Field Analysis and Multi-objective Design Optimization of E-Core Transverse-Flux Permanent Magnet Linear Motor

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A novel E-core transverse-flux permanent magnet linear motor (TFPMLM) is optimally designed in this paper. The operation principle and structural advantages of the TFPMLM are firstly presented. Then the inherently three-dimensional (3-D) magnetic structure of the TFPMLM is simplified equivalently into a 2-D one so that the Schwarz-Christoffel (SC) mapping method can be adopted to analyze its field distribution and then the electromagnetic performances. Finally, based on the SC model of the novel 3D motor, Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) is employed for solving its multi-objective design optimization, and some Pareto-optimal solutions are chosen which are verified by 3-D finite element method (FEM).

***Index Terms*—Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II), finite element method (FEM), Schwarz-Christoffel (SC) mapping, transverse-flux permanent magnet linear motor.**

I. Introduction

Linear motor can drive linear load directly without the rotary-to-linear conversion as needed for its counterpart rotary motor, which have the advantages of high acceleration, high precision and high operating life. Transverse-flux permanent magnet linear motor (TFPMLM) enjoys the additional merits resulting from the transverse-flux structure, such as high force density, high fault-tolerant ability and electromagnetic decoupling. However, the TFPMLM always features a complicate structure and suffers from large magnetic flux leakage. As a result, novel TFPMLMs appear from time to time and design optimization is carried out to improve its structure and performance [1].

Analyzing the motor efficiently and accurately is one of the key factors for motor's optimal design. And the intelligent optimization algorithm can be performed excellently only when it is incorporate with the suitable field and performance analysis methods, in terms of accuracy and time consume in the same time. In general case, optimizations of TFPMLM are base on 3-D FEM because of the complex structure resulting from the presence of a 3-D magnetic circuit. However, 3-dimensional finite element method (3-D FEM) features a high accuracy yet carries out an unbearable time period especially when it is incorporated with the intelligent optimization method. The magnetic network method is the another one which can be adopted to incorporated with the intelligent optimization algorithm, leads to a quick solution with low accuracy. Schwarz-Christoffel (SC) conformal mapping method is an analytical method being accurate and efficient to solve complex magnetic field problems which can take into account of the slotting effect, the end effect and the magnetic flux leakage [2]. However, the SC method is a 2D analysis method that applied to analyze TFPMLM that has 3-d magnetic circuit which can be adopted to incorporate with intelligent optimization algorithm in the optimal design of the 3D motor which has not been report yet.

In this paper, a novel TFPMLM which has a 3-D magnetic structure is presented, and then its equivalent 2-D magnetic structure is obtained so that SC method can be adopted to solve its field distribution and waveforms of its back voltage and force. Furthermore, Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) is employed to its optimal design based on the field analysis though SC method. Then, the E-core TFPMLM is optimally designed. Some Pareto-optimal solutions are chosen and verified by 3-D finite element method (FEM).

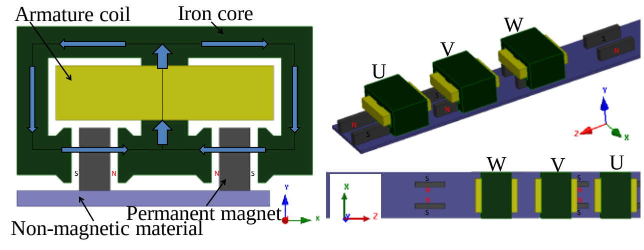

Fig.1. Configuration of proposed three-phase TFPMLM. (a) Armature and field units. (b) Structure along the moving direction.

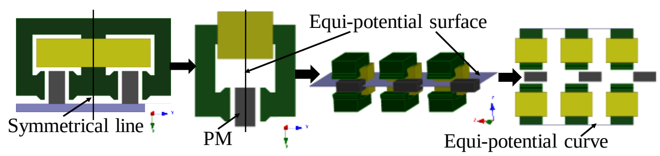

Fig.2. Equivalent transformation of the TFPMLM.

II. Analysis Method of The TFPMLM

A. Basic Structure and Operation Principle

Configuration of the three-phase E-core TFPMLM is shown in Fig. 1. It is composed of a stator with double-layer PMs and an E-core mover with concentrated coils placed in each middle tooth.

B. The SC Analysis Model of the TFPMLM

In order to solve the TFPMLM by SC method, the intrinsic 3-D magnetic structure of the TFPMLM should be changed into 2-D magnetic structure. The 3-D to 2-D procedure is shown in Fig.3. So the SC analysis model can be obtained as shown in Fig. 3.

