# IMPROVED DESIGN OF A LINEAR TRANSVERSE FLUX RELUCTANCE MOTOR

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***Abstract*—The paper deals with a new type of the reluctant linear transverse flux machine. Different possibilities to improve the basic structure's performance are outlined. The improved machine structure is compared with that of the initial one by means of FEM-based numerical magnetic field analysis. The flux densities in the two types of machines and their static characteristics (tangential and normal forces vs. displacement) are compared. The laboratory model of the improved machine is also given in the paper.**

## I. INTRODUCTION

At the beginning of the last decade of the 20th century a new type of machine has appeared in the category of the special electrical machines [1]. The transverse flux machine (TFM) offered several features which made it interesting for various applications. The researches made until now have focused mainly on its rotary variants [2, 3].

A linear variant of the variable reluctance transverse flux machine is taken into study in this paper. The factors that influence the behavior of the machine are also presented. Conclusions on the operating conditions of the machine are drawn.

## II. LINEAR TRANSVERSE FLUX MACHINES

As stated before, the machine in study is a variable reluctance one. It has a simple modular construction. The number of the modules is function of the desired positioning step [4]. In order to obtain continuous movement in both directions, the number of the modules must be at least three [5].

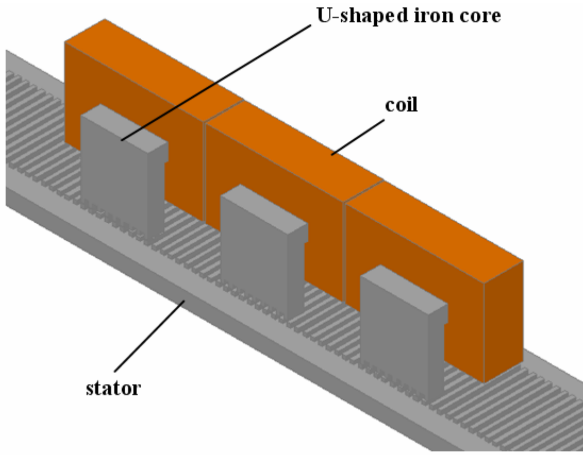


Fig. 1. The linear transverse flux reluctance machine.

In Fig. 1 the simplest variant with three modules is presented. This structure has been chosen because of the possibility to implement the control strategy of the machine from a customarily three-phased power converter existing on the market. The main advantage of this machine is the lack of permanent magnets [6].

The construction of the modules is very simple. It consists of a U-shaped pole, on which a coil is placed. The winding used is a concentrated coil, similar to one of the transformer.

As the machine's construction is concerned, one of its most important advantages is that its iron core can be build of classical steel sheets, contrary the most variants of the TFMs having expensive Soft Magnetic Composite (SMC) cores, one of the most important shortcomings of this type of machine [7].

The modules have to be shifted from the neighbored ones by $k\tau + \tau/N, \quad k \in \aleph$, where $\tau$ is the tooth pitch and $N$ is the number of the modules. The step length of the machine is $\tau/N$ [8].

The working principle of the machine is quite simple, similar to that of the linear switched reluctance machine. When supplying the coil of a module with the unaligned teeth with the stator ones its teeth will tend to align with the stator teeth. Hence, the mover will be displaced one step length into the desired direction. At a moment, only a single module of the mover is active (e.g. its command coil is energized) [9].

The most important issue concerning this machine is, of course, the developed tangential force. This is influenced by: the length of the air-gap, the magneto-motive force (MMF) of the coil, and the active cross section of the poles [10].

Next the solutions found to increase the performances of the motor will be given.

The air-gap length is an important parameter influencing the developed forces. It is ideal to be as small as possible in order to generate great forces, but its dimension is limited by the manufacturing possibilities and by the precision of the linear bearings guiding the mover.

The MMF of the coil is given by the current through a number of turns. When designing the command coil it must be considered that it is supplied only periodically, a third part of the total time. Hence greater current densities can be imposed as usually.

