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Comparative Study of Permanent Magnet Configurations of Short-Stroke Linear Motor for Reciprocating Compressor in Household Refrigerator Applications

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ABSTRACT

In this paper, two novel designs of linear permanent magnet motors (LPMM) with moving magnets armature and slotted stator are proposed. The aim of the designs is to drive a linear reciprocating compressor in a household refrigerator. The designs are analyzed and compared with conventional rectangular permanent magnets (PM) array, by evaluating their configurations and static characteristics based on finite element analysis (FEA). In contrast to a conventional reciprocating compressor, a direct-drive linear compressor in which the piston is driven directly by a linear motor (LM) and resonant springs is considered a positive displacement. The analysis on performance of LPMM using the proposed designs is carried out on the open-circuit magnetic field distribution, thrust force, flux-linkage, winding inductance, back-EMF and cogging force. The extensive simulation results indicate the effectiveness of the proposed designs and their superiority of the conventional design with rectangular PMs array.

Keywords: *Finite Element Analysis; Linear Motor; permanent magnets; quasi-Halbach; reciprocating compressor*.

1. INTRODUCTION

Nowadays, energy technologies have a crucial role in social and economic construction at all scales, ranging from household and community to national and international sectors. Among its welfare effects, energy is closely linked to economic development, and grade of living. This will give a big impact on energy supplies and necessitate energy conservation measures. Meanwhile, the impact of carbon and carbon dioxide (CO_2) emission from the Kyoto protocol has increased the major concern of the researchers [1]-[7].

Amongthe various loads, refrigeration devices represent significant and growing electrical loads, more than 14 % of the total energy consumption [8].

Undoubtedly, the household refrigerator represents one of the most important refrigerator devices in our lives today. Nevertheless, a household refrigerator comprises chlorofluorocarbons (CFCs) in its installation foam which contributes to the global warming and ozone layer depletion, also the household refrigerator load has a very significant impact on the emission of carbon and CO_2.

Furthermore, the electrical energy consumption of individual household refrigerator is small, however, their large number represents an appreciable potential for energy savings. All these problems come due to inefficient of a household refrigerator compressor system [9]-[13].

Besides, one of the important issues facing the current household refrigerator driven by a conventional compressor is the mechanical friction due to the crank-drive piston movement which uses the concept of rotary motor. This friction will lower the performance of the refrigerator. Also, the side force between the piston and cylinder is high, thus lowering the smoothness of operation system. Fig. 1 shows schematic representation of a conventional refrigerator compressor. The compressor involves a rotary single-phase induction motor, which drives a reciprocating pump through a crank. The overall efficiency is relatively low, due to the inherently low efficiency of induction motor and the mechanical friction of the crank-driven piston movement [14]-[16].

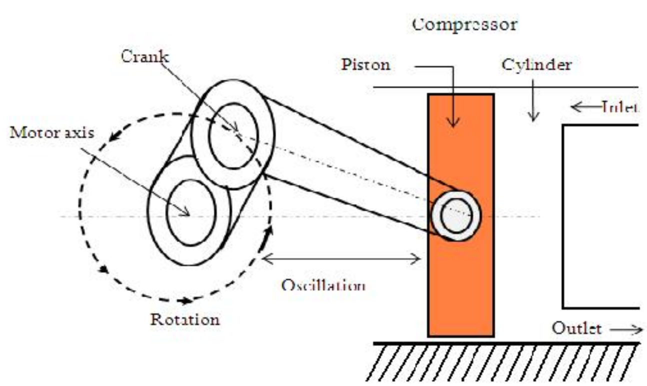

Fig. 1. Conventional refrigerator compressor [17].

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In order to improve the performance of the conventional compressor, it must eliminate the rotary-to-linear motion conversion crank. This can reduces the volume and complexity and removes the side force on the cylinder wall caused by the crank shaft. This results in reducing the cost and power loss as well as enables soft operation system. In contrast to a conventional reciprocating compressor, a direct-drive linear compressor in which the piston is driven directly by a linear motor (LM) and resonant springs is considered a positive displacement in the area of compressors manufacturing.

