Tubular Transverse Flux Variable Reluctance Motor in Modular Construction

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Abstract- A new topology of modular tubular motor is presented. It is a variable reluctance transverse flux machine with no permanent magnets. Firstly its construction is detailed. Some elements of the developed design algorithm are given, too. A sample machine was sized. It was analyzed by means of numeric field computations. The paper also contains a study concerning the influence of several parameters on the behavior of the machine. Finally, some possible applications are discussed.

I. INTRODUCTION

The most researches on the transverse flux machine, introduced at the beginning of the 80’s in the last century, were focused on the rotary variants [1]. The achievements in the field of the linear transverse flux machines were considerably less significant. In this paper a new type of modular variable reluctance tubular machine is proposed. In general terms, from the idea standing on the basics of this machine both rotating and tubular machines can be obtained.

The machine in study is originated from the linear transverse flux reluctance machine in modular construction. A group of researchers from the Technical University of Cluj-Napoca have proposed such a structure with hybrid excitation, Fig. 1.a [2]. It resulted as a combination between the already usual rotary variant of a transverse flux machine with passive rotor, and permanent magnets, and a modular hybrid linear motor.

A simpler variant from the constructive point of view, with similar performances as the structure described above, was obtained by removing the permanent magnets from the modules of the mobile armature, Fig. 1.b [3]. In order to increase the developed tangential force, the surface of the teeth was enlarged so that the module had the same section in all its parts.

In this case, the stator of the machine is the passive armature, and the mover, which carries the coils, is the inductor. It must have minimum three modules.

In general terms the main shortcoming of a linear machine is the existence of a big normal force, of about ten times greater than the tangential one. This shortcoming of any planar structure is removed at the tubular machines. In this case, such a machine is obtained by unfolding the structure given in Fig. 1b, on the direction of movement [4].

Many of the characteristics of the linear machine are found at the tubular variant. The most important aspect is the modular construction, affecting the operating principle which is basically the same as for the linear motor presented above. However, given the fact that the obtained machine is a cylindrical one, its component parts have some particularities that determine a different approach of the design algorithm than in the case of the linear machines. As we shall explain next, some parts of the iron core and the windings are similar with the ones of other types of machines [5], this being a significant advantage when constructing such a structure.

Fig. 1. Linear transverse flux reluctance machine: a) with permanent magnets; b) without permanent magnets and enlarged teeth surface; c) detail of the toothed part.
II. THE STRUCTURE OF THE TUBULAR MACHINE

The proposed tubular structure is given in Fig. 2, while the main component parts of the stator and mover are presented in Fig. 3 and Fig. 4. A cross section through the machine, evincing the stator and mover poles, is presented in Fig. 2.

The notations of the axial geometrical dimensions, presented in Fig. 1 are: $t_s$ – stator pole axial length (stator tooth), $s_s$ – stator slot axial length (stator spacer), $\tau$ – stator pole pitch, $t_m$ – mover pole axial length (mover tooth), $s_m$ - mover slot axial length (mover spacer).

The proposed tubular structure has short endwindings, low leakages and also short flux lines topology. In order to assure a continuous movement, the machine has a minimum number of three phases, each one being composed of a number of $m$ modules (magnetic pieces), separated by spacers (nonmagnetic pieces), Fig. 2. The number of modules is limited only by the length of the stator, on which are placed the coils in a transverse flux topology. The mover is passive.

The iron core of both the stator and the mover can be built up of steel sheets or SMC. For the construction of the stator the same type of steel sheets like in the case of a classical SRM can be used, as shown in Fig. 3.a. The non-magnetic pieces are of cylindrical shape, Fig. 3.b. The mover is obtained by alternating simple magnetic cylindrical shaped pieces with non-magnetic ones, Fig. 4.c and Fig.4.d.

The mover is built as long as necessary to assure on the entire stroke length and has an adequate poles configuration. Fig. 5 shows such a linear transverse flux reluctance machine built up.

Like in the case of the linear transverse flux reluctance machine, in order to work properly the modules have to be shifted one from each other by $k \tau + s_m + \tau / N$, $k \in \mathbb{N}$ [6].

But, unlike the linear machine where the modules were placed at the construction in an aluminum case, in such a way that this shifting between the modules was provided [7], at the tubular motor the shifting is created by using non-magnetic spacers between the stator’s modules.

