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Analysis of a Tubular Linear Permanent Magnet Motor for Reciprocating Compressor Applications

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Abstract. This paper describes a design optimization to achieve optimal performance of a two novel single-phase short-stroke tubular linear permanent magnet motors (TLPMMs) with rectangular and trapezoidal permanent magnets (PMs) structures. The motors equipped with a quasi-Halbach magnetized moving-magnet armature and slotted stator with a single-slot carrying a single coil. The motors have been developed for reciprocating compressor applications such as household refrigerators. It is observed that the TLPMM efficiency can be optimized with respect to the leading design parameters (dimensional ratios). Furthermore, the influence of mover back iron is investigated and the loss of the motor is computed. Finite element analysis (FEA) is employed for the optimization, and the optimal values of the ratio of the axial length of the radially magnetized magnets to the pole pitch as well as the ratio of the PMs outer radius-to-stator outer radius (split ratio), are identified.

Introduction

Finite element analysis (FEA) is being used by the most motor designers to analyze the performance characteristics in obtaining a successful design specifications. Linear permanent magnet motors (LPMMs) are dedicated to a widespread applications, such as linear reciprocating compressors. LPMMs provide continuous short-stroke reciprocating motion of controllable frequency and amplitude, with the displacement being normally less than one pole pitch. Of various LPMMs topologies, tubular linear permanent magnet motors (TLPMMs) with moving-magnet have shown a significant advantages in terms of efficiency, thrust control, position accuracy, and reliability [1], [2].

Energy technologies play crucial role in social grade of living and economic construction at all scales. This will further pressure on energy supplies and necessitate energy conservation measures. Meanwhile, the impact of carbon and carbon dioxide (CO_2) emission based on the Kyoto protocol has increased the major concern of the researchers [3]-[5]. Among various loads, the household refrigerators represent a significant growing loads and a very important appliance in our lives today. Nevertheless, they have a some disadvantages [6].

Furthermore, the electrical energy consumption of individual household refrigerator is small, however, their large number represent an appreciable potential for energy savings. All these problems are due to inefficient use of refrigerator compressor system [7], [8].

Meanwhile, the mechanical friction of the crank-drive piston movement is the additional challenge for the conventional refrigerators employing a rotary compressor most probably driven by a single-phase induction motor. The overall efficiency is relatively low; this is due to the low efficiency of the induction motor [9], [10].

The linear reciprocating compressor which consists of a linear motor (LM) and compressor system and both are integrated using a direct-drive shaft. Fig. 1 shows the schematic of the linear reciprocating compressor. Unlike the conventional compressor, it could reduce the volume, complexity as well as can operate without lubrication [11]. Actually, the design of a LM has a very important role in the operation of the linear reciprocating compressor. The leading criteria of the appropriate LM design depend on the simplicity, affordability as well as force capability. Basically, the performance of the TLPMMs can be well improved by using different permanent magnets (PMs) array structures or PMs array arrangement [12]. This paper aims to investigate the performance and also to optimize the leading design parameters of a two novel single-phase short-stroke TLPMMs with rectangular and trapezoidal PMs Structures.

Linear Motor Model

The two designs with various PMs shape configurations, such are, rectangular PMs and trapezoidal PMs array with quasi-Halbach magnetization are developed. Each moving-magnet armature comprises three radially magnetized magnets placed at the center and both ends and two axially magnetized magnets, as illustrated in Fig. 2. Airgap is selected as small as mechanical possible, because a large airgap leads to an increase in PMs volume and a reduction in the motor thrust force, whereas a very small airgap causes mechanical fault and manufacturing difficulties. To produce a higher airgap field, a ferromagnetic support tube is used. However, a non-magnetic support tube has an advantage in terms of reducing the mass and eddy current loss in the moving armature.