Fig. 2 shows the schematic representation of a direct drive linear reciprocating compressor, which can satisfy the aforementioned objectives, and can also operate without lubrication. In such compressor the piston is driven by a LM and resonant springs [16], [18]. The role of spring on the system is just to store or release the energy but does not consumes net energy over a cycle. The design of the LM will have an important influence on the operation of a direct-drive reciprocating compressor.

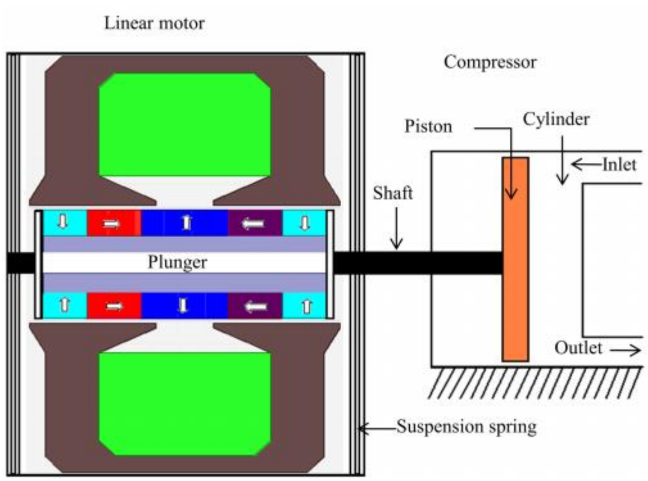


Fig. 2. Direct-drive linear compressor system [19].

2. EXITING DESIGNS

The vapor compressor designs have been proposed so far, for the household refrigerator applications only presented in a few papers. J. Wang, et. al. [20] proposed alternative winding configurations of a short-stroke, single-phase tubular PM excited motor with quasi-Halbach magnetized armature and slotted stator with single coil for linear compressor applications. It has been shown that the motor design with a single stator coil has a higher thrust force capability compared with the three-slot, distributed winding motor design. Besides, it has high specific force per moving mass capability and high efficiency, its relative simplicity, and the availability of emerging soft magnetic composite materials and high-energy rare-earth permanent magnets. These features are conducive to low manufacturing cost for the cost-sensitive applications [20].

A resonant frequency tracking technique was proposed by Z. Lin, et. al. [19]. The aim is to achieve high efficiency operation of a linear compressor system. This is based on the fact that for given amplitude of the motor current, the linear compressor system reaches its maximum stroke and maximum input and output powers at its resonant frequency. By evaluating the input power to the compressor and implementing a perturb and observe algorithm, the proposed technique can adjust the frequency of the motor current to match the resonant frequency of the compressor operation. The proposed technique does not require a position sensor, and can be easily implemented in a digital controller as claimed by [19].

A tubular, PMM topology which employs a 2-pole quasi-Halbach magnetized armature, having radially magnetized ring magnets placed at the center and both ends, and a soft magnetic composite (SMC) stator core which carries a single-phase coil was proposed in [14] for linear compressor applications. Such a coil is easy to manufacture and results in a very high packing factor, which is conducive to high efficiency. All the previous designs only used the quasi-Halbach magnetized with square PMs array.

It should be noted that the foregoing treatment of the magnetization and PMs array makes it possible to improve the magnetic field distribution of the short-stroke LPMM.

3. PROPOSED DESIGN

The selection of the appropriate design was based on numerous criteria; such are force capability and simplicity. As reported, the specific force capability of LPMM may be enhanced significantly by employing a slotted stator [8], [21]. Furthermore, C-core LM require significantly smaller volume of PM and have a largest back-EMF and force density due to the largest slot area [22], [23], thus in this paper C-core stator was selected.

