LINEAR TRANSVERSE FLUX RELUCTANCE MACHINE WITH PERMANENT MAGNETS

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Abstract — A new structure of linear transverse flux machine (TFM) is presented in this paper. It is in fact a variable reluctance linear machine having permanent magnets on the mover. Its structure and its working principle will be discussed. After a preliminary design of the motor a 3D FEM analysis was carried out before optimizing the designed linear motor. The flux densities in the machine and the static characteristics (tangential and normal forces vs. displacement) were computed.

I. INTRODUCTION

The transverse flux machine is a relatively newcomer in the class of special electric machines [1]. Despite its main advantages – high power density and specific torque – no mass production was reported yet. The proposed variants were mainly rotary machines. Three basic types of transverse flux rotary machines were built until now: one with active rotor having permanent magnets in it [2], and two structures with passive rotor [3, 4].

The research performed by the authors had as main purpose to obtain a linear variant of the transverse flux machine. After analyzing some possible structures (including a permanent magnets transverse flux (PMTF) arc rotor machine [5] and few variants of transverse flux reluctance machine [6]), a specific variant was selected to be presented here in detail.

The starting point was considered the TFM variant with passive rotor and permanent magnets placed on the stator. By unfolding its structure a linear machine having a similar operating principle was obtained. The linear machine has a modular structure [7]. Here the study on a three-phase variant of the proposed linear machine will be presented. First the theoretical approach will be detailed, followed by the results of the 3D FEM analysis.

II. THE NOVEL LINEAR TFM STRUCTURE

As mentioned above the linear machine variant proposed here was obtained from a rotary variant of TFM like the one given in Fig. 1 [8]:

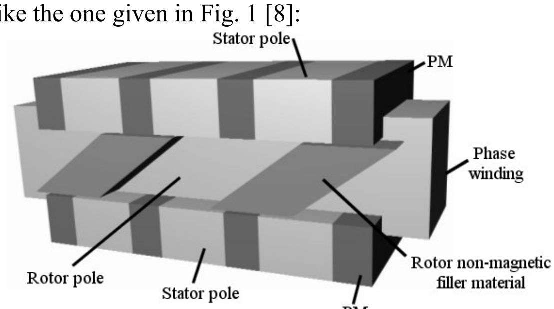


Fig. 1. A TF machine with passive rotor and permanent magnets in the stator.

This TF machine uses quite the same type of stator poles topology as the modules of a linear motor [9]. It is in fact a reluctance machine, since the permanent magnets assure only a part of the produced magnetic field. The machine has a passive stator and works upon the principle of minimal magnetic energy in the air-gap. Hence the mover is always placed in a position where the magnetic reluctance of its air-gap is minimal: in the position where the teeth of the mover are aligned with the teeth of the platen.

To work properly its modules have to be shifted one from each other by τ/N, where τ is the pole pitch and N is the number of the modules. The displacement step of the machine is given by the number of modules [10].

The single-sided three-phase variant of the proposed linear motor structure is given in Fig. 2. A three-phase (three modules) variant was selected because of the easy implementation of the control strategy on general purpose three-phase power converters [11].

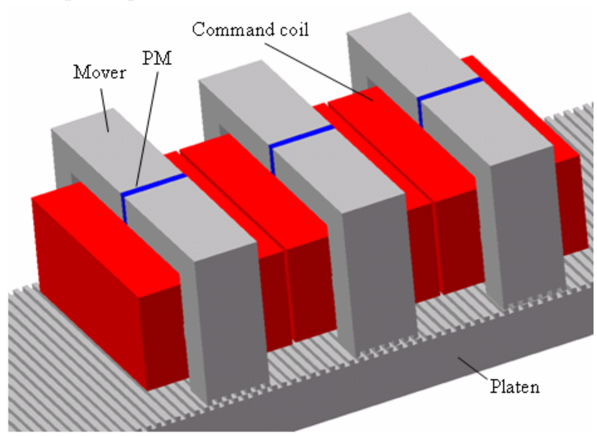


Fig. 2. The proposed modular linear machine.