As proved in previous studies performed via FEM analysis [3, 4, 5], the teeth of the modules of the structure shown in Fig. 1 are saturated. The increase of the iron core active surface (at the same MMF) will result in greater forces. However, by increasing it, the space available for the command coil will be diminished. That is why the simple increase of the active surface is not a good solution.

The authors propose a better solution. The structure of the improved linear machine is given in Fig. 2.

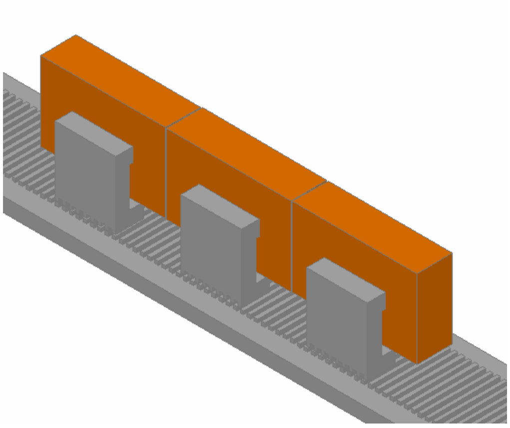


Fig. 2. Improved design of the linear transverse flux reluctance machine.

Fig. 3 shows such a linear transverse flux reluctance machine built in the laboratories of the Technical University of Cluj-Napoca.

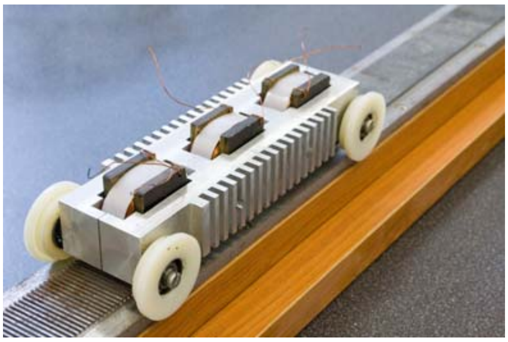


Fig. 3. Laboratory model of the proposed linear transverse flux reluctance machine

One module's iron core is shown in Fig. 4.

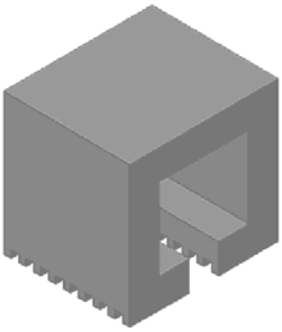


Fig. 4. The iron core of a module.

A detail of the toothed part of the built up machine is presented in Fig. 5.

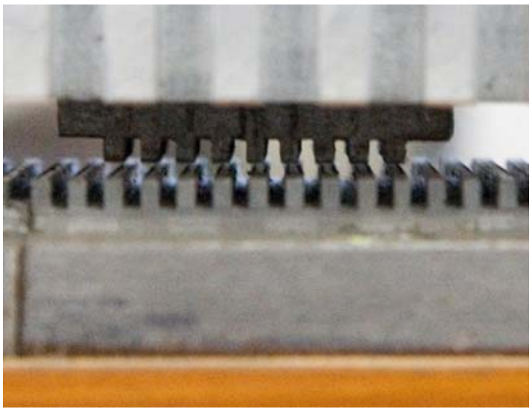


Fig. 5. Teeth of a module of the built machine

A design algorithm was worked out for such machines. Using it several machines had been designed, both with small teeth surface and with enlarged one. The designed variants were analyzed by means of 3D FEM computations.

## III. 3D FEM ANALYSIS

Two representative structures of the linear machines designed were analyzed in details by means of 3D FEM computations.

The main dimensions of the two sample machines are given in Fig. 6 and 7.

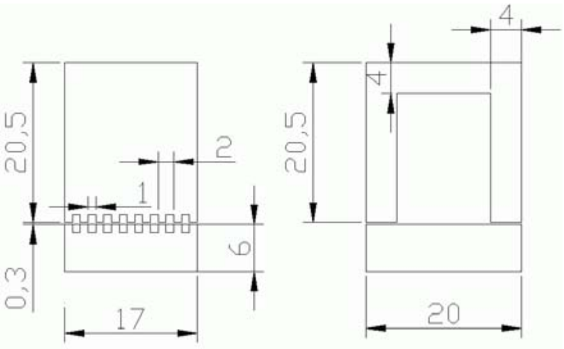


Fig. 6. Main sizes of a module with small teeth surface: a) lateral view; b) frontal view.