The airgap field of a LM can be enhanced by varying the PMs shape and using the supporting tube. Furthermore, the desired flux density waveform strongly depends on the LM topology, as introduced in [5], [24], [25], the airgap length should be as much as small mechanically possible. Then, the two LPMM designs were proposed for vapor reciprocating compressor in a household refrigerator, the design with conventional rectangular PM was developed her for comparing and validating purpose. These designs with different magnet shapes, viz, rectangular PM (Rec_PM), trapezoidal PM (Trap_PM) and T-shape PM (TS_PM) magnet arrays and using quasi-Halbach magnetization, as demonstrated in Fig. 3a, 3b and 3c, respectively. The conventional design despite easy to design, may produce less open-circuit magnetic field distribution and back-EMF. The proposed design with Trap_PM array, Fig. 3b may produce more open-circuit magnetic field distribution and back-EMF than Rec_PM, nevertheless the design of PM more difficult than Rec_PM. The proposed design TS_PM array, Fig. 3c may generate better open-circuit magnetic field distribution and back-EMF than the two previous designs but it is facing the complexity of PM shape design.

The common features of the proposed designs are no field winding requiring, may have a high thrust force capability, good dynamic performance and high efficiency. Moreover, the designs employing extended tooth shoe in order to reduce the cogging force associated in a linear motor due to interaction between PM and teeth of the slotted core. More comparison will be discussed in the section 4.

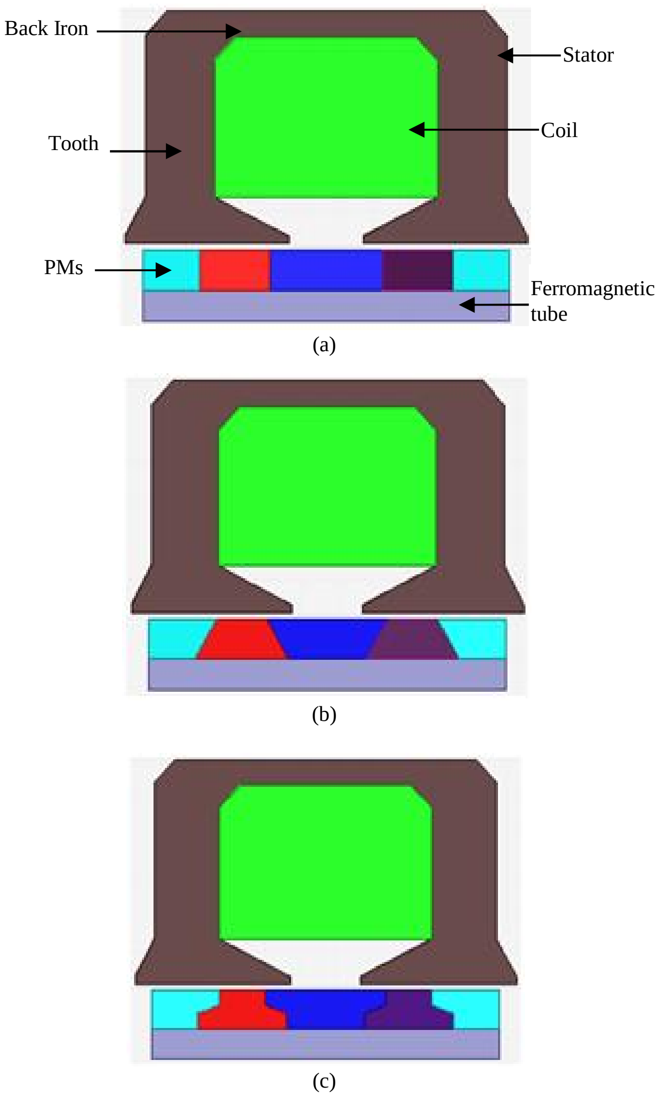


Fig. 3. 2-D FE models of a three proposed designs. (a) Geometry of Rec_PM (b) geometry of Trap_PM (c) geometry of TS_PM.

