300
Winding	Double-pancake coil

Fig. 2 shows the current waveform supplied to the stator HTS excitation windings. The positional relationship between the mover position and the excited stator coils are shown in Fig. 3. Where, x is the mover position. As shown in Fig. 3 (a), the mover position is zero when the position of the mover salient pole is in agreement with the stator C-phase salient pole. When the A-phase current is supplied to A_1, $A_1^{'}$, A_2, and $A_2^{'}$ coils at $x = 0$ mm as shown in Fig. 3 (a), the reluctance thrust is generated in the second and sixth mover salient pole from the left, and the mover moves to the right. When the mover arrives in $x = x_B$, the excitation of A-phase excitation windings are switched off and B_1, $B_1^{'}$, B_2, and $B_2^{'}$ coils are excited as shown in Fig. 3 (b). Then, the reluctance thrust is generated by exciting B-phase excitation windings. Next, when the mover arrives in $x = x_C$, the excitation of B-phase excitation windings are switched off and C_1, $C_1^{'}$, C_2, and $C_2^{'}$ coils are excited as shown in Fig. 3 (c). And A-phase excitation windings are again excited at $x = x_A^{'}$ as shown in Fig. 3 (d). Thus, the mover moves continuously with switching the excitation.

3. Analytical Model

Fig. 4 shows a cross-section view of an analytical model and Table 1 shows dimensions and specifications of the HTS-LSRM. The analytical model consists of the stator iron cores, the mover iron core, and the 3-phase excitation windings. A silicon steel sheet is used for the stator and mover iron core. In this paper, Bi-2223 or YBCO tape conductors are used for the excitation windings. The width and thickness of the Bi-2223 tape conductor are 2.8 mm and 0.31 mm respectively and the critical current is 70 A at 77 K under the self-magnetic field. The width and thickness of the YBCO tape conductor are 2.8 mm and 0.1 mm respectively and the critical current is 56A at 77 K under the self-magnetic field. The performance characteristics are investigated by a two-dimensional finite element method analysis. The analytical model is solved by using the axial symmetric model. The analysis is performed at intervals of 1 mm. The ideal pulse currents as shown in Fig. 2 are supplied to the 3-phase excitation winding.

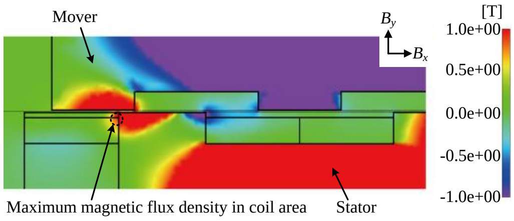

Fig. 5. Analytical result of the magnetic field distribution

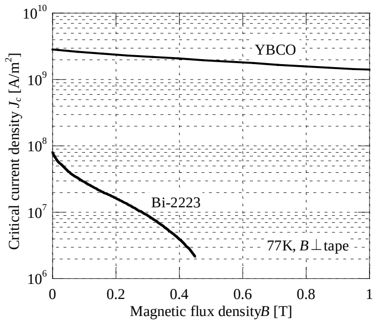

Fig. 6. Magnetic field dependence of Jc for Bi-2223 and YBCO tape at 77 K

4. Analytical Results

4.1 Magnetic Field Distribution and Ic-B Characteristics

A magnetic field applied to the HTS tape conductor was calculated when the ideal pulse current was supplied to the stator HTS coils. Here, the numbers of turns of the Bi-2223 and YBCO coil are 132 turns / pole and 400 turns / pole, respectively. Fig. 5 shows the analytical result of the perpendicular magnetic field distribution B_x applied to the HTS tape conductor when the YBCO coil is used. In the HTS-LSRM, the maximum perpendicular magnetic flux density applied to the HTS tape conductor surface is changed according to the mover position. Fig. 5 shows the magnetic field distribution when the perpendicular magnetic flux density applied to the YBCO tape conductor surface is maximized. The maximum value of the magnetic flux density applied to the YBCO tape conductor is 1.0 T. Also, that is 0.3 T when the Bi-2223 coil is used for the excitation windings.