A module of the machine consists of 2 iron poles separated by a permanent magnet and a core branch which holds the command coil. The two poles have teeth on the direction of movement. The iron core of one module is shown in Fig. 3 [12].

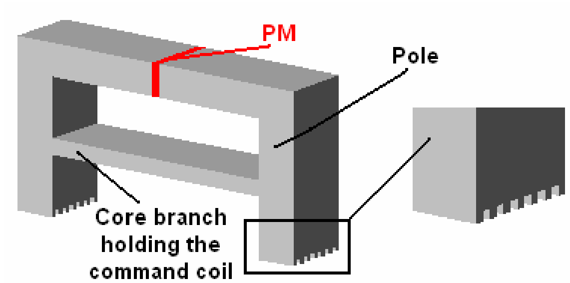


Fig. 3. The iron core of the mover.

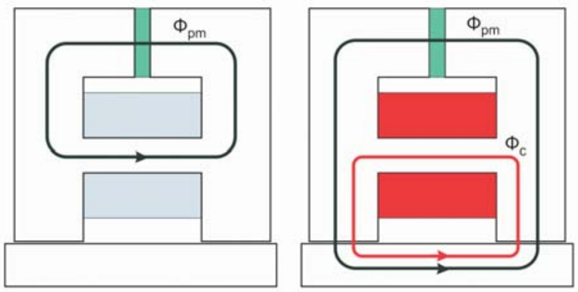


Fig. 4. The working principle of the linear machine.

The working principle of the machine is explained in Fig. 4. Because this linear machine is a variant of the rotary TFM with permanent magnets in stator and passive rotor, the operating principle is similar to that one's.

When the module is passive (having its command coil un-energized) the flux generated by the permanent magnet closes mostly inside the mover's iron core. When the command coil is energized, the magnetic flux produced by the coil practically enforces the flux of the permanent magnet through the air-gap, generating this way tangential and normal force. Energizing the command coil of one module its teeth will be aligned with the teeth of the platen [12].

For the linear motor having three modules the correct movement of the machine is possible only if the modules are shifted relatively by a third of the pole pitch. In general case the shifting between the teeth of the modules and the ones from the stator is given by the ratio between the pole pitch and the number of modules. By sequential feeding of the command coils continuous linear movement of any direction can be assured.

III. 3D FEM ANALYSIS OF THE LINEAR TFM

A design algorithm was performed specially for designing such machines. Using this several different structures had been designed.

In order to prove the validity of the design algorithm for the proposed machine, a motor having a tangential force of 5 N for the teeth shifting by a third of the teeth pitch (0.66 mm in this case) was designed and analyzed. The main dimensions of the sample motor are given in Fig. 5 [4].

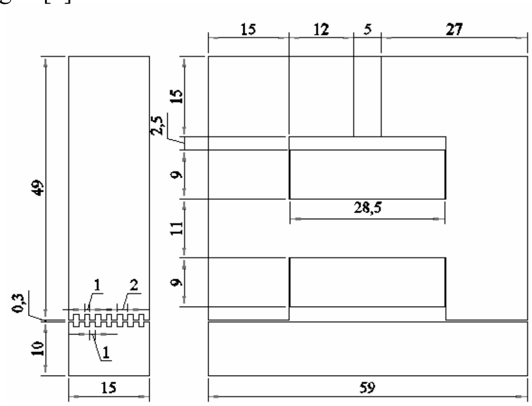


Fig. 5. Main sizes of proposed linear TFM module:
a) lateral view; b) frontal view.

As in any time moment only a single module is active in the linear machine it was enough to analyze only a single module and the portion of the stator under it (as shown in Fig. 6) [12].