4. RESULTS ANALYSIS AND DISCUSSIONS

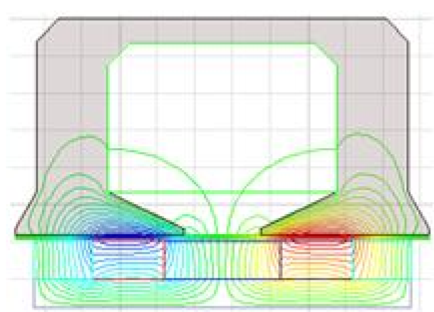
Finite element software is used to analyze and evaluate the performance of the proposed designs of LPMM; such are Trap_PM and TS_PM magnet array and compared with Rec_PM. Hence, the transient solver of this software is used to examine the electromagnetic characteristics of the proposed designs. Hence all results are established in cylindrical coordinate system. The main design specification parameters are tabulated in Table I.

TABLE I
DESIGN PARAMETERS

No	Description	Symbol	Value	Unit
1	Outer radius of stator core	R_e	50.0	mm
2	Yoke thickness	h_{ys}	3.3	mm
3	Outer radius of magnet	R_m	20.0	mm
4	Magnet height	h_m	5.0	mm
5	Airgap length	g	0.8	mm
6	Tooth width	T_w	9.4	mm
7	Slot opening width	b_o	10.0	mm
8	Tooth tip height	h_t	1.0	mm
9	Magnet remanence	B_{rem}	1.14	T
10	Frequency	f	50	Hz

The Fig. 4 shows the finite element calculated open circuit flux distributions in the conventional and the two proposed designs, at no-load and zero displacement between the armature and the stator ($z_d = 0$ mm). It can be seen, at the initial position, the magnetic field distribution is highly uniform and balance and the flux produced by the permanent magnets is virtually "short-circuited" by the tooth tips. Consequently, the net flux-linkage with the coil is zero, and the flux density in the tooth body and back-iron (yoke) is also zero.

The flux density waveform in the tooth tip region, both the radial and axial flux density waveforms can be approximated as trapezoidal. The peak flux entering the tooth tip occurs when the armature displacement is zero, as shown in Fig. 4.



(a)

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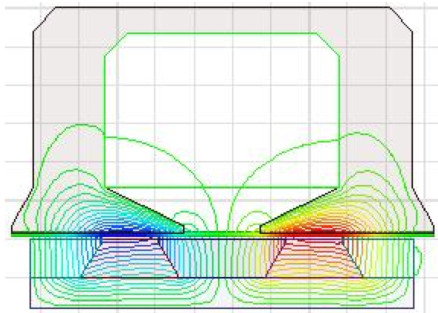
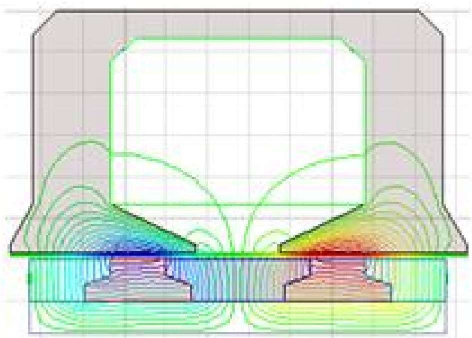


(b)

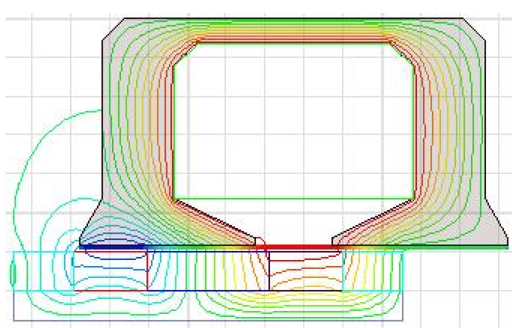


(c)