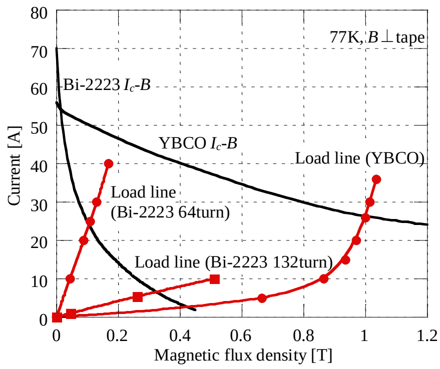

Fig. 7. Ic-B characteristics of the HTS tape conductors and the load lines of the HTS coils

Fig. 6 shows the magnetic field dependence of the critical current density J_c for Bi-2223 and YBCO tape at 77 K [7]. The critical current density of Bi-2223 tape is drastically reduced with increasing perpendicular magnetic flux density applied to the tape conductor surface. Fig. 7 shows the I_c-B characteristics of the Bi-2223 and YBCO tape conductor at 77 K. The critical current I_c is obtained for the product of J_c and the cross-section area of tape conductor. In addition, load lines of the Bi-2223 and YBCO coil are shown in Fig. 7. It is confirmed that the operating currents of the Bi-2223 and YBCO coil were 9.0 A and 26.4 A, respectively. Since the critical current of the Bi-2223 tape conductor is drastically reduced with increasing magnetic flux density, the operating current of the Bi-2223 coil is considerably small compared with that of YBCO coil. In addition, the critical current of the Bi-2223 coil is reduced by a bending strain because an inside diameter of the excitation winding in the analytical model is 19 mm. An admissible value of a bending diameter of used Bi-2223 tape conductor is 40 mm. When the Bi-2223 coil is wound at the inside diameter 40 mm, the number of turns of the Bi-2223 coil and the operating current are 64 turns / pole and 24 A, respectively. That load line is added to the Fig. 7. From these results, it is found that the magneto motive force of 64 turns / pole is larger than that of 132 turns / pole.

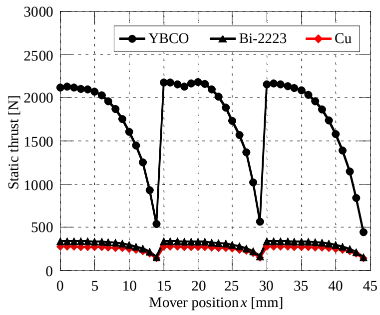

Fig. 8. Analytical results of static thrust vs. mover positi on characteristics

4.2 Thrust Characteristics

The analytical results of the static thrust versus mover position characteristics for the HTS-LSRM and the conventional LSRM are shown in Fig. 8. In the analysis for the HTS-LSRM, the amplitude of excitation current was 60 % of the operating current obtained in the foregoing section. The number of turns of Bi-2223 coil was 64 turns / pole. In the conventional LSRM, copper wires are used for the 3-phase excitation windings. A space factor of the stator conductor is 70 %, and the current density is 10 A/mm^2. In all the analysis, the configurations of the stator and mover iron core are the same. As shown in Fig. 8, it is confirmed that the thrust of the HTS-LSRM with the YBCO coil has more than quintuple as compared with other LSRMs.

