Electrical Power and Energy Systems 77 (2016) 263–270

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Development and optimization of a moving-magnet tubular linear permanent magnet motor for use in a reciprocating compressor of household refrigerators

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ARTICLE INFO

Article history:
Received 25 August 2014
Received in revised form 17 September 2015
Accepted 8 November 2015
Available online 10 December 2015

Keywords:
Design optimization
Moving-magnet
Quasi-Halbach array
Tubular linear permanent magnet motor

ABSTRACT

This paper presents the development, validation and design optimization of a moving-magnet tubular linear permanent magnet motor (TLPMM) with a trapezoidal permanent magnet shape. The design optimization was implemented by a two-dimensional Finite-Element Analysis (2-D FEA) and the validation was established by using Matlab software. The proposed motor has been designed to produce 85 W output power which is enough to operate the reciprocating compressor of a household refrigerator system. The purpose of the optimization is to achieve a maximum efficiency and minimum losses, where the angle of PMs, split-ratio and T_{mr}/T_p after optimized, the motor produced the highest efficiency by 93.8%.

Introduction

A tubular linear permanent magnet motor (TLPMM) provides direct linear electro-mechanical energy conversion and offers numerous advantages over its rotary-to-linear counterpart, notably the absence of mechanical gears and transmission systems, which result in a higher dynamic performance, improved reliability, high thrust density, high efficiency and simple structure [1–3].

TLPMM provides a continuous short-stroke reciprocating motion of controllable frequency and amplitude, with the displacement being normally less than one pole-pitch. TLPMM is dedicated to a widespread of applications. For years, the design of TLPMMs has been limited mainly to a conventional rectangular shape of permanent magnets (PMs). Here, a TLPMM with trapezoidal shaped PMs is presented and simulated.

In order to analyze the performances of the proposed TLPMM, an accurate knowledge of the magnetic field distribution in the air-gap regions is required. The magnetic field distribution can be evaluated analytically or numerically. The numerical solutions, like the Finite-Element Analysis (FEA), present the merit of taking into account the real geometry of the proposed design as well as the magnetic saturation of the iron parts. On the other hand, analytical solutions, which are based on some simplifying assumptions (simplified geometry, linear characteristic for the material, simple boundary conditions), generally require much less computational time than FEA and can be effective tools for the first step of design optimization. The exact solution of the magnetic field can be obtained by solving the partial differential equations issued from Maxwell's equations [4,5].

The FEA has been used in this study to design, develop and optimize the proposed TLPMM. Fig. 1 shows the 3-D FE schematic representation of the proposed moving-magnet TLPMM, of which the initial dimension and operational conditions are tabulated as in Table 1, and demonstrated as in Fig. 2.

The TLPMMs can be categorized into three kinds, such as moving-coil, moving-iron and moving-magnet. The moving-iron type is rarely used due to the need of a heavy moving mass as well as has a low force density. The difficulties of dissipating heat from the coil and limited moving access are the major unreliability sources of the moving-coil type. Due to the fact that the copper coil is directly wound around the yoke of the moving-magnet TLPMM, the superior thermal dissipation capability and high reliability can both be expected. Therefore, the moving-magnet TLPMM seems to be more suitable for the linear reciprocating compressors [6–8].

The schematic of the linear reciprocating compressor, which consists of a linear motor and compressor system and both being integrated, using a direct-drive shaft, is already deployed in previous papers [9,10]. The major merit of the linear compressor is its considerable linearity of a thrust force with respect to the position as well as waiver of any mechanical motion-conversion mechanism. Thus, the linear reciprocating compressor possesses

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http://dx.doi.org/10.1016/j.ijepes.2015.11.020
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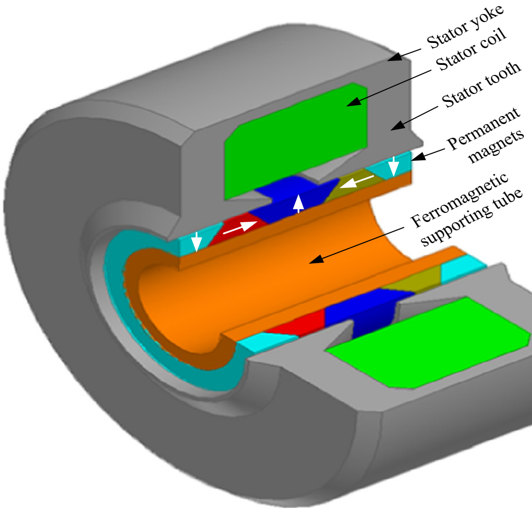

Fig. 1. 3-D FE model of the proposed moving-magnet TLPMM.

Table 1
Initial dimension and operational conditions.