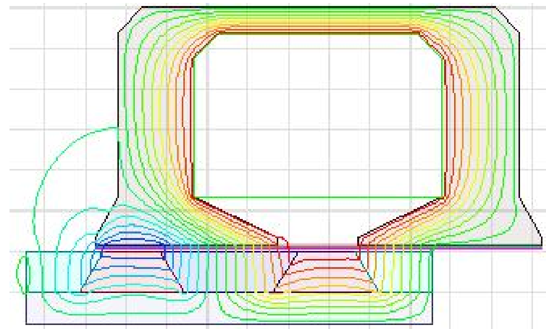
Fig. 4. 2-D FE open-circuit magnetic flux distribution in the conventional and the proposed designs of LPMM at $z_d = 0$ (a) flux-lines of Rec_PM (b) flux-lines of Trap_PM (c) flux-lines of TS_PM.

In a similar manner, the finite element calculated open circuit flux distributions in the conventional and the proposed designs at no-load and maximum armature displacement ($z_d = 11$ mm) is shown in Fig. 5. 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.

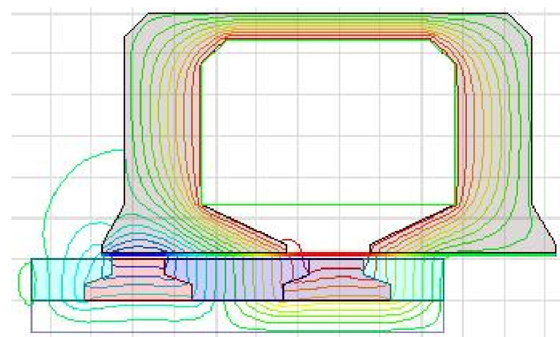
The flux is dominantly in radial direction. The resulting flux density in the tooth region varies with time as the armature reciprocates. The flux passing through the yoke is the same as in the tooth. However, the resulting flux density component in the yoke region is essentially in the axial direction.



(a)



(b)



(c)

Fig. 5. 2-D FE open-circuit magnetic flux distribution in the conventional and the proposed designs of LPMM at $z_d = 11$ mm (a) flux-lines of Rec_PM (b) flux-lines of Trap_PM (c) flux-lines of TS_PM.

In order to compare the performances of the proposed designs with conventional design which are given in section 3 with parameters given in Table I, the simulation results were established for the open- circuit magnetic field.

Fig. 6 shows comparison among magnetic flux-lines distribution at the airgap of the conventional and the proposed designs, such are rectangular, trapezoid and T-shape magnet array. All the results are showed at $z_d = 0$. Simulation results reveal that the higher flux lines obtained for Rec_PM shape magnet array, red line with solid triangles, the second higher flux line is showed for trapezoid magnet array, black line with solid circles and the blue line with solid boxes showed for the rectangular magnet array.

From the Fig. 6 the maximum flux is found, 0.0842 mwb/m, 0.0806 mwb/m and 0.0773 mwb/m for the Rec_PM, Trap_PM and TS_PM magnet array, respectively. While the average values were found, 0.0026 μwb/m, 0.0062 μwb/m and 0.0054 μwb/m, respectively. This makes actuating force of the LM with Trap_PM and T-shape magnet array larger than the conventional design. It can be seen that the waveform is very close to sinusoidal, subsequently, the back EMF can be determined by the waveform of the flux, which approximately sinusoidal, equation (1) shows the back-EMF calculation method by using flux.

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$$E = \sqrt{2}® f N_c k_N ¤ \qquad (1)$$

where f in Hz is the operating frequency, N_c is the number of turns of coil, and k_N is the winding factor, which equal 1[26], [27].

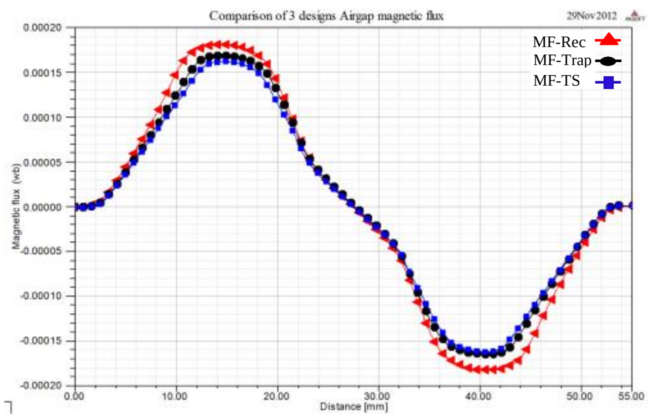

Fig. 6. Comparison between the simulation results of magnetic flux lines distribution at the airgap of the conventional and the proposed designs.

