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RESEARCH ARTICLE - ELECTRICAL ENGINEERING

A Novel Design of Three-Phase Transverse Flux Linear Motor to Minimize Force Ripples

Usama Khaled[1,2] · Rashid Meer[1] · Abderrahmane Beroual[3]

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Abstract A new modeling of transverse flux linear motor (TFLM) is proposed in this paper. The design consists of three separate stators and one common inner mover. The stators are fed by a three-phase alternating current, and the mover is excited by permanent magnets placed within it. The field distribution of the machine is investigated by using 3D finite element analysis and MagNet® software for electromagnetic simulation. The thrust force characteristics of three-phase TFLM are compared with the single- and two-phase models. It is shown that the average force is increased and the ripple effect of the thrust force is minimized as compared to either single- or two-phase model.

Keywords Finite element · Flux · mmf · Mover · Permanent magnets · Ripples · TFLM · Thrust force

1 Introduction

Linear motors are electromagnetic devices that produce thrust force without the needing to convert the state of motion from rotatory to linear by using gear, belts or any other mechanical converters. Some of the advantages of linear motors include more flexibility of operation due to gearless feature, reduced maintenance and operating cost, and lower noise. They have been used in high power applications such as railways [1], free piston generators, and electrodynamic vibrators.

Classic linear motors had the disadvantage of small power density caused by large air gap, but that problem was solved with the introduction of permanent magnet of transverse flux linear motors (PM-type TFLM). It can be considered for high reluctance and magnetic force in a relatively small air gap [2]. The discovery of highly performance permanent magnets has led to even powerful and smaller motors of this type.

The PM-type TFLM with inner mover has a number of useful features. One of them is that there is no comparison between the space taken by iron cores and the armature windings space which increases design variety. The other advantage is that increasing the number of poles or decreasing the pole pitch for a given dimension leads to raising the density of force [3]. The main disadvantage in a PM-type TFLM is the force ripple. As the moving part of the TFLM has permanent magnets attached to it. When it moves in between the stator electromagnets, the magnets move between aligned and unaligned positions. The aligned position has minimum force, while the unaligned position has maximum perpendicular thrust force which causes force ripples in TFLM. The force ripple can be minimized by adequately reshaping the current waveform or by increasing the number of motor phases.

Analytical model is required to simulate any given motor model to analyze and predict its performance. Eventually, the parameters obtained from simulation runs are used to design the motor at industrial level [4]. Due to symmetry of rotational motors, a 2D analysis is often enough to simulate and obtain the motor parameters. However, due to complexity and non-symmetric configuration of linear motors, a 3D analysis is required. One of the methods used for this type of analysis

✉ Usama Khaled
ukhaled@ksu.edu.sa

1 Department of Electrical Engineering, College of Engineering, King Saud University, Riyadh, Saudi Arabia

2 Department of Electrical Engineering, Faculty of Energy Engineering, Aswan University, Aswan, Egypt

3 Ampere Lab CNRS 5005, Ecole Centrale de Lyon, 36 Avenue Guy de Collongue, 69130 Ecully, France

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is the 3D equivalent magnetic circuit method (EMCM). It utilizes both the 2D FEM and the 3D FEM together. EMCM is actually a numerical analysis technique that uses numerical approach to formulate the magnetic equivalent circuit. In this method, the model is comprised of small hexahedral shapes which are known as elements. The magnetic circuit is built by joining the nodes of adjoining elements.

Chang et al. [5] used the 3D EMCM method combined with 2D FEM to study and design the TFLM with permanent magnet excitation. The apparent and incremental inductances as well as static flux linkage are found out using 3D EMCM, while 2D FEM is used to get the multiplication factor as a correction factor. This factor is multiplied with the 3D EMCM analysis where the end effect at the mover cannot be taken into consideration in 3D EMCM.

The 3D-FEA (finite element analysis) is another method that has been used for 3D analysis [6]. This method is being used more and more nowadays to solve various differential equation problems in engineering. In the 3D-FEA technique, the actual area of the model is split into small elements. The magnetic field is then calculated in each element using polynomial equations, and the numeric solution is obtained according to a specified criterion. The 3D-FEA method combined with different optimization algorithms [7] have proved to be valuable in design and optimization of motors because the meshes can easily be adjusted with any boundary and geometry.