III. COMPUTATION OF THE TUBULAR TRANSVERSE FLUX RELUCTANCE MOTOR MAIN DIMENSIONS

The modern approach of the design procedure of any type of electric machine consists of four compulsory stages. These represent a combination between classic approach and new techniques of optimizing design. Hence, the first stage corresponds to the sizing designing one, when, based on simplified mathematical models and on existing experience, the main dimensions and performance are obtained. The second stage focuses on checking the previous calculations, usually by employing a specific numerical method, mostly FEM, and obtaining a quasi optimal structure. The third stage is dedicated to the heating and cooling calculation via FEM or any other method which is accurate enough, as the one based on thermal equivalent circuit. In the final stage, the entire drive system (supply source-motor-load) is simulated on computer in order to check if the dynamic and steady-state required performances are obtained [8].
This paper deals with the first two stages presented above. Using the design algorithm a motor developing a certain force will be obtained and analyzed by means of numeric computations.

Before starting the designing process of any modular structure, one has to establish the phase number. The minimum number of phases for this machine, as for a symmetrical conventional SRM, is three. There are some structures with one or two phases [5], but these are particular ones implying special construction.

There is no upper limit for the number of phases. Basically, by taking a number of phases larger than three the force ripple can be reduced and, by supplying adequately more than one phase at the same time, the traction force can be increased. In fact, since the exterior diameter is limited in most cases, the designer must consider a tubular transverse flux machine with the maximum number of modules, but with minimum number of phases. It means that the length of a phase will be the shortest possible and the converter the cheapest one. With a three phase converter there will be no need for a sophisticated control to overlap the phases’ conduction period.

The traction force is the main specification for any type of linear motor. Consequently, the designed motor must produce a minimum traction force equal to the one required by the drive system. The main parameter considered at the beginning of the design procedure at a linear motor is the traction force. Consequently, any designed structure can be optimized in order to obtain not only the imposed specifications, but also the best force to mass ratio possible.

One of the most important characteristics of a tubular machine is the compensation of all the attraction forces between the two armatures due to the cylindrical structure.

The traction force of any linear motor can be calculated analytically or by finite element analysis. The analytical computation takes into consideration that the developed force is function of the air-gap length to mover pole pitch, the ratio between the common axial length of the stator and mover pole and the polar pitch, the flux density in the air-gap.

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Based on these general relationships, a connection between the force and the magnetic and geometric dimension of the machine can be established as [10]:

\[ R = \frac{\mu_0 K_C K_S C_f f_I}{4 r B^2 g \cdot a \cdot m \cdot Z} \]

where \( K_C, K_S \) are the Carter's and saturation coefficient, \( r \) is the ratio between the common axial length of the stator and mover pole and the polar pitch, \( C_f \) is the air-gap equivalent reluctance coefficient, \( Z \) is the number of poles of a module. One must take into account that \( K_C \) and \( C_f \) coefficients are function of the air-gap length to mover pole pitch \( g / \tau \) and mover pole axial length to mover pole pitch, \( \tau / \tau \) ratios, and also that the value of \( r \) is at designer's choice. Hence, by imposing all the values mentioned above, one can obtain the mean value of the radius in the air-gap.

We can consider that the area of a slot is given by

\[ A_s = \frac{2g \cdot B_g}{\mu_0 J \cdot K_{fill}} \]

where \( J \) is the current density of the coil and \( K_{fill} \) the slot fill factor, which must also be imposed from the start.

By considering the air-gap, the inner stator radius \( R \) and the radius of the mover result easily. The stator pole height, \( h_p \), can be obtained using all the known geometric dimensions:

\[ h_p = \sqrt{2 \cdot A_s \cdot \sin \alpha + \left(\frac{2\pi}{Z} - \alpha\right) \frac{(1 + \cos \alpha)}{2}} \]

The outer stator radius is computed in a similar manner with the classic SRM. The section of the yoke must be equal with 0.8 of the pole section [11], so:

\[ R_e = R \cdot \left(1 + 0.8 \frac{\alpha}{2}\right) + h_p \cdot \cos \frac{\alpha}{2} \]