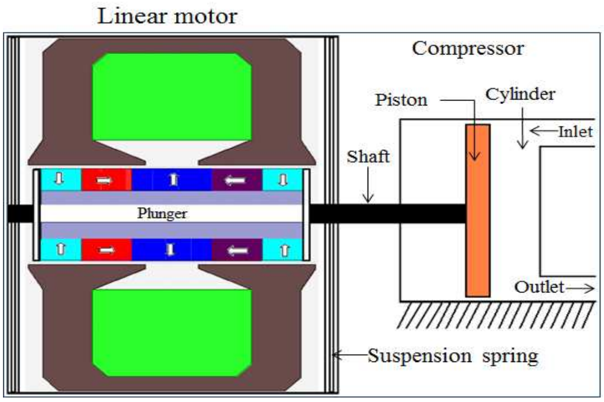

Fig. 1. Schematic of a linear reciprocating compressor

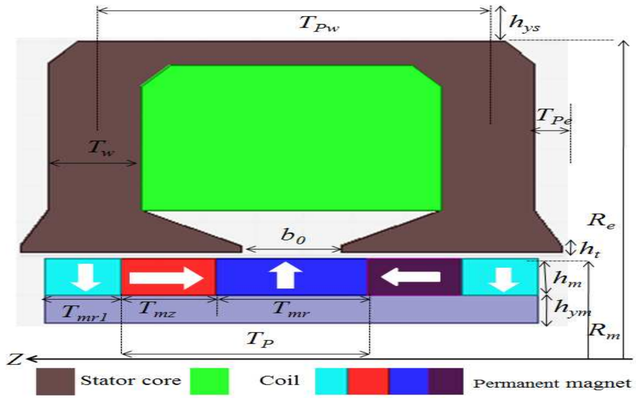

Fig. 2. Schematic and design parameters of a TLPMM with quasi-Halbach magnetization

The voltage equation of the LM is governed by

$$v(t) = L_e \frac{di_a}{dt} + R_{ei} i_a + K_e(z_d(t)) \frac{dz_d}{dt} \quad (1)$$

where K_e is the back-EMF coefficient, i_a is the coil current, z_d is the displacement of the mover, L_e and R_{ei} are the winding inductance and resistance of the LM, respectively [13].

Finite element simulations and analysis

The two-dimensional FEA (2D-FEA) is used to design and analyze the performance of the two TLPMMs. Hence, the transient solver of this software is used to examine the characteristics of these designs. The main design parameters are tabulated in Table I, and Fig. 2 demonstrated the schematic and design parameters of a single-phase short-stroke TLPMM equipped with a quasi-Halbach magnetized moving-magnet armature and slotted stator with a single-slot carrying a single coil.

Table I
Design parameters of a TLPMM

Outer radius of stator core, R_e	50.0 mm	Tooth tip height, h_t	1.0 mm
Yoke thickness, h_{ys}	3.3 mm	Magnet remanence, B_{rem}	1.14 T
Outer radius of magnet, R_m	20.0 mm	Length of the radial mag. T_{mr}	5.5 mm

Magnet height, h_m	5.0 mm	Ferromagnetic height h_{ym}	3.9 mm
Airgap length, g	0.8 mm	Tooth pitch width, T_{pw}	40 mm
Tooth width, T_w	9.4 mm	Pole pitch T_p	25 mm
Slot opening width, b_0	10.0 mm	Inner radius of supporting tube	11.1 mm

Fig. 3 shows the 2D-FE calculated flux distributions at no-load for zero displacement between the stator and the mover part ($z_d = 0$ mm). The results are plotted for both TLPMM designs equipped with quasi-Halbach magnetized magnets. As can be observed from Fig. 3 in both motors (a) and (b), at the initial position, the magnetic flux distribution is highly uniformed and balanced.

Fig. 3. Open-circuit flux distributions in the TLPMMs at $z_d = 0$ (a) rectangular PMs (b) trapezoidal PMs

Similarly, the 2D-FE calculated flux distributions in the two designs at maximum armature displacement ($z_d = 11$ mm) is shown in Fig. 4. At the maximum stroke position, most of the flux from the PMs flows through the teeth and back iron, and the flux-linkage with the coil is at maximum value.

