

# Preface

A linear machine is a counterpart of rotary machine except that the stator and rotor are unrolled, so that instead of producing torque and rotation, it generates force and translation along its length. Typically, there are two ways to improve the force output of linear machines, i.e., increasing current input and increasing magnetic flux density in the air gap. Although large current input is a straight way to improve the force output, it may lead to high temperature and cause the problem of heat dissipation. The thermal property of materials strictly constrains the performance improvement of electric machines. Employment of large size of permanent magnets (PMs) also helps to increase the flux density and force output. However, the system size is increased in an exponential way. The study in this monograph aims to increasing magnetic flux density and force output by reorganizing the magnet poles. Specifically, the conventional two-dimensional (2D) magnet arrangement is extended to magnet array in 3D space, and thus a novel dual Halbach array is proposed for the design of linear machines. It offers two advantages. One is to increase the magnetic flux density in radial direction, which in turn helps to improve the axial force output. The other is to decrease the flux density in axial direction, and thus depresses the vibration in radial direction. This monograph covers systematic study on design and analysis of tubular linear machines with dual Halbach array.

Chapter 1 introduces fundamental concepts, advantages, applications, and typical designs of linear machines. Different types of magnet arrays such as alternatively radial magnetization and alternatively axial magnetization are presented and analyzed. As a result, the dual Halbach array is proposed to increase the force output of the system. It is worth pointing out that the proposed dual Halbach array is applicable to other electric machines such as flat linear machines and rotary machines.

Chapter 2 presents the magnetic field formulation of the proposed linear machine. Magnetic field formulation is one precondition of force modeling. It helps to optimize the magnet arrangement and thus the system output performance. The governing equations are obtained based on magnetic properties of region materials

in the linear machine. The general solution of magnetic vector potential is thus derived. By utilizing boundary conditions between different regions, the particular solution of magnetic vector potential is obtained. Finally, we have the magnetic flux density from the curl of magnetic vector potential. The magnetic flux density consists of three components in the space, one of which is equal to zero. Numerical results are employed to validate the derived magnetic field formulation.

Based on the magnetic field formulation, Chap. 3 mainly concerns the mathematical modeling of force output. Force output model is important for design optimization and control implementation of linear machines. Lorenz force law is especially suitable for force modeling of current-carrying conductors in external magnetic field, and thus it is used in this study. The force output for single-phase, double-phase, and three-phase windings are formulated. The force output of three-phase winding is also related to the starting point of mover. Therefore, the corresponding mathematic models are obtained. Similarly, numerical results are used to validate the analytical models of force output.

Chapter 4 focuses on analysis of armature reaction field and inductance. So far most studies of electric machines concern only the magnetic field of permanent magnet poles, whereas less work has been done on armature reaction field. Analysis of armature reaction field and inductance is extremely important for design and control implementation of electromagnetic machines. This chapter proposes a novel analytical modeling method to predict the armature reaction field of the coreless PM tubular linear machine. Unlike the conventional modeling approach, the proposed method formulates the armature reaction field for electromagnetic machines with finite length, so that the model precision can be improved. In addition, winding inductance is also analytically formulated to facilitate dynamic motion control based on the reaction field solutions. Numerical result is subsequently obtained with finite element method, and employed to validate the derived analytical models.

By utilizing the analytical models obtained in previous chapters, Chap. 5 studies the parameter optimization and back iron influence of tubular linear machines with dual Halbach array. Penalty method and scanning method are employed to conduct parameter optimization to maximize the force output for a given machine volume. The influence of structure parameters on force output and force ripple is discussed, and thus the optimal parameter values are determined. Ferromagnetic material is one key component that influences the force generation of electric machines significantly. Numerical computation from finite element method is employed to calculate the force output of linear machines with various types of back iron patterns including internal back iron, external back iron, double-sided back iron, and without back iron to achieve large force output in a certain volume.

Chapter 6 presents the experimental investigation on the tubular linear machine with dual Halbach array. One research prototype has been developed. An automatic measuring apparatus has also been developed to measure the magnetic field distribution in the space. The measuring procedure and corresponding data processing and analysis are presented. Similarly, measuring apparatuses for force output and armature reaction field are built up. The experimental results of the magnetic

field distribution, the force output variation, and the armature reaction field are visualized, and utilized to verify the analytical models developed in previous chapters.

Chapter 7 concludes the major works in this monograph. More subsequent works could be conducted on the proposed novel design of linear machines. The same design method and analyzing approaches could be implemented to other linear and rotary machines.

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