5. Design of YBCO Coil Configuration

5.1 Design Parameter

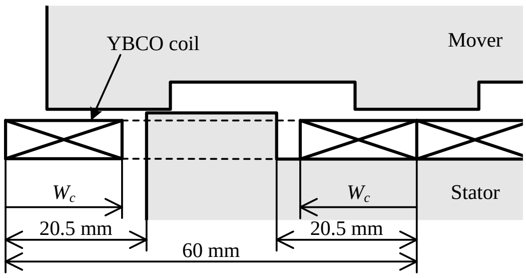

Fig. 9. Design parameter for design of the YBCO coil configuration

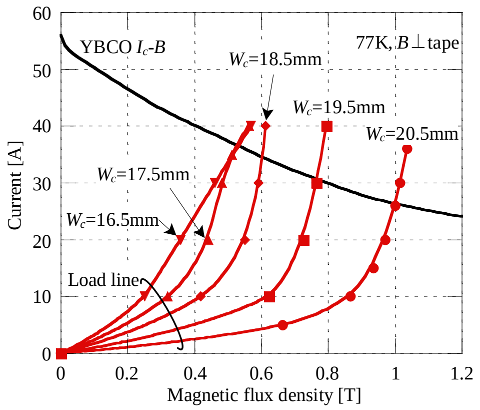

Fig. 10. Ic-B characteristic of the YBCO tape conductor and load lines of various Wc

As shown in the preceding chapter, it was confirmed that we can obtain large thrust by using the YBCO tape conductor. Here, the configuration of YBCO coil is roughly optimized for improvement of the average thrust. The design parameter is the coil area width W_c as shown in Fig. 9. The external diameter of the coil is fixed at 60 mm. The position where the perpendicular magnetic flux density applied to YBCO tape conductor surface becomes the maximum is the portion near the stator salient pole as shown in Fig. 5. Therefore, the reduction of the perpendicular magnetic flux density and the improvement of the operating current are expected by fixing the external diameter and changing the width of the coil.

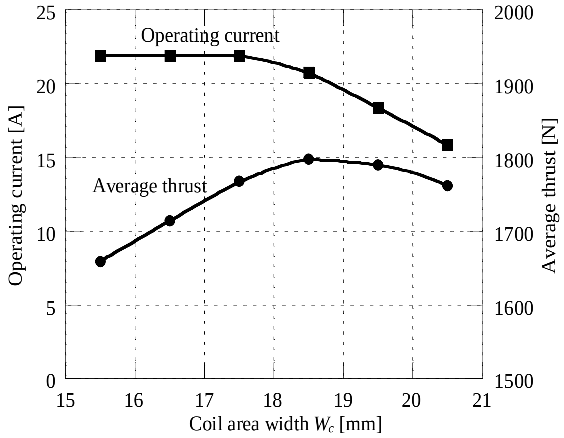

Fig. 11. Effects of Wd on the operating current and the average thrust

5.2 Effects of the Coil Configuration

Fig. 10 shows the I_c-B characteristic of the YBCO tape conductor and the load lines of the YBCO coil when the design parameter W_c is changed. YBCO tape conductor gets in touch with the stator salient pole at W_c = 20.5 mm. The number of turns of the YBCO coil is 400 turns / pole at W_c = 20.5 mm. If W_c becomes narrow 1 mm, the number of turns of YBCO coil will be decreased 20 turns. The operating current increases with decreasing W_c as shown in Fig. 10, because the coil area can avoid the large magnetic flux density region according to decreasing W_c. However, it is confirmed that the operating current is not improved even if W_c becomes smaller than 17.5 mm, because the perpendicular magnet flux density applied to the YBCO tape conductor surface is not reduced.

Fig. 11 shows the effects of the coil area width W_c on the operating current and the average thrust. The current values shown in Fig. 11 are 60 % of the operating current obtained by Fig. 10. Although the operating current decreases in W_c larger than 17.5 mm, the average thrust is the largest at W_c = 18.5 mm. It is considered that the magnetomotive force becomes the maximum value at W_c = 18.5 mm. As above, the average thrust can be improved even if the number of turns of the excitation winding decreases by designing the coil configuration so that the perpendicular magnetic flux density applied to the HTS tape conductor surface may be reduced and the operating current can be improved.

6. Conclusions

This paper presented performance characteristics of the HTS-LSRM with YBCO coil by performing the finite element analysis. It was confirmed that the magnetomotive force of the YBCO coil was larger than the Bi-2223 coil and the thrust of the HTS-LSRM with the YBCO coil was very large compared with HTS-LSRM with the Bi-2223 coil or the conventional LSRM. Furthermore, the effects of the YBCO coil configuration on the average thrust were investigated. As a result, the average thrust was able to be improved by optimally designing the coil configuration even if the number of turns of the YBCO coil decreased.

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