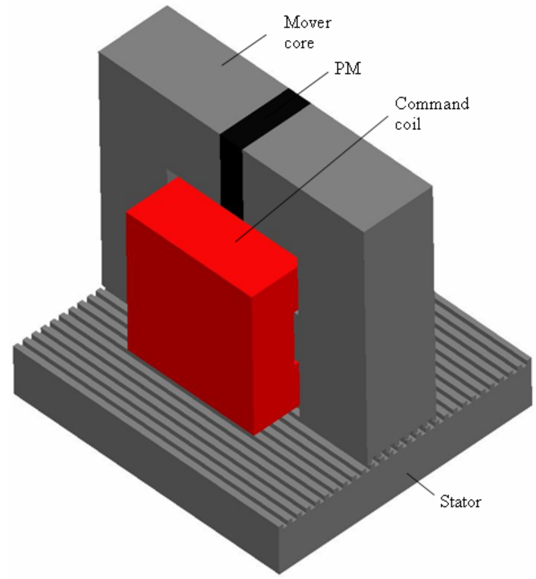


Fig. 6. The analyzed motor structure.

The frontal and lateral view of the analyzed motor part is given in Fig. 7 for better understanding of the problem to be solved.

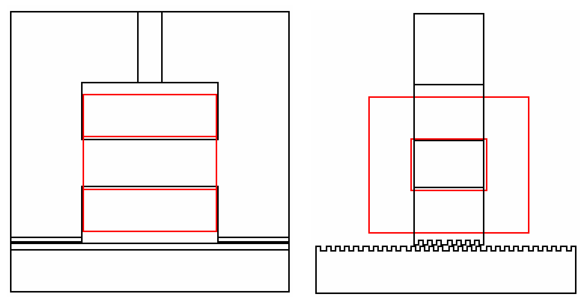


Fig. 7. Two views of the analyzed motor structure.

The three-dimensional mesh, automatically generated by the program, over the analyzed structure is given in Fig. 8.

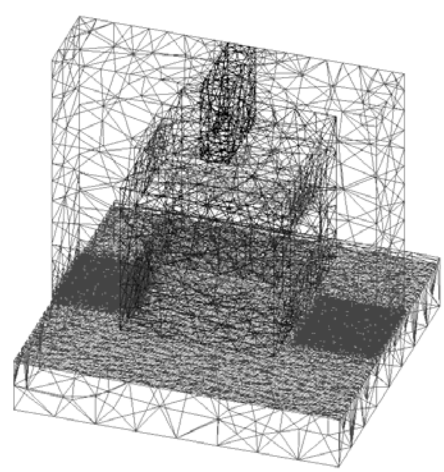


Fig. 8. The 3D mesh generated.

Two situations were basically analyzed. The first one is when the module has the teeth shifted by a third of a pole pitch relatively to the stator ones and consequently its coil is excited with such a current that will determine a nil flux in the core branch. For the motor analyzed here, with the geometrical dimensions given in Fig. 5 the necessary current in order to achieve this goal was computed to be 1 A in a coil with 400 turns. The second case analyzed is when the module has the teeth aligned with the stator ones and the coil is not excited.

In the first case the flux density vector and the value of flux density in the whole structure were plotted. Fig. 9 and Fig. 10 show the obtained results.

