Research Article

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Cogging force reduction in linear tubular flux switching permanent-magnet machines

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Abstract: The aim of this paper is to explore the possibility of using linear tubular flux switching permanent magnet machines in a free piston energy conversion (FPEC) system. In FPEC systems, acceleration and therefore speed are often relatively high, which impose to have a reduced number of poles, meanwhile the cogging force will be relatively high. In order to reduce the cogging force two techniques are combined. The analysis is done using finite element method.

Keywords: linear tubular machines; flux switching permanent magnet; cogging force

PACS: 82.47.-a, 84.50.+d, 84.60.-h

1 Introduction

Flux switching permanent magnet linear tubular machines (FSPMLM) have some advantages over other types of permanent magnet linear machines. In these machines all magnetic excitation sources are placed in the same armature (stator or rotor), and the other armature is completely passive, as for the switched reluctance machines. This structure allows to reduce costs if the longer armature is the passive one [1]. Moreover, if both magnetic sources are placed in the stator, which is the case of the structures studied in this paper, the cooling is made easier, which insure a better and more stable performance. Furthermore, due to their high power density and efficiency, and the fact that they have no end-windings, tubular linear machines are superior to the planar linear structures [2]. Tubular linear structures are then being developed for an increasing variety of applications, ranging from free-piston energy converters and reciprocating compressors, to healthcare devices and active vehicle suspensions [2].

In this paper, the possibility of using linear tubular flux switching machines (LTFSM) in free piston energy converters [3] is explored. Free piston energy conversion (FPEC) systems are used in series hybrid vehicles as electric power source [3]. In FPEC systems, acceleration and therefore speed are often relatively high, which impose to have a reduced number of poles, meanwhile the cogging force will be relatively high.

In this study, two techniques are combined in order to reduce the cogging force [4]. The first technique consists of dividing the stator armature in two separate modules and adjust the separation length in order to reduce the cogging force. The second technique consist of adding teeth at the static armature ends [1].

2 Structures and operating principle of the LTFSPM

Figure 1(a) shows a 3D cut view of a 6/4 LTFSPM structure. Figure 1(b) shows main geometric dimensions of elementary cells of the stator and moving armatures. Table 1 gives the main machine's dimensions and material characteristics. The operating principal of flux switching machines has been described in many publications [1, 5]. According to the relative position of the mobile part regarding the static armature, the magnetic flux linkage in the armature windings can be counted as either positive or negative, and is then alternative [1, 5].

Two machines are studied in this paper. They are both 3 phased structures and their mover is longer than the static armature. The mobile part is similar to linear switched reluctance (SR) machine moving armatures, and therefore, has a simple and robust structure. The stator is composed of six modules and the rotor is composed of 8 (6/4 LTFSPM) or 10 (6/5 LTFSPM) modules. In their initial configuration, there is always 4 or 5 rotor modules covered by the static armature of the machine. The 6/5 LTFSPM have same main dimensions as the 6/4 LTFSPM, the

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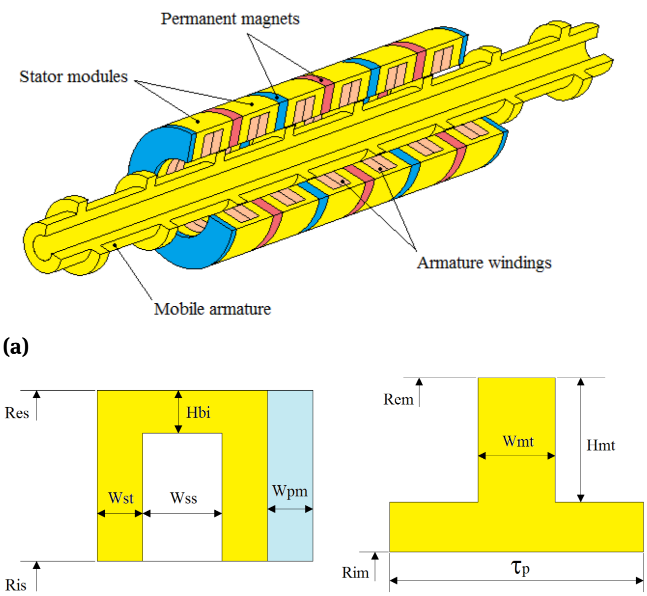


(a)