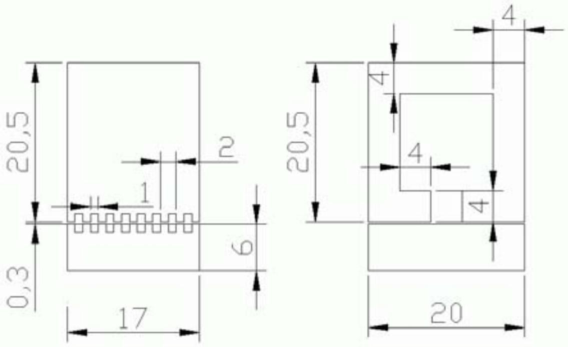


Fig. 7. Main sizes of module with enlarged teeth surface: a) lateral view; b) frontal view.

It should be noticed that in order to a correct comparison of the two variants all the dimensions excepting the pole surfaces are identical.

Considering the complicated three dimensional structure of the transverse flux machine it is obvious that only a 3D FEM analysis should give correct results.

By the field analysis two major issues were followed: to obtain the distribution of the flux density in the machine and to compute the developed forces. Since only the coil of a single module is supplied during a step displacement, it was enough to analyze only a single module and the portion of the stator under it, considering that the other two modules are not contributing to the force development [11].

Two dedicated relative positions of the mover have to be mentioned: when the relative displacement between the two armatures is 0.66 mm, and respectively 0.5 mm. The first situation corresponds to the position when a new step is initiated (where the module's coil begins to be supplied). In the second position the maximum tangential force is achieved.

Results of four cases analyzed will be given next: the initial variant and that having enlarged teeth surface, in both cases the filed computations were performed for two MMFs: 220, respectively 310 ampereturns. In Fig. 8 the flux density distributions obtained via the 3D FEM computations for the four cases mentioned above are given.