The simulation results of magnetic field intensity (H) at airgap at $z_d = 0$ were established for the conventional and the proposed designs and compared as shown in Fig. 7. From the results it is found that the higher amplitude of airgap magnetic field intensity obtained for the Rec_PM, red line with solid triangles. Second higher amplitude showed for the proposed design Trap_PM, black line with solid circles and the blue line with boxes showed for the proposed TS_PM.

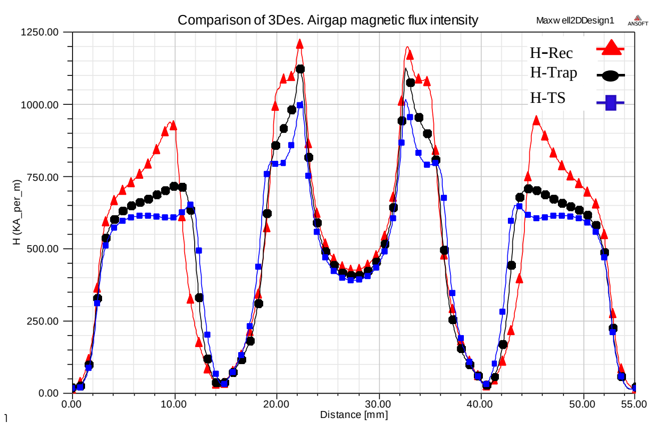

Fig. 7. Comparison between the simulation results of the magnetic field intensity at airgap the conventional and the proposed designs.

Fig. 8 shows a comparison among the simulation results of the magnetic flux density (B) at airgap of the conventional and the proposed designs at $z_d = 0$. It is found that the amplitudes of airgap flux density of motors as follow the higher amplitude obtained for the Rec_PM, red line with solid triangles. Second higher amplitude showed for the proposed design Trap_PM, black line with solid circles and the blue line with boxes showed for the proposed design TS_PM. Meanwhile, the average value of the magnetic flux density is 0.507634 T for the Rec_PM, 0.523129 T for the proposed design Trap_PM and 0.518091 T for the proposed design TS_PM. The relation between magnetic field intensity and magnetic flux density at the motor airgap, is expressed as in equation (2) [28].

$$B = \mu_0 H \qquad (2)$$

Where μ_0 is the permeability of free space, $\mu_0 = 12.57*10^{(-7)}$ H/m.

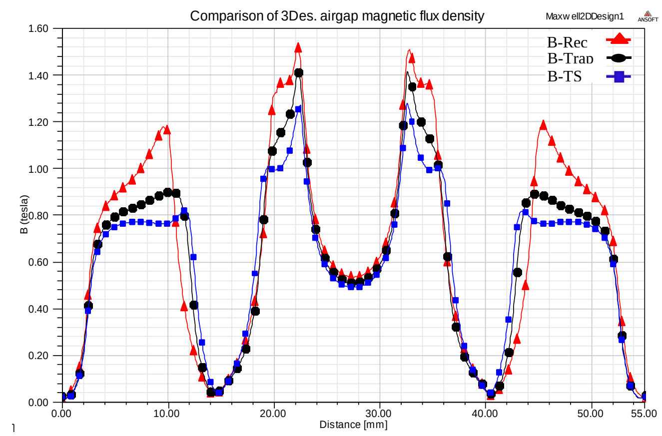

Fig. 8.Comparison of airgap magnetic flux density components of the conventional and the proposed designs.