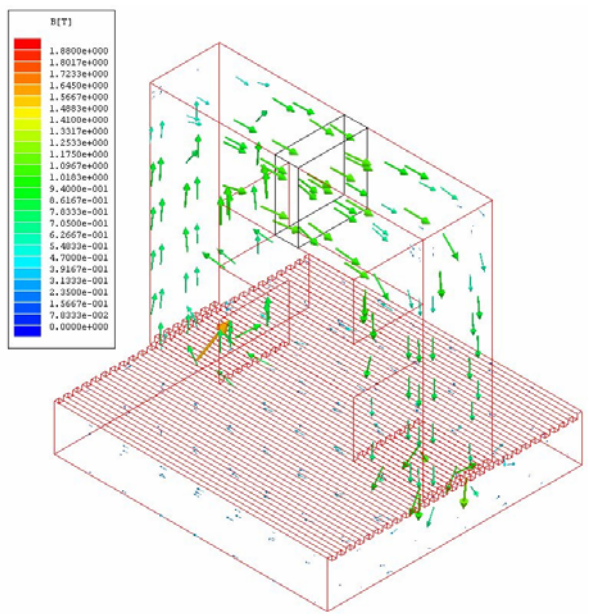


Fig. 9. The flux density vector in an active module obtained via 3D FEM analysis.

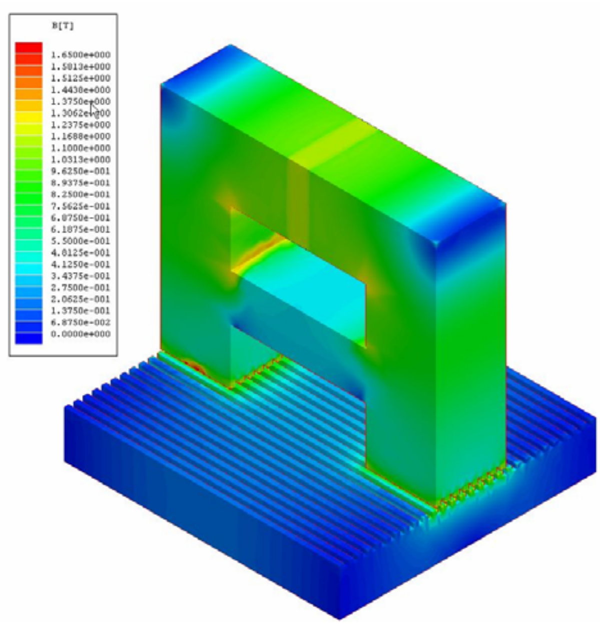


Fig. 10. The flux density distribution in an active module obtained via 3D FEM analysis.

When the teeth are unaligned the coil is supplied in order to obtain a nil flux in the core branch and to force its flux path through the U-shaped poles and to cross the air gap. As it can be noticed, the flux density has a uniform distribution almost in the whole armature. This fact, besides the values of the flux density in the core branch, proves that the computed current in the design stage in the coil has the right value. The higher values of the flux density in the upper parts of the poles are found at the inner corners, while the lower ones are met at the outer corners.

Another observation is related to the flux density values in the mobile armature's and in the stator's teeth. The saturation is found mainly in the mobile armature's teeth but also the stator's teeth.

One of the particularities of this motor is that the poles can be constructed both from steel sheets and SMC [13], and for the stator solid iron can be used too. The analyses carried out here were made considering both the mobile armatures and the stator built of steel sheets. The variation of the flux density in air-gap on the module's length is given in Fig. 11. As expected, the higher values correspond to the zones where the teeth of the mover are aligned with the platen's teeth.

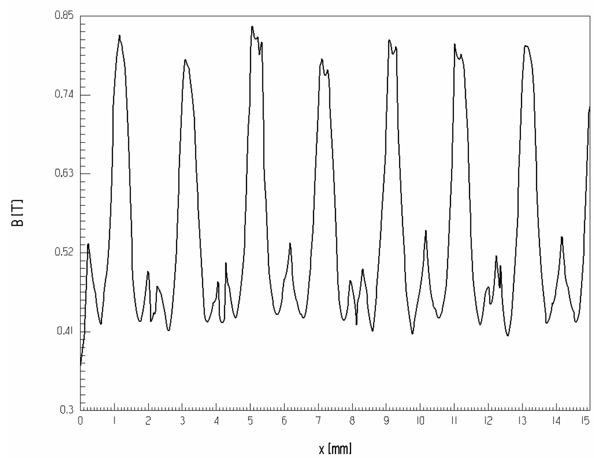


Fig. 11. The air-gap flux density variation vs. length for unaligned teeth with supplied coil.