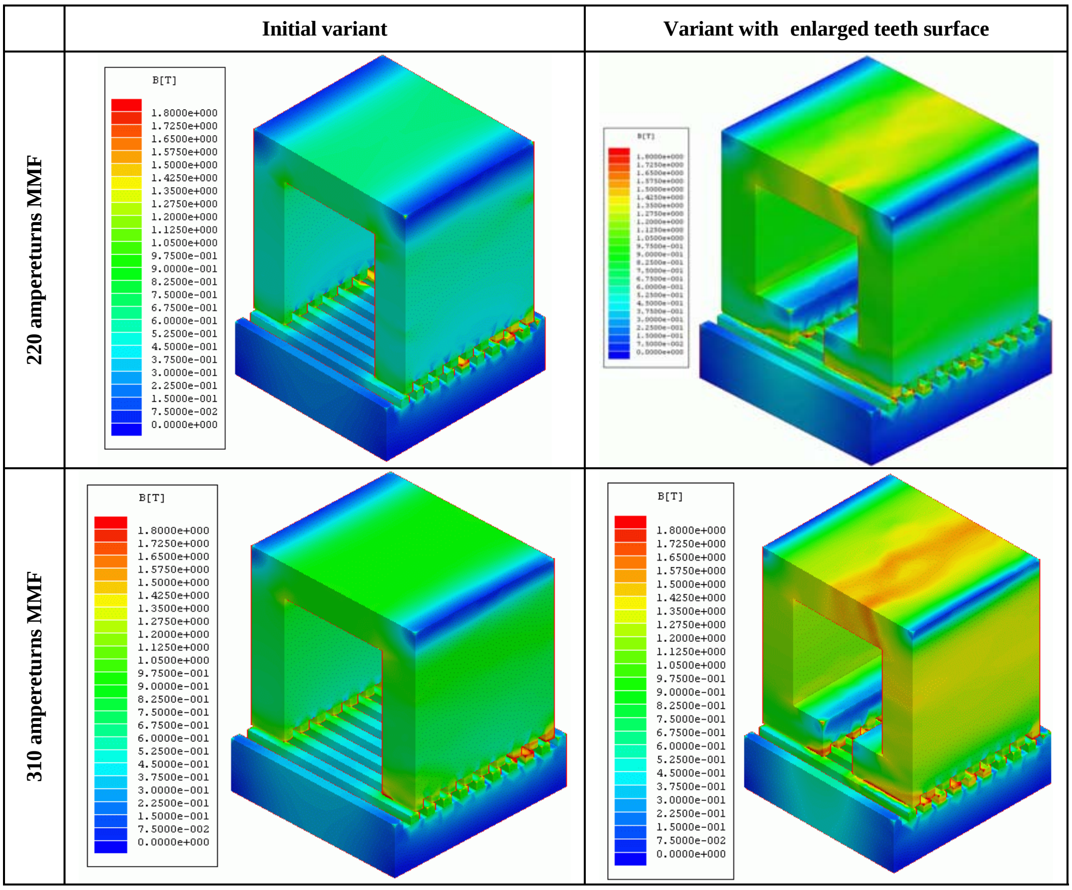


Fig. 8. Distribution of the flux density in a module

Another relevant issue to be studied in this case is the variation of the flux density in the air-gap.

The flux density was computed for several points placed on the line in the middle of the air-gap, having the length of the module. Fig. 9 and 10 shows the variation of the flux density vs. length in the air-gap for the four cases mentioned above.