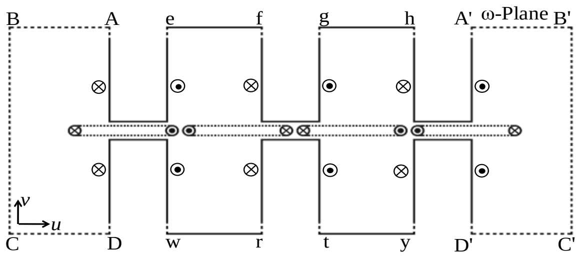

Fig.3. Equivalent SC analysis model of the TFPMLM.

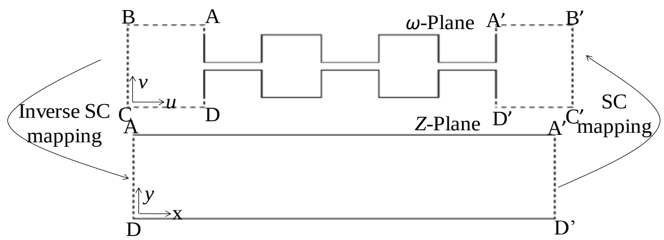

Fig.4. Illustration of SC mapping between different domains in SC method.

C. Analysis of SC Mapping Method

The polygon of the TFPMLM's equivalent 2D model in the ω-plane is mapped to a rectangle in the z-plane by the inverse SC mapping as shown in Fig. 4. The analytical solution is easier to obtain in the rectangle of z-plane, which can be mapped back to the ω-plane. Then, the field distribution and performance parameters such as back-EMF and thrust force can be obtained.

III. Multi-Objective Optimal Design

A. Multi-objective Optimization Problem

The search space for the optimization problem is defined by the PM width l_n, PM Pole pitch l_m, PM height l_w, mover height h, mover core length l_s, and mover core number n. And the objective function can be defined as follows.

$$\text{Objective function}\begin{cases}\max g_1 = F/I \\ \min g_2 = V_m\end{cases} \quad (1)$$

where the objective function g_1 and g_2 are the ratio of thrust force versus current and the mover volume, respectively; F is the thrust force under the phase current I. Taking into account of motor's requirements, the design constraints are given as follows,

$$\text{Constraint function}\begin{cases}h_1 = E \le 220V \\ h_2 = F \ge 250N\end{cases} \quad (2)$$

where the constraint function h_1 and h_2 are the back-EMF and the thrust force, respectively.

B. The NSGA-II

NSGA-II is first proposed by Kalyanmoy Deb [3], which is one of the most efficient multi-objective evolutionary algorithms. Optimization procedure of the TLPMLM by NSGA- II, based the results from SC methods is shown in Fig. 5. The optimization is performed with modeFRONTIER software, which is a multi-objective optimization and design environment.

IV. Results and Discussion

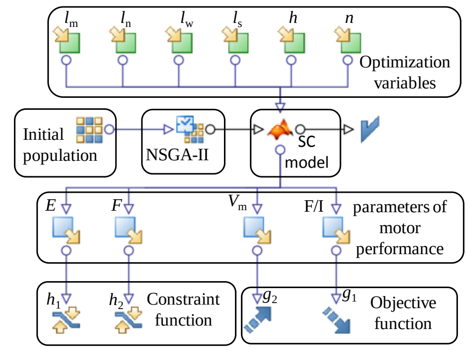

Fig.5. Illustration of NSGA-II using SC mapping method

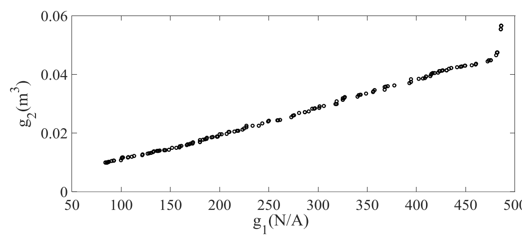

Fig.6. The Pareto frontier that satisfied with the constraint functions.

The prototyped TFPMLM is optimized by NSGA-II with incorporation with the SC method. High optimization efficiency is acquired and the Pareto set is obtained as shown in Fig.6 by considering the constraints. Some Pareto-optimal solutions are chosen to analyze the motor's performance by using 3-D FEM. Some Pareto-optimal solutions are chosen which are verified by 3-D finite element method (FEM).

V. Conclusion

In this paper, a novel E-core TFPMLM is optimally designed using NSGA-II based on SC mapping method. The objective of the optimization is to reduce the mover volume whilst maximizing the ratio of thrust force versus current. SC mapping method is applied for the motor analysis, which greatly improves the optimization efficiency. The Pareto-optimal set and associated Pareto-optimal front are obtained. Some Pareto-optimal solutions are chosen to analyze the motor's performance using 3-D FEM, in order to verify the accuracy of SC mapping method.

Acknowledgment

The authors would like to thank the Department of Science and Technology of Shandong Province (2015ZDXX0601b01)

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