When the mover is moving along the z-direction, the magnetic field is moving while the stator is static; hence, the distribution of the airgap magnetic field varies with the position of mover. So, the flux coupled with winding is variants with time. The back EMF can be written as in (3)

$$E = \frac{d\cdot}{dt} = \frac{d\cdot}{dz} * \frac{dz}{dt} = v * \frac{d\cdot}{dz} \qquad (3)$$

Where v is the motor velocity along the z-direction. Thus, back-EMF is given by the product of velocity v and the rate of change in flux linkage with respect to position.

Based on finite element (FE) analysis, the open-circuit flux-linkage and back-EMF waveforms of the conventional and the proposed designs are compared in Fig. 9 and Fig. 10, respectively. The average value of the back-EMFs at an armature velocity 2.2 m/s were found, 228.128 V, 233.4009 V and 232.8276 V for Rec_PM, Trap_PM and TS_PM, respectively. Obviously, the flux-linkages and back-EMF of the proposed designs with T-shape magnet array and trapezoidal magnet arrays are superior over the conventional rectangular magnet array.

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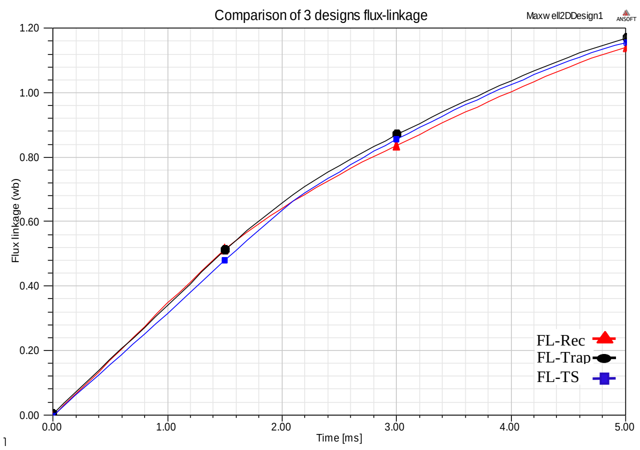

Fig. 9.Comparison of flux-linkage of the conventional and the proposed designs.

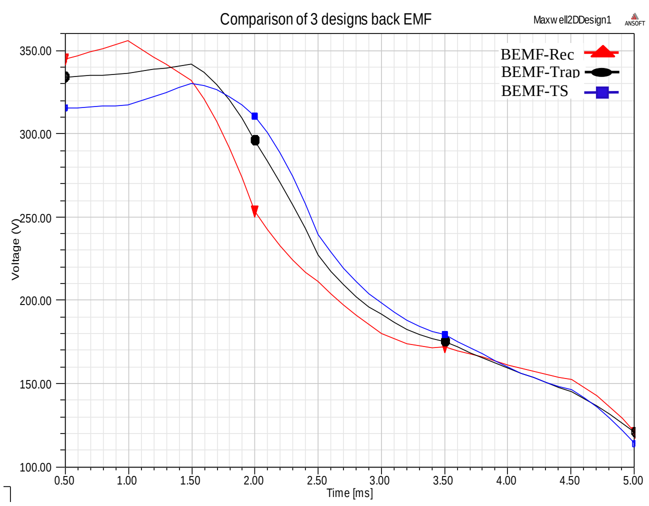

Fig. 10.Comparison of back EMFs of the conventional and the proposed designs.

Fig. 11 compares the thrust force of the conventional and the proposed designs for an excitation current of 0.5 A. The average thrust forces are quantified as 51.81488 N, 45.43742 N and 40.04353 N for the Rec_PM, Trap_PM and TS_PM, respectively. The generated thrust force when the stator winding carries a current *i* is expressed by:

$$F_T = \frac{Ei}{v} = K_E(z_d)i = K_T(z_d)i \qquad (4)$$

where $K_T(z_d)$, defined as the thrust force coefficient of the machine, is identical to $K_E(z_d)$ and also dependent on the displacement of the permanent magnet armature.