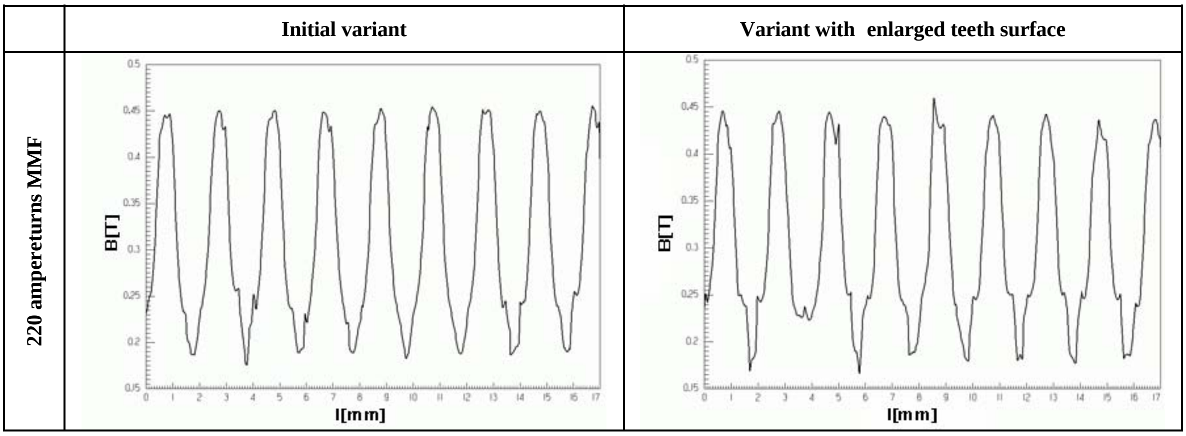


Fig. 9. Variation of the flux-density in the air-gap on the length of a module

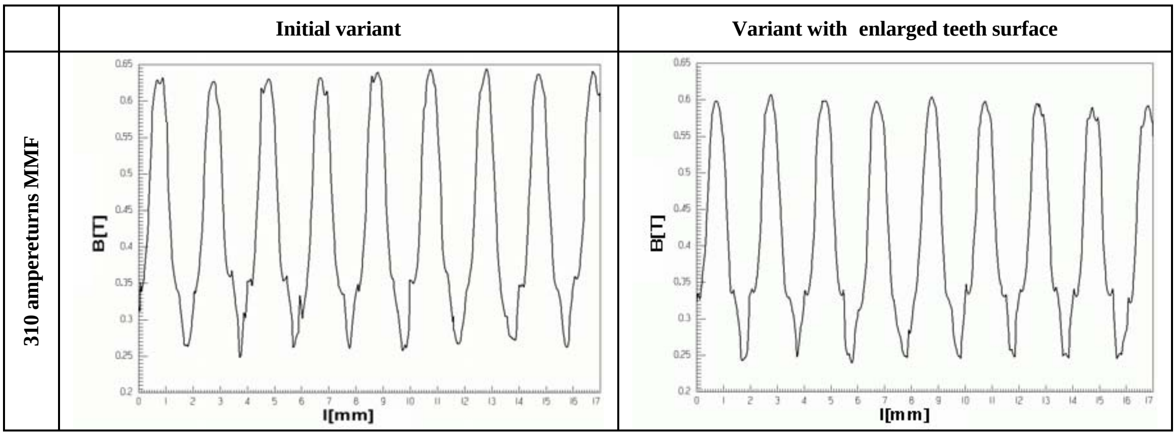


Fig. 10. Variation of the flux-density in the air-gap on the length of a module

In order to have a make a complete vision over the developed forces by the two machine variants, their static characteristics (forces versus displacement) were computed as well by 3D FEM analysis.

A transient regime simulation was imposed. The mover was displaced automatically from its initial position (0 mm, the teeth of the two armatures aligned) until the completely unaligned position (the displacement of 1 mm). The forces were computed for the intermediate positions from 0.1 to 0.1 mm on the length of the half teeth pitch.

The static characteristics were computed for the case when the MMF of the coil is 220 ampereturns. This value was chosen in order to avoid the teeth saturation.

The obtained tangential and normal force values are given in Table I. The two static characteristics obtained this way are given in Fig. 11.

TABLE I.
The forced computed at different relative displacements of the mover

| Shifting [mm] | Tangential force [N] | | Normal force [N] | |
|---|---|---|---|---|
| | Initial variant | Improved variant | Initial variant | Improved variant |
| 0 | 0 | 0 | 32.8 | 69.65 |
| 0.1 | 0.95 | 2 | 32.2 | 68.45 |
| 0.2 | 1.75 | 3.7 | 31 | 65.5 |
| 0.3 | 2.25 | 4.75 | 29.35 | 61.8 |
| 0.4 | 2.45 | 5.1 | 27.5 | 57.55 |
| 0.5 | 2.5 | 5.25 | 25.7 | 53.65 |
| 0.6 | 2.35 | 4.9 | 23.95 | 50.25 |
| 0.7 | 1.95 | 4.25 | 22.4 | 47.25 |
| 0.8 | 1.5 | 3.2 | 21 | 43.85 |
| 0.9 | 0.8 | 1.7 | 20.05 | 42.5 |
| 1 | 0 | 0.05 | 19.8 | 42.1 |