This paper introduces a novel three-phase TFLM with PM excitation. The purpose of proposing this new topology is not only to reduce the ripple effect of thrust force but enhance it as well. 3D-FEA method is used to design the mathematical model of the three-phase TFLM. MagNet®, version 7.1, is the simulation application which used to achieve this goal. The obtained results are compared with TFLM models reported in [8,9] to validate the improvement in the new proposed model. The difference between the proposed TFLM and the TFLM given in [8,9] is the increase in number of motor phases with slight changes to the design, keeping the same working principle.

2 Basic Structure and Principle

The proposed model of three-phase TFLM with PM excitation depends on the enhancement of single- and/or two-phase models [8,9]. Figure 1a shows the basic structure of one of the three phases of TFLM with PM excitation.

The stator and mover are separated by a small air gap. There are windings on the stator of the TFLM, whereas the mover has no windings on it. The mover consists of permanent magnets and iron cores placed alternately after one another as shown in Fig. 1b. The number of poles on the inner

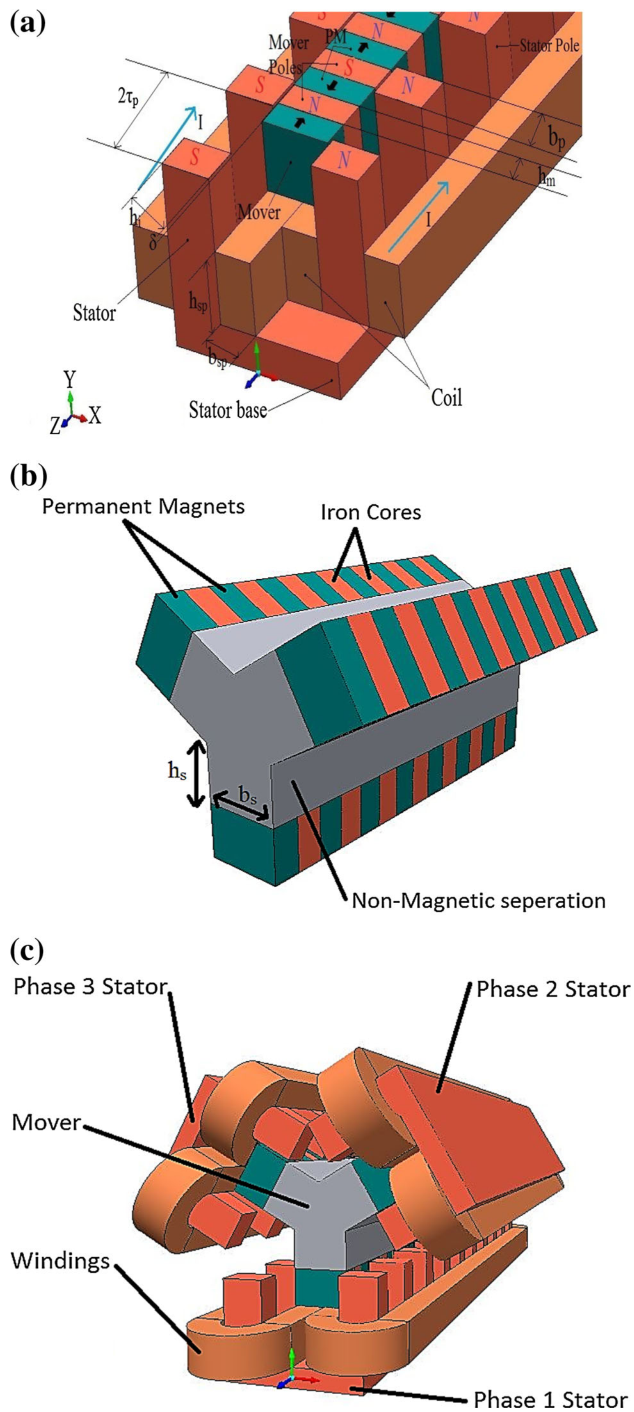

Fig. 1 Basic structure of three-phase TFLM **a** geometric parameters. **b** Inside view showing inner mover. **c** 3D front view showing all three phases

mover and that of stator are unequal due to the linear nature of the motor.

All three phases of the TFLM are arranged facing each other in such a way that there is a 120° phase shift between them as shown in Fig. 1c. The poles of each phase are separated by 1/3 pole pitch. The mover is a single unit consisting