(b) Stator module Mobile armature module

Figure 1: LTFSPM Machine

Table 1: Machine's Characteristics (6/4 structure)

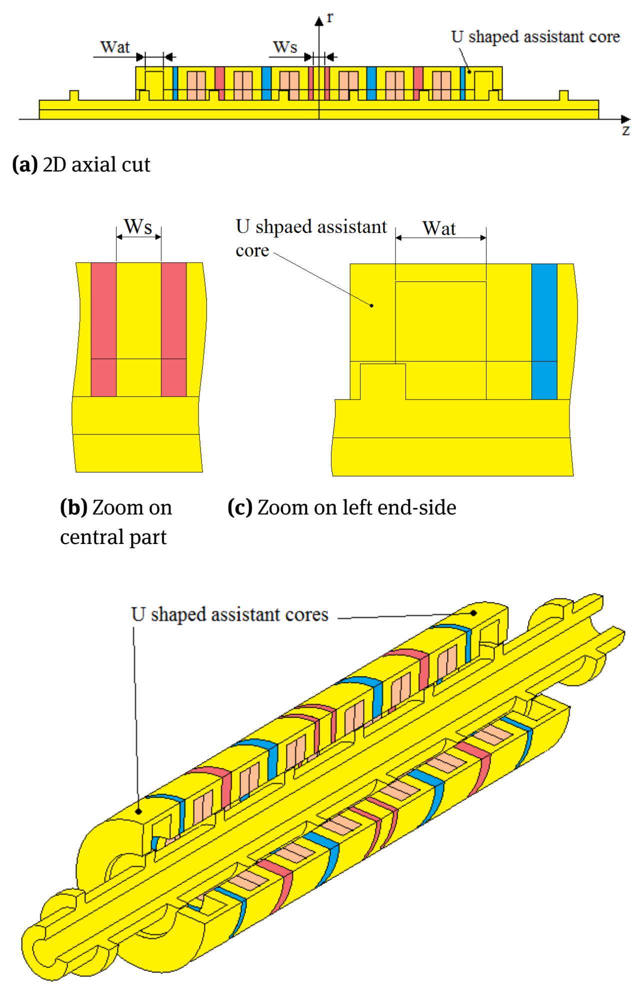
Mobile armature inner radius Rim	10(mm)
Mobile armature outer radius Rem	30(mm)
Pole pitch τp	75(mm)
Mobile armature tooth width Wmt	10(mm)
Mobile armature tooth height Hmt	10(mm)
Stator inner radius Ris	31(mm)
Stator outer radius Res	56(mm)
Stator teeth width Wst	10(mm)
Stator slots width Wss	20(mm)
PM width Wpm	10(mm)
Stator back iron height Hbi	5(mm)
PM characteristics Br, μr	1 (T), 1
Iron cores material	M330-35A

only difference is the pole pith length which is equal to 60 mm for the 6/5 structure. The mobile armature is 600 mm length for both structures. In the initial structure of the stator, two magnets of same polarity are placed at both axial ends. Their thickness is equal to Wpm/2. The initial dimensions of these machines have been arbitrary set without any optimization.

3 Cogging force reduction

In linear permanent magnet machines, the cogging force is due to both slot-effect and end-effects. Many techniques are used for the reduction of cogging force in linear permanent magnet (LPM) machines [1, 6–9]. In this paper two techniques will be combined in order to reduce the cogging force (Figure 2).

- The first technique consists of dividing the stator in two modules, each one containing three elementary cells [Figure 1(b)]. The gap between the two modules is filled with iron and its width (Ws) is adjusted in order to reduce the cogging force.
- For the second technique, additional U shaped teeth (cores) are placed at both ends of the stator [1]. The width of the slot (Wat) in the additional cores is varied in order to reduce the cogging force. The dimen-