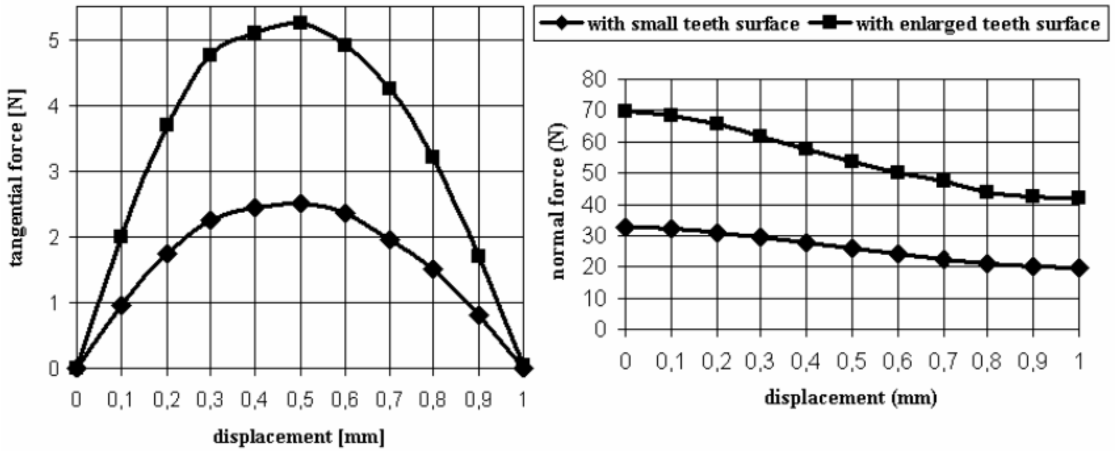


Fig. 11. The static characteristics for the two variants in study
a) tangential force; b) normal force.

In both cases, as it was expected, the tangential force has a near sinusoidal variation. Its peak is obtained, as was mentioned before, at the quarter of a teeth pitch (0.5 mm in this case).

Next the variation of the tangential and normal forces for different air-gap lengths was analyzed for the two linear machines in study.

The forces were computed for five air-gap lengths from 0.1 to 0.5 mm, including 0.3 mm the air-gap of the built up laboratory model of the machine given in Fig. 3. All the other geometrical and electrical parameters of the machine were kept constant during the computations.

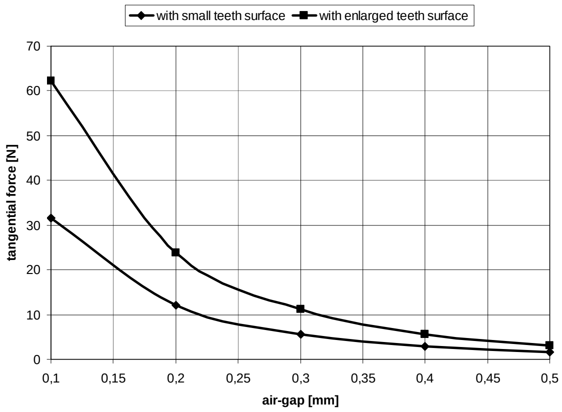
The tangential and normal forces obtained for the four cases mentioned above are given in Table II.

The computations performed via 3D FEM analysis were made in all the cases at the relative position of the mover of 0.5 mm and for a MMF equal to 310 ampereturns.

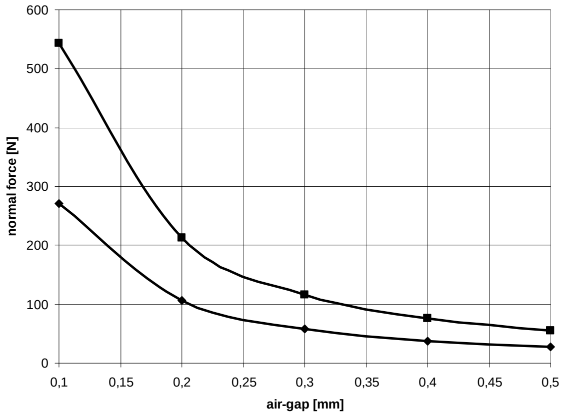
TABLE II.
The forced computed at different relative displacements of the mover

| **Air-gap [mm]** | **Tangential force [N]** | | **Normal force [N]** | |
|---|---|---|---|---|
| | **Initial variant** | **Improved variant** | **Initial variant** | **Improved variant** |
| 0.1 | 31,5 | 62,27 | 271,55 | 542,9 |
| 0.2 | 12,15 | 23,81 | 106,2 | 212,6 |
| 0.3 | 5,6 | 11,18 | 58,1 | 116,1 |
| 0.4 | 2,85 | 5,62 | 38 | 76 |
| 0.5 | 1,55 | 3,03 | 27,5 | 55 |

The variations of the two forces versus the air-gap are shown in Fig. 12. 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. 12. The variation of the forces versus the air-gap.

Another interesting study was concerning the effect of the control coil's MMF over the force development capability of the two machine variants in study. Also in this case all the sizes of the two machines were kept unchanged during the computations. The computations were performed at the relative position of the mover of 0.5 mm. The computed tangential and normal forces are included in Table III, respectively in Table IV.