The force computed via the 3D FEM analysis is very closed to the one imposed when starting the design of the machine. The tangential force developed in the position of commutation which is done at a 0.66 mm shifting between the platen's and one module's teeth is 5.14 N. The error comparative to the design data is only of 4%.

In the second situation we performed the same analysis as in the first case, the results being shown in Fig. 12 and Fig. 13. In the aligned position of the teeth the flux passes mainly through the core branch where the flux densities have high values.

The tangential force developed in this case is, of course nil, and the normal force is of 2.53 N. We also plotted the variation of the air-gap flux-density on the module's length, Fig. 14.

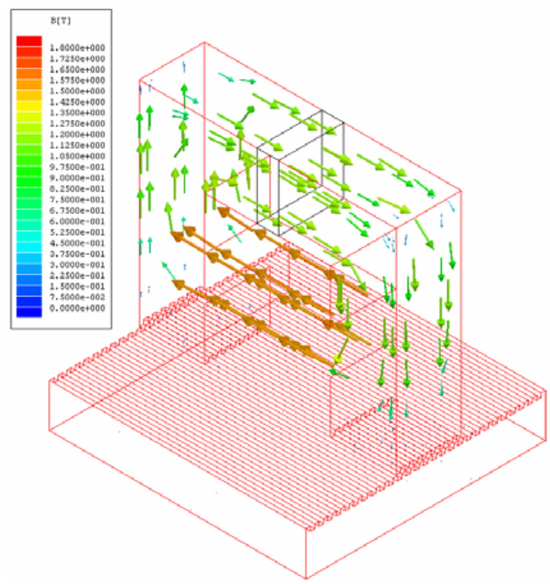


Fig. 12. The flux density vector in a passive module obtained via 3D FEM analysis.

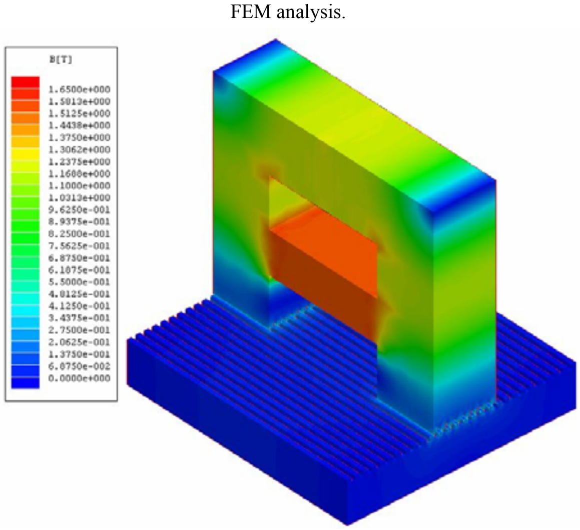


Fig. 13. The flux density distribution in a passive module obtained via 3D FEM analysis.

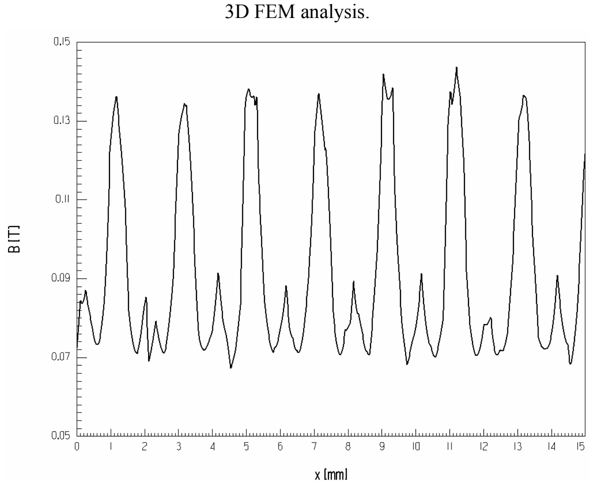


Fig. 14. The air-gap flux density variation vs. length for aligned teeth with unsupplied coil.