(a) 2D axial cut

(b) Zoom on central part **(c)** Zoom on left end-side

(d) 3D cut view

Figure 2: Illustration of the reduction techniques

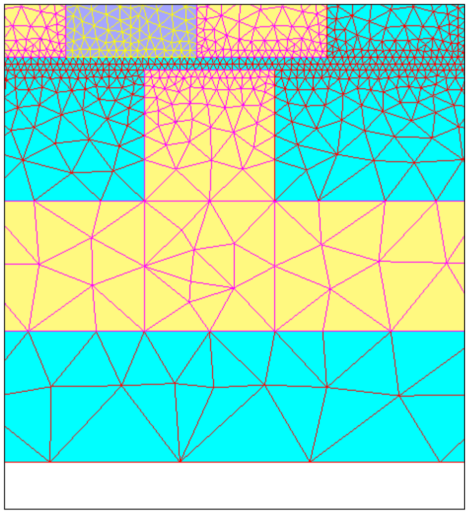
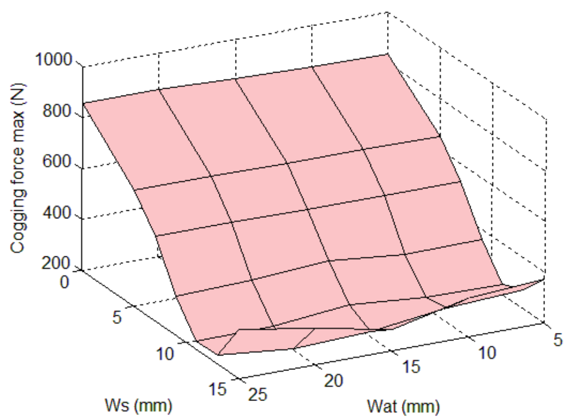
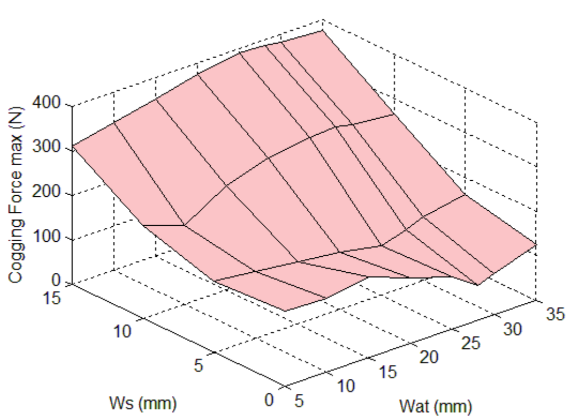


Figure 3: 2D Mesh

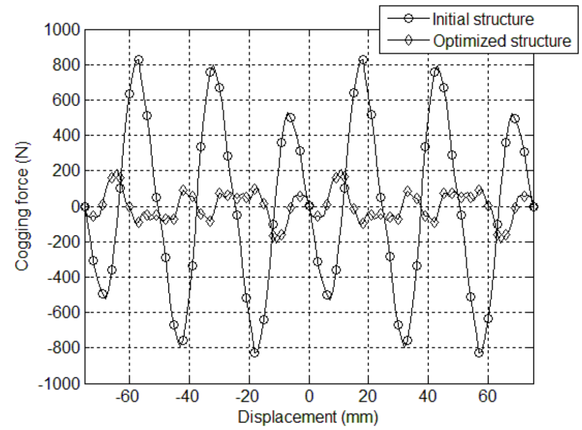


(a) 6/4 LTFSPM

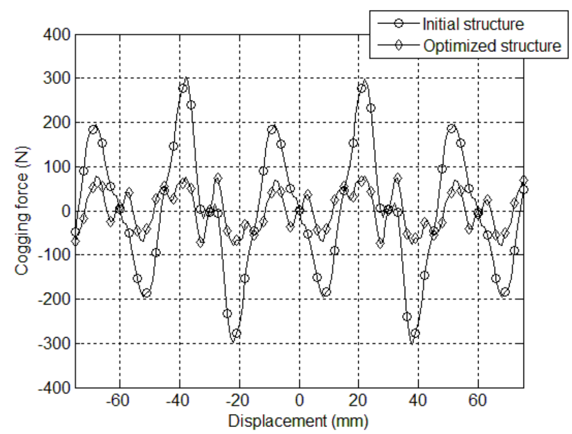


(b) 6/5 LTFSPM

Figure 4: Maximum value of cogging force variations with Wat and Ws



(a) 6/4 LTFSPM

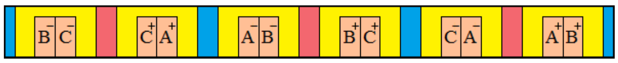


(b) 6/5 LTFSPM

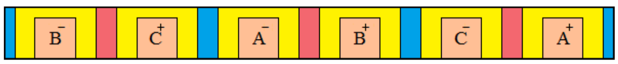
Figure 5: Cogging forces comparisons

sions of teeth and back-iron of the two U shaped cores are similar to those of the elementary cell [Figure 1(b)].