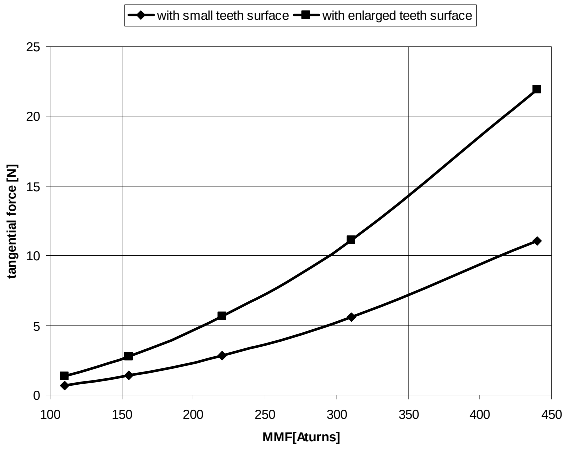
TABLE III.
Tangential forces [N] at different MMFs

| **MMF [Aturns]** | **Initial variant** | **Improved variant** |
|---|---|---|
| 110 | 0,7 | 1,38 |
| 155 | 1,4 | 2,75 |
| 220 | 2,5 | 5,25 |
| 310 | 5,6 | 11,1 |
| 440 | 11,05 | 21,9 |

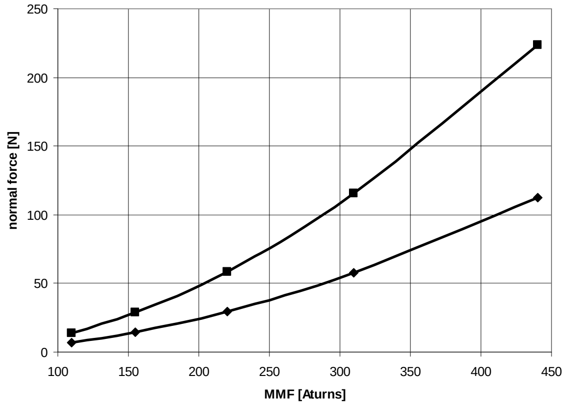
TABLE IV.
Normal forces [N] at different MMFs

| **MMF [Aturns]** | **Initial variant** | **Improved variant** |
|---|---|---|
| 110 | 7 | 13,95 |
| 155 | 14,6 | 29,12 |
| 220 | 29,3 | 58,45 |
| 310 | 58,1 | 115,78 |
| 440 | 112,5 | 223,82 |

Finally the variation of the tangential and normal forces versus the MMF computed at 0.5 mm relative displacement of the mover are given in Fig. 13a), respectively 13b).



a) tangential force



b) normal force

Fig. 13. The variation of the forces versus MMF

As it was expected, both forces are getting greater non-linearly with the increase of the MMF values.

## IV. CONCLUSIONS

In the paper a new structure of a linear reluctance transverse flux machine was presented. The machine having modular construction is easy to be manufactured. It has relatively low production costs comparing to most of the TFM variants due to the lack of permanent magnets and to the possibility to be constructed of classical steel sheets instead of expensive SMC.

By enlarging its teeth surface the performances of the linear machine were improved. The two major advantages of this enlarging are: in order to obtain the same force the MMF of the control coil can be reduced and the level of saturation in the teeth is also reduced. In the case analyzed here the MMF of the coil was possible to reduce from 310 to 220 ampereturns.

As it was shown in Table 1, the value of the forces given at the same MMF by the module with enlarged teeth surface is almost double comparing to the initial motor variant.

The enlargement of the teeth surface has also certain benefits from the economical point of view. A smaller coil means a lower quantity of copper. Besides that, the increase of the iron volume required to enlarge the teeth surface is compensated by the decrease of the height of the module due to the smaller dimension of the coil.

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, 13].

The laboratory model of the improved linear reluctance TFM in study built up in the laboratories of the Technical University of Cluj-Napoca was also presented. Its test bench is under construction. The experimental examination of the machine will be the next step in our study.

## ACKNOWLEDGMENT

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