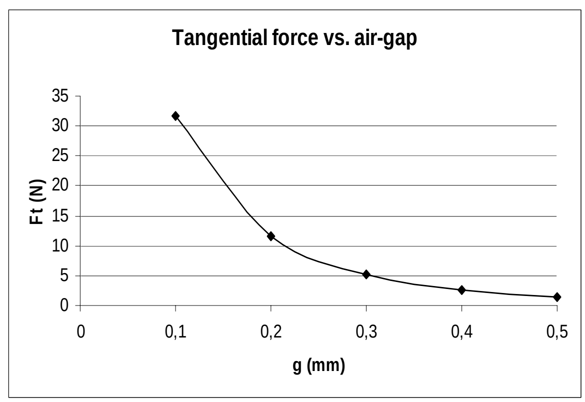
Next the variation of the tangential and normal forces for different air-gaps was analyzed. The forces for five air-gaps were computed. In the situations presented so far the value of the air-gap is 0.3 mm. Four more cases were considered, from 0.1 to 0.5 mm. All the other geometrical and electrical values of the motor presented in Fig. 5 were maintained constant. The flux density vector has the same direction and orientation like the one presented in Fig. 9. The only difference is represented by its values. In the situation of a 0.3 mm air-gap a uniform distribution of the flux density in the poles of the mobile armature could be noticed.

In Table 1 the tangential and normal forces obtained for the cases mentioned above – air-gap of 0.1 mm to 0.5 mm – are given. All the forces are computed for the same geometrical and electrical values (current in coil of 400 A).

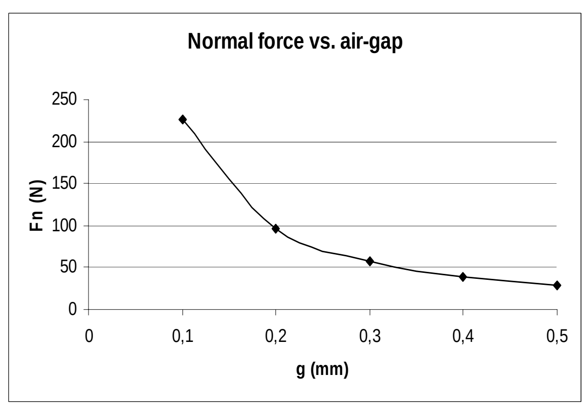
Table 1. Tangential and normal forces obtained for various air-gaps for a relatively shifting by a third pole pitch.

Air-gap / Forces	0.1 mm	0.2 mm	0.3 mm	0.4 mm	0.5 mm
Tangential	31.61 N	11.56 N	5.14 N	2.5 N	1.35 N
Normal	226.52 N	96.79 N	56.9 N	38.51 N	27.93 N

The variation of the two forces vs. air-gap is shown in Fig. 15, a) and b). As it can be seen in both cases the variation is of hyperbolic type, the forces decreasing greatly with the air-gap increase.



a) tangential force



b) normal force

Fig. 15. The variation of the forces with the air-gap.

Another interesting comparison taken into account by the authors was the computation of the tangential and normal forces for the structure presented in Fig. 5, by supplying the coil with different currents and maintaining all the other geometrical values constant. In the FEM analysis the displacement on a tooth pitch was considered, several positions of the moving armature relatively to the stator being studied. The obtained values are brought in Table 2 for the tangential forces, and respectively Table 3 for normal forces.

Table 2. Tangential forces computed in different positions of the mobile armature at different currents in the coil.