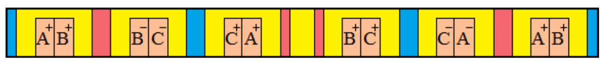
Figure 2 shows the new structure, obtained when the two techniques are applied. Figure 2(a) shows a 2D axial cut, and Figures 2(b) and 2(c) show zooms on central and left end-side respectively. Figure 2(d) shows a 3D cut view of the new configuration. In order to analyze the performance of the machines, finite element method (FEM) is used. Flux2D commercial package is used for that purpose. Since the studied machines have tubular structure, 2-D axi-symmetric finite element analysis is used. The air surrounding the machine is modeled using the well known mapped infinite elements technique for open boundary problems. The studied domains are meshed with second order elements. The number of nodes is around 50 000 nodes. Figure 3 shows a zoom on the mesh of the air-gap. The air-gap is meshed with two layers of elements. The ma-



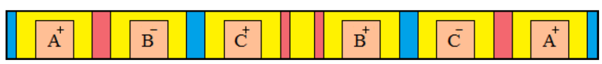
(a) Initial 6/4 LTFSPM with conventional windings (CW)



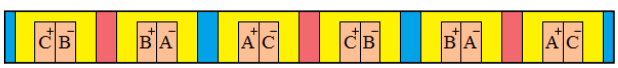
(b) Initial 6/4 LTFSPM with alternative windings (AW)



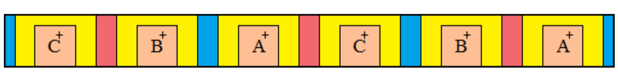
(c) Optimized 6/4 LTFSPM with conventional windings (CW)



(d) Optimized 6/4 LTFSPM with alternative windings (AW)



(e) 6/5 LTFSPM (initial and optimized) with conventional windings (CW)



(f) 6/5 LTFSPM (initial and optimized) with alternative windings (AW)

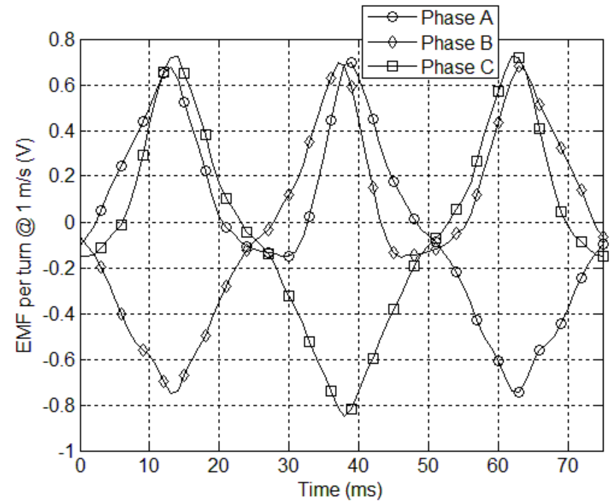
Figure 6: Windings configurations for the different machines

chines are analyzed using multi-static magnetic formulation.

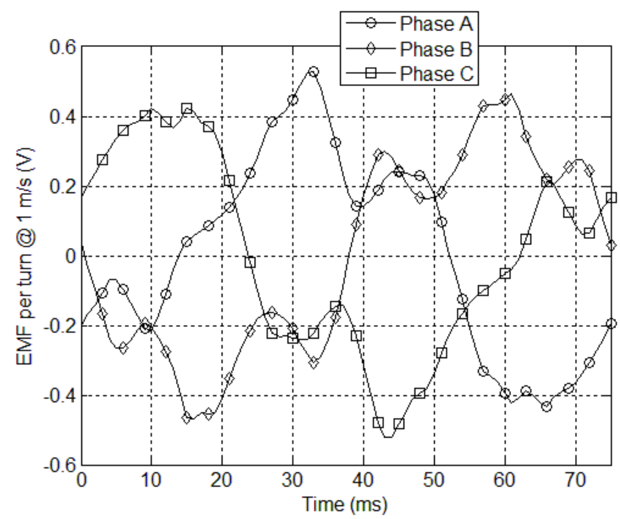
Figures 4(a) and 4(b) show the variation of maximum cogging force when the two widths Wat and Ws are varied for 6/4 and 6/5 structures respectively. As can be seen the cogging force is more sensitive to the variation of the spacing width (Ws) as compared to the slot width (Wat). However, the assistant cores helped also to reduce the cogging force even if it is in a less important fashion. Figures 5(a) and 5(b) show a comparison of cogging forces obtained for initial structures and optimized ones (Ws = 13 mm and Wat = 20 mm for the 6/4 structure, and Ws = 0 mm and Wat = 28 mm for the 6/5 structure). As can been seen a significant reduction is achieved.