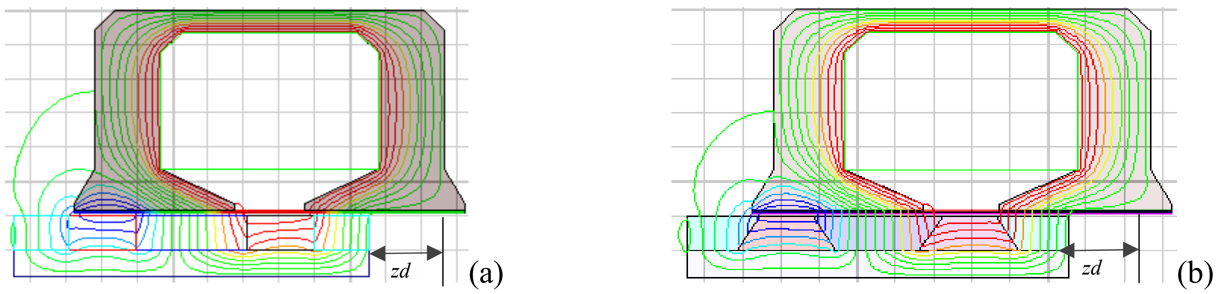

Fig. 4. Magnetic flux distribution in TLPMMs at $z_d = 11$ mm (a) rectangular PMs (b) trapezoidal PMs

Iron loss calculation

The iron losses of the motor can be predicted by synthesizing three different components, such are hysteresis losses P_{hi}, classical eddy current losses P_{ci} and excessive losses P_{ei}. The total iron loss can be expressed as

$$P_{fe} = \sum (P_{hi} + P_{ci} + P_{ei}) \tag{2}$$

FEA has been implemented to assist in motor loss computation. By using the 2D-FEA with a transient solver, we are able to compute iron losses within the stator and rotor or hysteresis losses, classical eddy current losses and excessive losses, assuming constant mover speed.

The iron losses of every element inside meshed stator and rotor are first determined at every time step, and after that added up on the entire stator and rotor iron to get the total iron losses of the motor.

Design optimization

The goal of the optimization is to obtain maximum efficiency of the both TLPMMs by the optimizing the leading design parameters T_{mr}/T_P (ratio of the axial length of the radially magnetized magnets to the pole pitch) and R_m/R_e (spilt ratio or mechanical load to electrical load ratio). In order to improve the efficiency of the motor, the objective function for optimization is defined as $1/\eta$, where η is the motor efficiency. Actually, the objective function is called profit function in case of maximization and cost function in case of minimization. The influence of the leading design parameters on the performance of the two TLPMMs have been investigated. Some design parameters listed in Table I, such are, b_0 and h_t have insignificant influence on the motor performance and therefore, their values are fixed to 10 mm and 1 mm, respectively. The motor efficiency improves as the outer stator radius R_e increases. However, an initial design scan shows that for the given design specification, the efficiency improvement decreases when R_e is greater than 50 mm. Hence, this value is chosen for the outer stator radius R_e [9].

Fig. 5 shows the influences of T_{mr}/T_P and R_m/R_e on the iron loss and copper loss of the TLPMM with rectangular PMs structures. Also it is clear from Fig. 5 (a) that, the iron loss decreases when the ratio of T_{mr}/T_P increases from 0.6 to 0.72, while copper loss decreases when the ratio of R_m/R_e increases from 0.36 to 0.40 as observed in Fig. 5 (b). This is because the slot area decreases as R_m/R_e increases, which yeilds increasing in the resistance of the coil, subsequently, the motor current will decrease and resulting in decrease of copper loss.

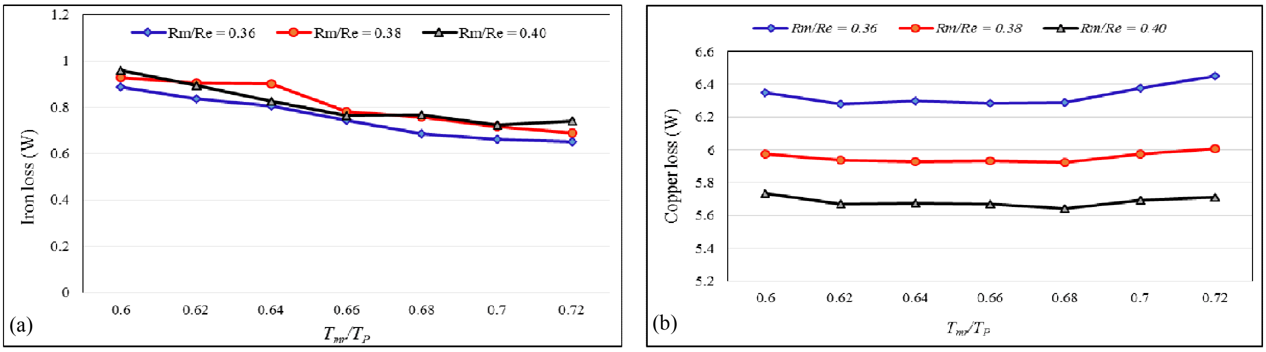

Fig. 5. Influence of T_{mr}/T_P and R_m/R_e on the TLPMM losses (a) iron loss and (b) copper loss