MMF / Shifting	200 A	300 A	400 A	500 A
0 mm	0 N	0,01 N	0,02 N	0,04 N
0,2 mm	1,1 N	2,37 N	4,17 N	6,52 N
0,4 mm	1,56 N	3,4 N	5,88 N	8,98 N
0,5 mm	1,63 N	3,48 N	6,07 N	9,38 N
0,6 mm	1,46 N	3,22 N	5,6 N	8,62 N
0,66 mm	1,33 N	2,86 N	5,14 N	7,6 N
0,8 mm	0,81N	1,74 N	3,39 N	5,18 N
1 mm	0 N	0,01 N	0 N	0,01 N

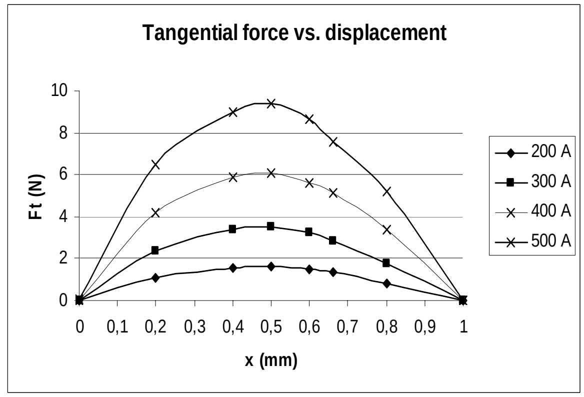
Table 3. Normal forces computed in different positions of the mobile armature at different currents in the coil.

MMF / Shifting	200 A	300 A	400 A	500 A
0 mm	21,49 N	46,25 N	80,23 N	122,95 N
0,2 mm	20,49 N	44,01 N	75,63 N	117,6 N
0,4 mm	18,77 N	39,55 N	67,49 N	102,6 N
0,5 mm	16,81 N	36,32 N	63,44 N	97,97 N
0,6 mm	16,59 N	33,43 N	58 N	89,19 N
0,66 mm	15,12 N	32,64 N	56,9 N	86,46 N
0,8 mm	14,52 N	30,51 N	52,06 N	80,08 N
1 mm	13,63 N	28,95 N	48,96 N	75,23 N

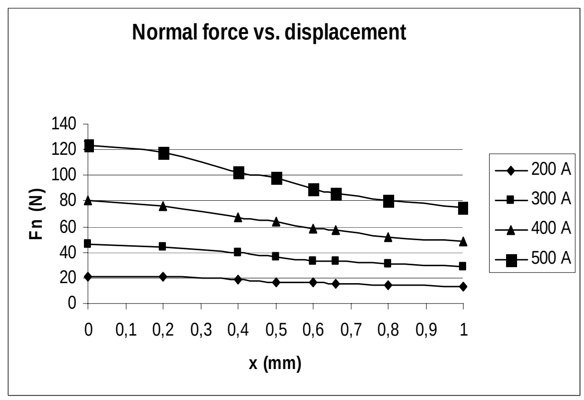
In these tables the positions for which the forces were computed are considered relatively to the aligned position of the mobile armature with the stator ones. The first one – 0 mm – corresponds to the perfectly aligned teeth. The last position – 1 mm – means the opposite situation, unaligned teeth. The positions considered are from 0.2 to 0.2 mm on the length of the tooth pitch. Besides that the cases of a half tooth pitch shifting (where the tangential force has the maximum value) and a third of a pole pitch shifting (where the position of commutation is) was analyzed.

The variation of the two forces for different magneto motive forces was represented too and is given in Fig. 16, a) and b). In this case the plots differ significantly, unlike the previous case presented. The tangential force has a quite sinusoidal variation no matter the value of the current through the winding. Its peak is obtained, as was mentioned before, at half of the teeth pitch. On the other hand, the variation of the normal force is almost linear. The characteristic is more inclined as the coil is supplied with a greater current.

When analyzing the results obtained via 3D FEM analysis we have to take into account the error which can not be avoided in such cases. For this motor a good quality mesh was considered and the error of the results was set at 1%.



a) tangential force



b) normal force

Fig. 16. The variation of the forces function of the module shifting for different currents through the coil.

IV. CONCLUSIONS

In the paper a new structure of a linear reluctance transverse flux machine is presented. The static characteristics of the motor for different air-gaps and different currents in the coil's conductors were obtained. The machine having modular construction is easy to be manufactured and have relatively low production costs comparing to most of the TFM variants proposed until now, since the price of the permanent magnets have a decreasing tendency.

An important aspect concerning the construction of this machine is that for the iron poles, besides SMC, the classical steel sheets can be used.

As its coil's end-windings are placed in the direction of the movement they are very compact and thin, hence they can be used also in very narrow places [12].

Its modular structure enables to easy adjust the motor's performances to the user's requirements without substantial changes in its basic structure. They are simple to control by unipolar current pulses.

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REFERENCES

[1] H. Weh, *Transverse flux (TF) machines in drive and generator applications*, Stockholm Power Tech, June, 1995.

[2] B.E. Hasubek, *Analysis and design of passive rotor transverse flux machines with permanent magnets on the stator*, Ph.D. Thesis, University of Calgary, Canada, 2000.

[3] M. Crivii, I.A. Viorel, M. Jufer, I. Husain, *3D to 2D equivalence for a transverse flux reluctance motor*, Proc. of ICEM'02, Brugge, Belgium, on CD-ROM.

[4] R. Blissenbach, G. Henneberger, *New design of a transverse flux machine for a wheel hub motor in a tram*, Proc. of PCIM'99, vol. Intelligent Motion, pp.189-194.

[5] D.C. Popa, V. Iancu, I.A. Viorel, *On the Transverse Flux Linear Motor Design*, Proceedings of the 5th International Conference on Electromechanical and Power System (SIELMEN '2005), Chisinau (Rep. of Moldova), 2005, vol. 2, pp. 800-803.

[6] D.C. Popa, V. Iancu, I.A. Viorel, L. Szabó, *C.A.D. of Linear Transverse Flux Motors*, Annals of the Polytechnic Institute of Iasi, vol. LI (LV), fasc. 5, Electrotechnics, Energetics and Electronics, 2005, pp. 79-84.

[7] I.A. Viorel, L. Szabó, *Hybrid Linear Stepper Motors*, Mediamira, Cluj-Napoca (Romania), 1998.

[8] I.A. Viorel, G. Henneberger, R. Blissenbach, L. Löwenstein, *Transverse flux machines. Their behaviour, design, control and applications,* Mediamira, Cluj-Napoca (Romania), 2003.

[9] G. Henneberger, I.A. Viorel, *Variable reluctance electrical machines*, Shaker Verlag, Aachen, Germany, 2001.

[10] L. Szabó, D.C. Popa, V. Iancu, Kovács E., Tóth F., *3D FEM Models of Linear Electrical Machines Used in Fault Detection Studies*, Proceedings of the International Scientific Conference MicroCAD '2006, Miskolc (Hungary), Section J (Electrotechnics and Electronics), Miskolc, pp. 89 – 95.

[11] L. Szabó, D.C. Popa, V. Iancu, Kovács E., Tóth F., *On the Usefulness of Simulation in Designing a Permanent Magnet Modular Surface Motor for Advanced Mechatronic Systems*, Proceedings of the 2006 IEEE International Conference on Mechatronics (ICM '2006), Budapesta (Hungary), pp. 88 - 93.

[12] L. Szabó, D.C. Popa, V. Iancu, *Compact Double Sided Modular Linear Motor for Narrow Industrial Applications*, Proceedings of the 12th International Power Electronics and Motion Control Conference (EPE-PEMC '2004), Portoroz (Slovenia), in print.

[13] L. Szabó, I.A. Viorel, V. Iancu, D.C. Popa, *Soft Magnetic Composites Used in Transverse Flux Machines,* Oradea University Annals (Romania), Electrotechnical Fascicle, 2004, pp. 134-141.