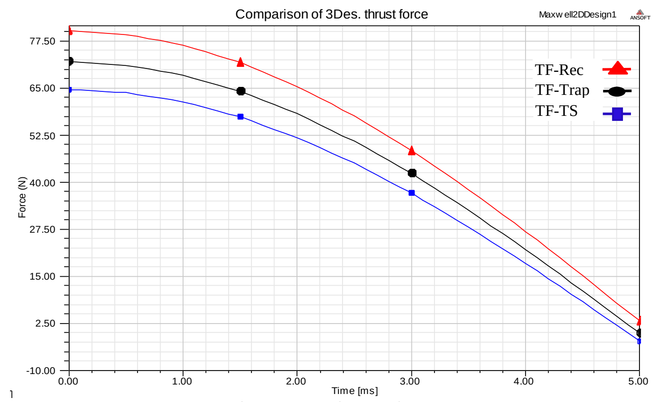

Fig. 11. Comparison of the thrust force of the conventional and the proposed designs.

Fig. 12 compares the winding inductance of the three proposed designs. The average values are found 1.04201 H, 1.09135 H and 1.088899 H for the Rec_PM, Trap_PM and TS_PM, respectively

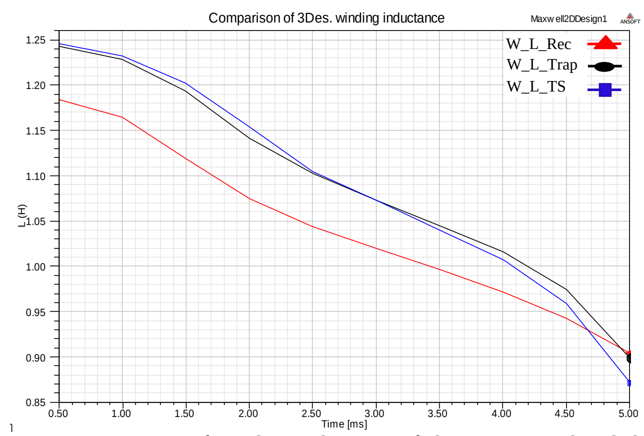

Fig. 12.Comparison of winding inductance of the conventional and the proposed designs.

Fig. 13 compares the cogging force of the conventional and the proposed designs. The average cogging forces are found 1.772636 N, 1.735461 N and 1.737054 N for the Rec_PM, Trap_PM and TS_PM, respectively. It is found that the higher cogging force is associated for with Rec_PM.

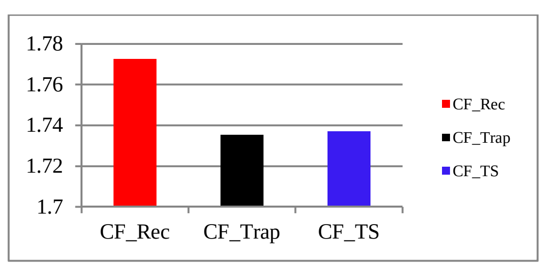

Fig. 13. Comparison of the cogging force of the conventional and the proposed designs.

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5. CONCLUSION

This paper has proposed two novel designs of moving-magnet LPMM for vapor reciprocating compressor in a household refrigerator. The proposed designs have different magnet shapes; viz, trapezoidal (Trap_PM) and T-shape (TS_PM) magnet array with quasi-Halbach magnetization. A Maxwell 2-D model was developed for each one and the results have been established which ensured efficient operation of the proposed LPMMs as compared with the conventional design with a rectangular (Rec_PM). The simulation results reveal that the moving-magnet LPMM with T-shape magnet array and trapezoidal magnet arrays are superior over the conventional rectangular magnet array design, in term of flux linkage, back-EMF and cogging force. Subsequently, the analysis of motor performance reveals that the flux density increases with the increase of magnet width.

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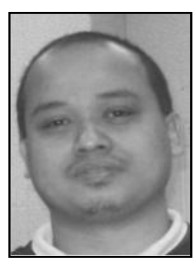

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