No	Parameter	Symbol	Value
1	Outer radius of the stator	R_e	50.0 mm
2	Outer radius of the magnet	R_m	20.0 mm
3	Magnet height	h_m	5.0 mm
4	Thickness of the yoke	h_{ys}	3.30 mm
5	Tooth tip height	h_t	1.0 mm
6	Tooth width	T_w	9.4 mm
7	Axial length of the radial magnetized PM at the center	T_{mr}	15.5 mm
8	Thickness of the ferromagnetic tube	h_{ym}	3.9 mm
9	Pole pitch	T_p	25 mm
10	Opening of the slot	b_0	10.0 mm
11	Airgap length	g	0.8 mm
12	Inner radius of the ferromagnetic tube	R_0	11.1 mm
13	Stator under cut angle	α	30°
14	Tooth pitch width	T_{pw}	40 mm

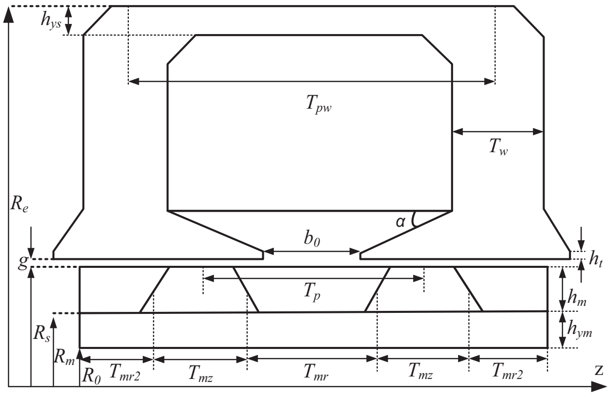

Fig. 2. Schematic and design parameters of the TLPMM.

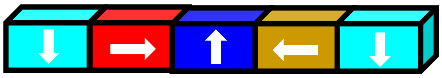

Fig. 3. Quasi-Halbach magnetization patterns.

the nature of high reliability, more dynamic stability performance, more outstanding servo characteristics, light weight as well as it can work without lubrication [10,11].

For the development of the motor, the appropriate selection of the materials represents a significant issue. Permanent magnets (PMs) of both high coercivity and high remanence at a wide range of temperatures and with an affordable cost have a significant role in the design of electrical machines. The rare earth elements, such as neodymium–iron–boron (NdFeB) and samarium–cobalt (SmCo), can be considered as the best candidates to the fulfillment of those requirements. As a comparison, the PMs of SmCo have better chemical properties, while NdFeB is superior in terms of physical properties. Nevertheless, the PMs of the two groups have complementary characteristics to each other. Their energy product is high thus they are permitted to be used with the new technical designs of electrical machines. Moreover, these new PM materials offer numerous merits as compared with the conventional ferrite PMs. They can reduce the volume of the required PMs and have significantly higher flux densities. The pursuit of a higher power density by using these high-energy PM materials as well as the operation at a higher current level will lead to the increasing of the saturation and armature reaction problems. Thus, a combination of saturation and armature reaction has undesirable effects [12–15].

The usage of quasi-Halbach magnetization patterns in a motor offers numerous attractive features, such as a sinusoidal field distribution as well as sinusoidal waveform of a back-EMF, which results in a minimum electro-magnetic force ripple and the possibility of being optimized to have an almost zero cogging force [16,17]. However, these features make a quasi-Halbach array widely applied in linear electrical motors. Fig. 3 shows the quasi-Halbach magnetization patterns, which have been used in this study.

This paper presents the development, validation and design optimization of a moving-magnet tubular linear permanent magnet motor (TLPMM) with a trapezoidal permanent magnet shape. The motor is a single-phase, short-stroke TLPMM. The motor is equipped with a quasi-Halbach magnetized moving-magnet armature and slotted stator with a single coil. The design optimization was implemented successfully by using the two-dimensional Finite-Element Analysis (2-D FEA) and the design validation was established by using Matlab M-file. The paper is organized as follows. The modeling of the linear motor is introduced in the second section. Third section reports the analytical method used for validation. The simulation results of the open-circuit flux distributions are presented in the fourth section. The design optimization results are presented in the fifth section. Sixth section presents the conclusions.

Linear motor model

The study is based on the TLPMM of which the design and operational specifications are tabulated as in Table 1. This proposed TLPMM consists of a slotted stator with a single coil and a 2-pole PMs translator with the trapezoidal PMs shape. The moving-magnet armature employed quasi-Halbach magnetization patterns, which comprised three radially magnetized magnets placed at ends and the center as well as two axially magnetized magnets, as demonstrated in Figs. 1 and 3; as well, the airgap was selected as small as possible, mechanically. In order to produce a higher airgap field, a ferromagnetic support tube has been used. However, a non-ferromagnetic support tube has an advantage in terms of mover mass reduction as well as the translator eddy current loss diminishing [2,18].

The mathematical modeling of the proposed motor has been given by the following equations: motion equation and voltage equation; the mechanical motion equation for the proposed moving-magnet TLPMM was given by: