ON THE DESIGN OF THE MODULAR LINEAR TRANSVERSE FLUX RELUCTANCE MOTORS

Dan-Cristian POPA, Vasile IANCU, Ioan-Adrian VIOREL, Loránd SZABÓ

Department of Electrical Machines, Technical University of Cluj-Napoca
RO-400750 Cluj-Napoca, Romania; e-mail: Dan.Cristian.Popa@mae.utcluj.ro

Abstract **– In the last decades different topologies of special electrical machines were studied. One of the most interesting machine belonging to this category is the transverse flux machine. The authors focused their attention on the linear variant of this type of machine. Up today a small number of studies have approached the linear transverse flux machine, so the new perspective given should be of real interest.**

Keywords: *transverse flux linear machine, design algorithm, 3D FEM analysis.*

1. INTRODUCTION

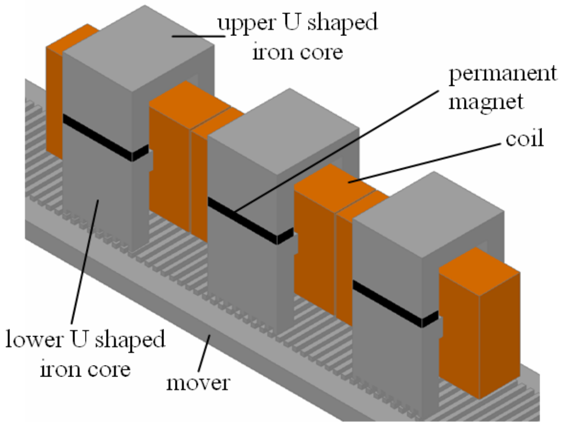
The variants of transverse flux machines presented so far belong either to the class of synchronous machines (permanent magnets transverse flux machine) or to the class of variable reluctance machines [1, 2].
The paper deals with a new type of transverse flux machine from the variable reluctance machines category. Two models, with and without permanent magnets, were analyzed. Both of them are stepper linear motors.

2. LINEAR TRANSVERSE FLUX RELUCTANCE MOTORS

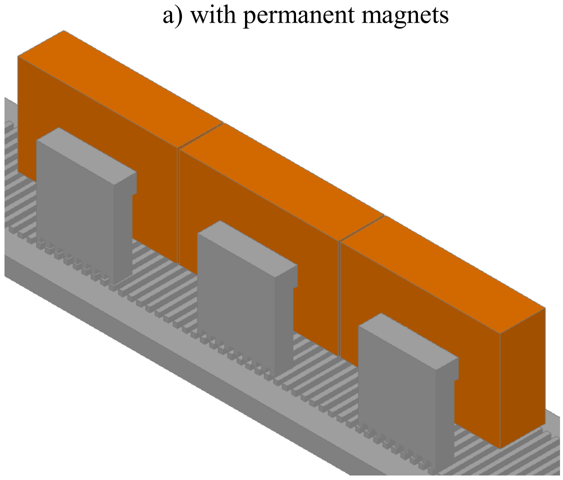
Until now several variants of linear stepper machines have been presented in the literature. However no transverse flux machine with such topology was presented.
We propose here two structures, with and without permanent magnets. The first variant was obtained from a rotary variant of TFM with passive rotor. The rotary machine has a compact structure and it is a variable reluctance machines. In order to control the motor an encoder on the shaft of the machine is necessary. For the linear variant we had to adopt a modular structure. To work properly the motor's 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 easiest variant to construct is the one with three modules because of the control possibilities. As in the case of the rotary machine an encoder placed on the mobile armature is necessary.

In figure 1,a) the structure of the machine with permanent magnets is shown [3].

The second variant (without permanent magnets) has the same operating principle as the one presented above, the major difference consisting of the absence of the permanent magnets and of the upper U-shaped iron core (figure 1,b) [4]. The only source of the magnetic field in this case is the coil produced m.m.f.

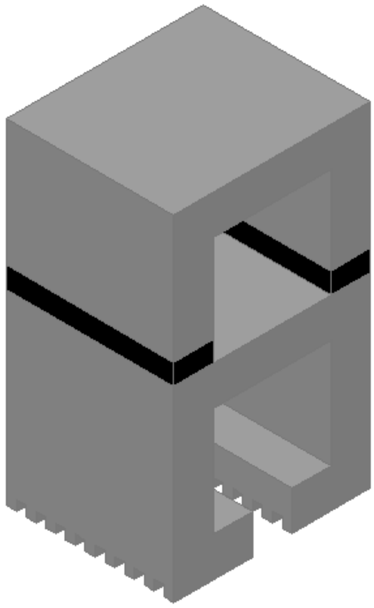


a) with permanent magnets

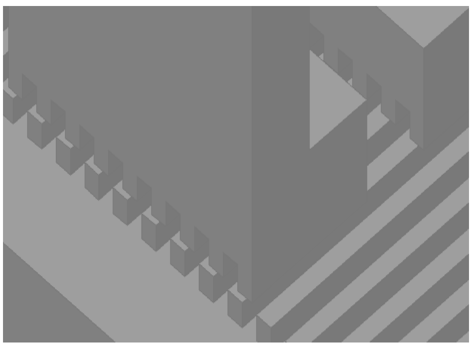


b) without permanent magnets
Fig.1. Two structures of linear transverse flux reluctance machine.

An improved variant can be obtained by enlarging the teeth surface. A module of the obtained motor is given in figure 2, a). The toothed part of the mover and of the platen is presented in figure 2, b).



a) iron core of the mover's module with enlarged teeth



b) toothed part – detail

Fig. 2.

3. DESIGN PRINCIPLES FOR THE LINEAR TRANSVERSE FLUX RELUCTANCE MACHINE

The design algorithms differ significantly for the two machines presented above, with and without permanent magnets. In the first case the starting point is considered to be the volume of the permanent magnets required in order to obtain a certain tangential force. In the second case, the dimensions of the iron core mover have to be computed in order to obtain the desired tangential force.

The starting design data in both cases are the same: the required maximum tangential force F_{tmax}, the width of the running track w_s, the accuracy of the positioning (step length x_i), and the number of modules N. During the design procedure other geometrical and electrical quantities have to be imposed [3].

The design procedure is based on the concept that the flux of the permanent magnet passes entirely through the air-gap and therefore the volume of the permanent magnet will be computed function of the desired tangential force and the flux density in the iron core and in one of the magnets. The active surface of the permanent magnet and its length are:

$$S_{pm_{\min}} = h_{pm} \cdot l_{pm} = k_p \frac{F_{t\max}}{B_p B_{mp}};$$

$$w_{pm} = k_x \cdot \frac{B_r \cdot B_{pm}}{H_c \cdot (B_r - B_{pm})} \qquad (1)$$

where h_{pm}, l_{pm} and w_{pm} are the height, length, respectively the width of the permanent magnet (PM), B_r is the residual flux density and H_c the coercive force of the selected PM. The dimensioning factors k_p, k_x are chosen based on similar design experiences [5].

One of its dimensions, the width, can be chosen function of the teeth number of the machine. This can be subject of an optimization study. Depending on the application requirements the machine can be either longer and less tall or shorter and taller. By knowing the value of the permanent magnet's width and its surface, the height can be easily determined. In this way the dimensions of the permanent magnet are completely determined. At the same time the iron core's section is obtained, as this is equal with the active surface of the permanent magnet.

The stator's length and height are imposed by the application. Its height is computed considering the flux in the circuit, the flux density in the stator and the surface crossed by the flux.

One of the most important problems of the designing procedure is related to the winding calculation. This is a simple coil, like the one used in the transformer, which, when supplied, must cancel the permanent magnet flux through the iron core branch and direct it through the lower parts of the mover poles and consequently through the air-gap. In order to do that, the equivalent magnetic circuit of the module must be built. In figure 3 the magnetic circuit for the module with permanent magnet is given.

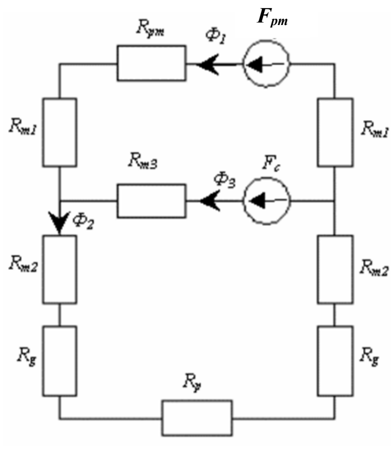


Fig.3. The equivalent magnetic circuit of the machine with PM.

The magnetic circuit for the module without permanent magnet is given in figure 4.

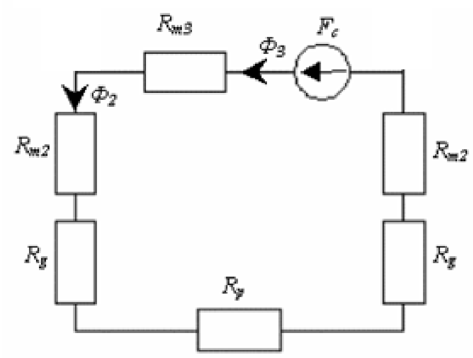


Fig.4. The equivalent magnetic circuit of the machine without PM.

For the machine without permanent magnets the sizes of the iron core are computed in a different way. As for the machine with permanent magnets, one can choose also in this case the value of the poles width. In order to determine the height of the poles, it can be considered that the difference of the energy in two positions represents the work done by the tangential force for a certain displacement. This is a valid hypothesis only for small variations of energy, as it is the case here. So we can consider this equation for two positions of the mover:

$$W_1 - W_2 = F_t \cdot x_i \qquad (1)$$

where W_1 is the air-gap energy corresponding to the aligned position and supplied winding; W_2 is the air-gap energy corresponding to the unaligned position and supplied coil. The air-gap energy can be expressed as:

$$W = \frac{{B_g}^2}{\mu_0} \cdot L \cdot w \cdot g \qquad (2)$$

where B_g is the mean value of the air-gap flux density; L, w are the length and the width of the iron core poles; g is the air-gap (L and g must be imposed).

In (1) we have considered the peak force value. This can be true considering such a control of the machine that gives a constant tangential force on the displacement. After determining the poles surface the flux through the module when the coil is supplied can be computed by imposing the flux density in the iron core. Considering the first Kirchhoff equation for the magnetic circuits we can determine the m.m.f. of the coil in order to obtain the imposed tangential force. So

$$F = \Phi \cdot R_m = B_g \cdot S \cdot \frac{g}{\mu_0 \cdot S} = B_g \cdot \frac{g}{\mu_0} \qquad (3)$$

An important remark regards the values of the flux density and tangential force. The flux density is chosen based on previous design experiences on stepper linear machines developing similar tangential forces. The variation of the tangential force with the displacement has a near sinusoidal form [6].

As it can be noticed the m.m.f. is independent of the iron core size. Only the tangential and normal forces vary with the poles dimensions and with the m.m.f.

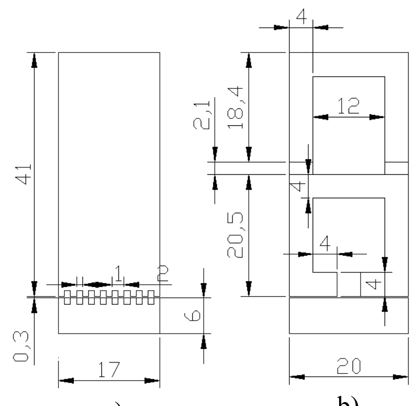
By enlarging the teeth surface, as shown in figure 2, the magnetic reluctance is reduced. So, at the same m.m.f., we shall have a greater flux and consequently, a greater force.

4. 3D FEM ANALYSIS

In order to prove the validity of the theoretical approach presented so far a laboratory model of the machine was designed. Both variants presented here, with and without permanent magnets, were designed and analyzed by means of numeric field computations.

The comparison made by 3D FEM (finite element method) focuses on two aspects: the difference which exists on the one hand between the machine with and without permanent magnets, and on the other hand between a variant with small teeth and the one with enlarged teeth.

For general presentation the motor considered here is the one with permanent magnets and enlarged teeth surface. It is a small dimension motor, designed to develop a tangential force of 1 N. The width of the running track is 20 mm and the tooth and the slot width are the same – 1 mm. The number of modules is 3, hence its step is 0.66 mm. In figure 5 the above mentioned variant with enlarged teeth surface is presented.

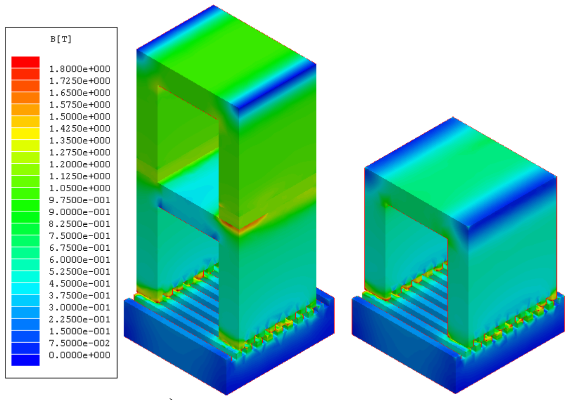


a) b)

Fig. 5. Main sizes of linear TFM module with enlarged teeth surface: a) lateral view; b) front view.

As stated before, the difference between this machine and the one with small teeth surface is that the inferior poles are U-shaped. For the variant without permanent magnets the upper poles and the permanent magnets are missing. The maximum value of the developed tangential forces corresponds to a shifting between the module’s teeth and the stator ones of 0.5 mm.

In figure 6 the flux density distribution in the machine with and without permanent magnets with small teeth surface is presented.

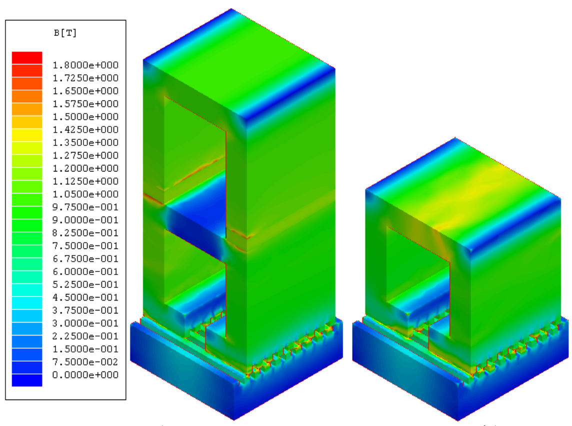


a) b)

Fig.6. The flux density distribution in an active module with small teeth surface: a) with permanent magnets; b) without permanent magnets.

As one can notice, the value of the flux density in the poles of the two structures is fairly equal. Hence, the developed forces are very similar: 0.58 N, respectively 0.57 N for the tangential forces and 6 N, respectively 5.9 N for the normal forces.

In figure 7 the flux density distribution in the machine with and without permanent magnets with enlarged teeth surface is presented.



a) b)

Fig.7. The flux density distribution in an active module with enlarged teeth surface: a) with permanent magnets; b) without permanent magnets.

In this case the developed forces have considerably greater values. For this particular situation the teeth surface was doubled. Consequently, the forces computed by 3D FEM are: 1.09 N, respectively 1.04 N for the tangential forces and 11.11 N, respectively 10.73 N for the normal forces.

5. CONCLUSIONS

We presented here two variants of linear transverse flux reluctance machines, with and without permanent magnets. Both of them are stepper motors, of modular type. The operating principles were exposed and the design principles to be applied for dimensioning such types of machines were shown. FEM analysis was performed on the designed structures and a short comparison on their capabilities was made. These motors represent possible solutions for different conveyors and the ideas presented in this paper can be the point to make an extended comparison between these two variants.

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