Fig. 6 shows the variations of the efficiency of the TLPMM as a function of T_{mr}/T_P and R_m/R_e assuming that a constant values of magnet height, tooth pitch width and magnets remanence as well as constant material for magnet and stator core. As can be observed in Fig. 6 (a), the optimal ratio of $T_{mr}/T_P = 0.68$, which yields the maximum efficiency of 92.95 %, while $R_m/R_e = 0.48$, yields the efficiency of 93.45 % as shown in Fig. 6 (b). The R_m/R_e ratio represents an optimal balance between electrical and magnetic loadings, whereas the T_{mr}/T_P ratio results in a maximum coil flux linkage produced by the two-pole quasi-Halbach magnetized magnets.

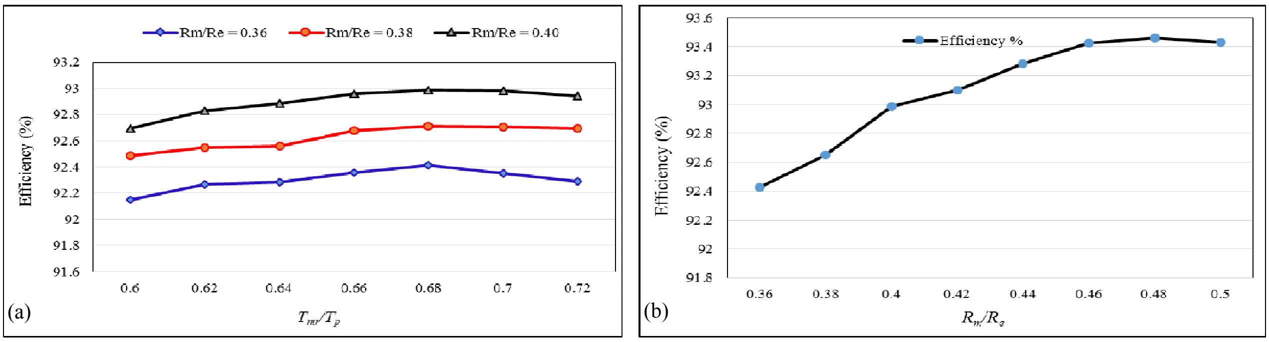

Fig. 6. Influence of the dimensional ratios on the efficiency of the motor (a) T_{mr}/T_P (b) R_m/R_e

Fig. 7 shows the influence of R_m/R_e on the iron loss and copper loss of the TLPMM equiped with trapezoidal PMs structures. Fig. 7 (a) demonstrated that, the iron loss increases when the ratio of R_m/R_e increases from 0.36 to 0.60. While the copper loss decreases when the ratio of R_m/R_e increases from 0.36 to 0.52 and then increase in the range of 0.52 to 0.60 as observed in Fig. 7 (b).