4 Performance Analysis

In this section, the effects of the techniques used for the reduction of cogging force on the machines performances are explored. Two windings configurations are studied [2].



(a) Initial machine



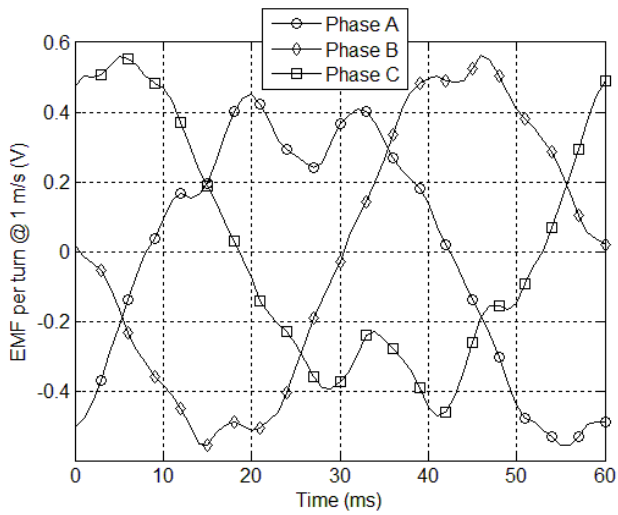
(b) Optimized machine

Figure 7: Comparison of EMF waveforms for initial and optimized 6/4 structure with alternative windings configuration

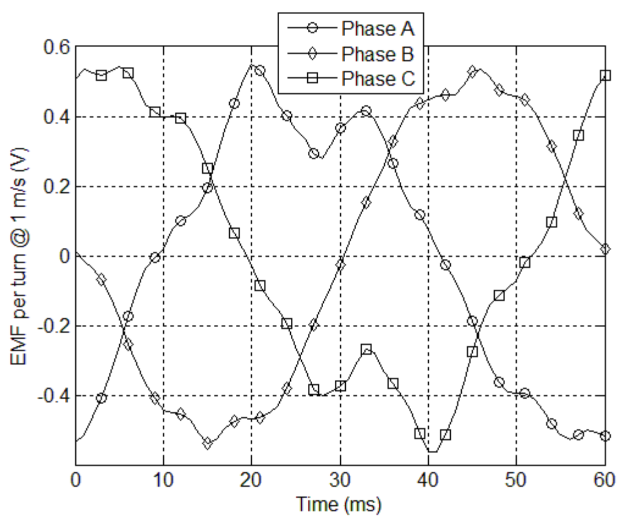
Figure 6 shows the two windings configurations for the two machines in their initial and optimized configurations.

The armature windings are distributed in order to form a three-phase windings. Each phase is formed from 4 annular coils in their conventional configuration, and 3 annular coils in their alternative configuration. The coils are distributed in order to maximize the flux in each phase. For the sake of clarity, the U shaped additional cores are not represented. For the 6/5 structure, since Ws = 0 mm for the optimized machine, the windings configurations [Figures 6(e) and 6(f)] are identical for the initial and optimized machines.

Figure 7 shows comparison of EMF waveforms for the 6/4 structure with the alternative windings configurations.