The presented algorithm was used to obtain a motor developing a maximum force of 200 N. The chosen values are: peak air-gap flux density in the aligned position \( B_g = 1.5 \) T, air-gap length \( g = 0.5 \) mm. For the proposed machine, \( Z = 6 \) poles were considered, and the number of magnetic pieces of a module \( m = 2 \). The angle of a pole was imposed to be \( \alpha = 50^\circ \). The tooth axial length, equal to the spacer's length, is 5 mm, and the total length of the stator is of 61.66 mm. The rated current \( I \) was considered to be 10 A, and the voltage \( U \) is of 12 V.
The inner stator radius is \( R = 48 \text{ mm} \), while the height of the pole was computed \( h_p = 40 \text{ mm} \) and the outer stator radius results \( R_e = 125 \text{ mm} \). The shaft of the tubular structure was considered to have a radius of 10 mm. The total mass is 29.6 kg, and the peak force / mass ratio (considering the mass of the mover) is of 39.6 N/kg.

IV. THE FEM ANALYSIS

The results of the design algorithm and the analytic analysis of the above proposed machine were check also by means of finite elements method (FEM) based analysis. Cedrat’s Flux 3D program was used [12]. The need to use a 3D analysis is justified by the structure of the machine since the flux lines that close from the stator to mover are perpendicular on the direction of movement, as presented in Fig. 6.

Since only the coils of a single module are supplied any time, it is enough to analyze only a single module and the corresponding part of the mover [2, 3]. Due to the symmetry of the module, the analysis was carried out on a single pole of a module's magnetic piece. However, when computing the developed force we must consider this aspect, as the obtained force from the FEM analysis is given just by one pole of a single module. In order to have the total force, this must be multiplied by the number of poles of a module and the number of modules of a single phase.

The numeric analysis focused on two major aspects: the flux density distribution in the machine and the developed forces. After taking into consideration the designed structure, few geometric and electric parameters were modified in order to characterize the performances of such a machine.

We shall present first the flux density distribution in the designed motor in the aligned position, Fig. 7.

The flux density variation, obtained on a radial line starting from the center of the shaft to the exterior limit, is presented in Fig. 8.

In order to show the value of the flux density in the air-gap, an arc was drawn at its middle, and the values plotted as presented in Fig. 9.

The values of the relative magnetic permeability in the analyzed parts were also plotted, Fig. 10. The values of the relative magnetic permeability are very different in the stator pole, yoke, and mover. This explains clearly the errors that occur in the analytical analysis. This is one of the reasons the FEM analysis gives in such cases more accurate results than the analytical one.

As mentioned above, the most important aspect at any linear machine is the traction force. In this case the variation of the force was computed by taking into account a displacement of the mover related to the stator from the aligned position to the completely unaligned position, Fig. 11.
Here, the considered displacement is 5 mm. A step of 0.5 mm was set in order to obtain an accurate variation of the force. The variation of the force was obtained for 9 different situations, corresponding to three values of air-gap and three values of current. Giving the fact that this force is given only by a pole of a module and taken into account the total number of modules of a single phase, we can conclude that the designed machine develops a total force of about 190 N, very close to the imposed starting data.

Another parameter that influences greatly both the characteristic shape and the value itself of the developed forces is the module’s thickness (the axial length) [13]. The tooth and the spacer were considered equal in the original design, 5 mm each, as was the case in all the plots presented so far. In our case we have kept the polar pitch constant, of 10 mm, and hence changed both the tooth and the spacer. The obtained static characteristics when varying the module’s thickness are presented in Fig. 12.

Four different values were considered for the tooth, two of them lower than the initial one, 4 and 4.5 mm, and the other two greater, of 5.5 and 6 mm. As in the previous analysis, we have considered the same three values of the air-gap and the values of the current. One can notice that the biggest value of the maximum force is obtained for a tooth of 4 mm. The saturation of the iron core influences significantly the shape of the static characteristics [14].
V. CONCLUSIONS

A new type of tubular variable reluctance machine, of transverse flux type, is presented in the paper. The innovative construction, consisting of alternating magnetic and non-magnetic pieces, has the advantages of a lower weight and price than using the classical iron core, and very good performances.

The basic concept of the design algorithm is presented here. A motor was designed and its performances were checked by means of numeric analysis. The obtained results show good accordance with the design imposed data. Various analyses were presented in order to show the influence of different parameters on the developed forces. These have shown similarities with other variable reluctance motors.

Due to their force/mass ratio such tubular machines present good potentials for applications like precise industrial linear positioning systems, membrane pumps or for short track transfer system drives against other linear motors.

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