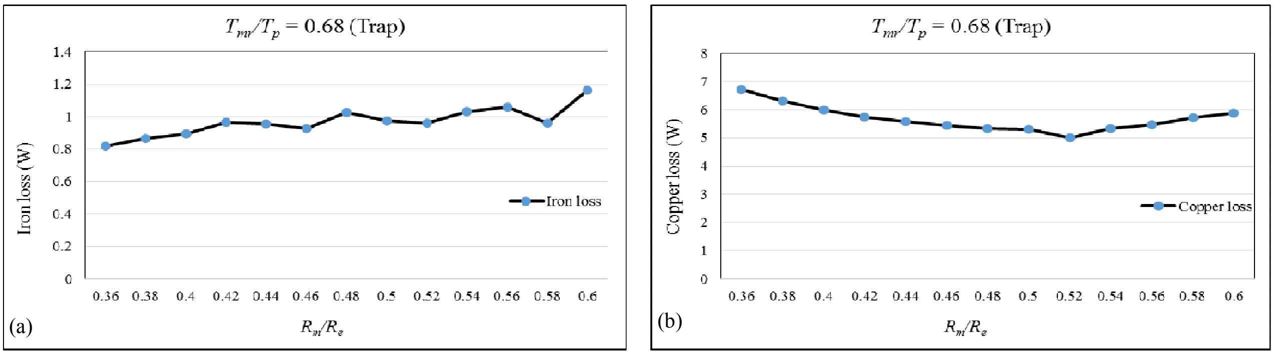

Fig. 7. Influence of R_m/R_e on the TLPMM losses (a) iron loss and (b) copper loss

The performance variations of the TLPMM with respect to the influence of the dimensional ratios are illustrated as in Fig. 8. The optimization conducted with constant values of magnet height, tooth pitch width and magnets remanence as well as constanat material for magnet and stator core. As will be observed in Fig. 8, there are optimal ratios of T_{mr}/T_P and R_m/R_e. The optimal ratio of T_{mr}/T_P is 0.68, which yields the maximum motor efficiency of 92.58 % as shown in Fig. 8 (a), whereas, the optimal value of R_m/R_e is 0.52 at which the motor efficiency is 93.43 % as shown in Fig. 8 (b). In this study the efficiency of the TLPMM equiped with trapezoidal PMs structures is optimized with respect to the leading design parameters. The output power kept constant by adjusting the magnitude of the current, while the leading design parameters change and assume constant speed of the mover.

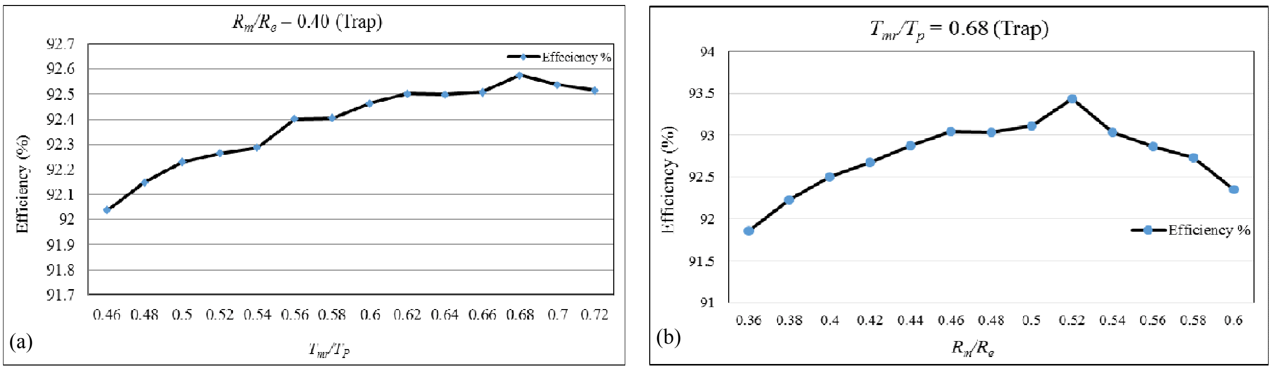

Fig. 8. Influence of the leading design parameters on the efficiency of the motor (a) T_{mr}/T_P (b) R_m/R_e

Conclusions

An improved designs of tubular permanent magnet motors (TLPMMs) with different PMs shape configurations, such as, rectangular PMs and trapezoidal PMs array with quasi-Halbach magnetization have been modeled and designed. The influence of the leading design parameters on the motor losses and efficiency have been studied by using FEA. The optimal axial lengths of the radially and axially magnetized magnet and the optimal split ratio have been established. It has been shown that the optimal magnet-length ratio, ratio of the axial length of the raidlly magnetized magnets to the pole-pitch length is 0.68 for both TLPMM with rectangular PMs and trapezoidal PMs as well. While the optimal split ratio, ratio of the mover outer radius to the stator outer radius is 0.48 and 0.52 which yeild efficiency of 93.45 % and 93.43 % for TLPMM with rectangular PMs and trapezoidal PMs, respectively.

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