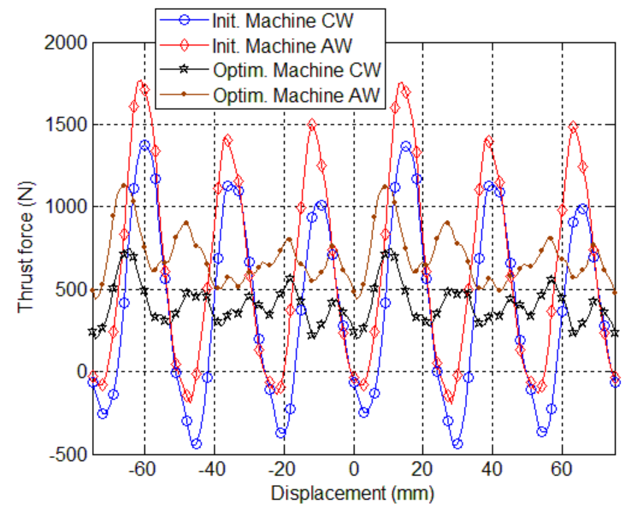


(a) Initial machine

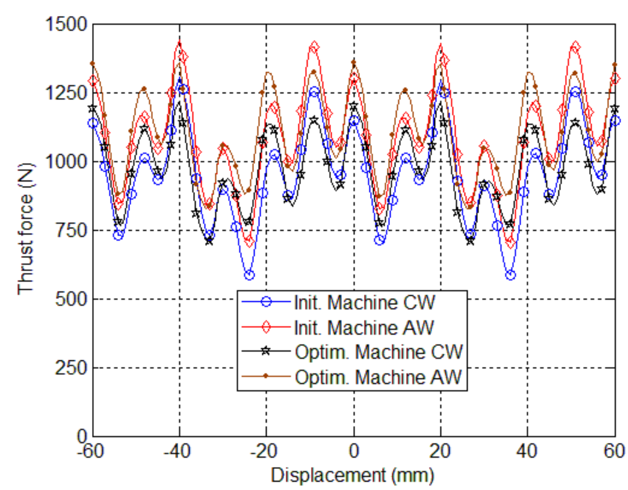


(b) Optimized machine

Figure 8: Comparison of EMF waveforms for initial and optimized 6/5 structure with alternative windings configuration



(a) 6/4 LTFSPM structure



(b) 6/5 LTFSPM structure

Figure 9: Comparison of thrust force waveforms

In order to save space, only EMF waveforms for the alternative winding configuration are shown. Figure 8 shows same comparison for the 6/5 structure. The alternative windings configuration allows obtaining a higher fundamental amplitude as compared to conventional one at the price of a more significant imbalance in the phase EMF waveforms [2]. Figure 9 shows comparison of thrust force waveforms for the two structures for the different windings configurations. The thrust force is computed for a current density of 10 Arms/mm^2, with a null phase shifting between current and EMF in each phase. A slot filling factor of 0.6 is considered. As can be seen the alternative windings allows increasing the force capability as compared to the conventional ones. The optimized structures have lower force ripple as compared to initial structures (Table 2).

Table 2 gives mean values of thrust forces and the force ripple ratios for the different machines. Again, the alternative windings allows increasing the force capability as compared to the conventional ones, and optimized machines have lower force ripple as compared to initial machines. For both configurations (6/4 and 6/5) optimized structures with alternative windings give the best compromise between force capability and force ripple. Indeed, they have the higher mean force values and the lower force ripple ratios (Table 2). It should be highlighted that these comparisons, for a given configuration, are done with same PM and copper volumes.

Table 2: Comparison of Thrust Force Characteristics

Machine	Means thrust force (N)	Force ripple ratio (%)
Initial 6/4 LTFSPM CW	387	471
Initial 6/4 LTFSPM AW	631	311
Optimized 6/4 LTFSPM CW	407	136
Optimized 6/4 LTFSPM AW	**695**	**99**
Initial 6/5 LTFSPM CW	953	76
Initial 6/5 LTFSPM AW	1087	68
Optimized 6/5 LTFSPM CW	971	52
Optimized 6/5 LTFSPM AW	**1104**	**48**

Regarding the EMF waveforms, it should be noticed that the 6/4 structure, in its initial version, presents a large second order harmonic [10]. The second order harmonic amplitude is even higher than fundamental component amplitude. The spacing between the two stator modules, for the optimized machines, helped reduce this amplitude to an acceptable level.

5 Conclusion

In this paper, two techniques have been combined in order to reduce the cogging force in linear tubular flux switching PM machines. Two structures have been studied (6/4 and 6/5 structures). The combination allowed to significantly reduce the cogging force and subsequently the force ripple of these machines. Two windings configurations have been investigated. It has been verified that the machines equipped with alternative windings configuration have higher force capability [2]. Furthermore, as expected the peak-to-peak force ripple decreases as the smallest common multiple between the pole number and slot number increases [2]. This study helped designing a 6/5 LTFSPM machine which is being built. The experimental performance of designed machine will be reported in a future contribution.

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