Design of a Novel Tubular Transverse Flux Reluctance Machine

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Abstract

In the paper a novel modular tubular motor is proposed. It works upon the variable reluctance principle and it has a transverse flux topology. Practically it is a tubular variant of the linear transverse flux reluctance machine with electromagnetic excitation. The structure of the two armatures' (the stator's and the mover's) iron core, respectively two winding variants are detailed in the paper. Also the design algorithm of the machine is presented. In order to validate the design both analytical and numeric field computation based analysis was performed. A short comparison between the linear and tubular machine variants, evincing the resemblances and the differences between the two structures, is also given in the paper. Few conclusions concerning the promises of this machine are finishing the paper.

1 Introduction

The most researches on the transverse flux machines, 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 variable reluctance tubular machine is proposed. In general terms, both rotating and tubular machines can be obtained on the basis of the proposed construction idea [2].

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 (Romania) proposed such machines both with hybrid excitation [3] and with electromagnetic one. The last variant was designed with enlarged teeth surface, as shown in Fig. 1 [4].

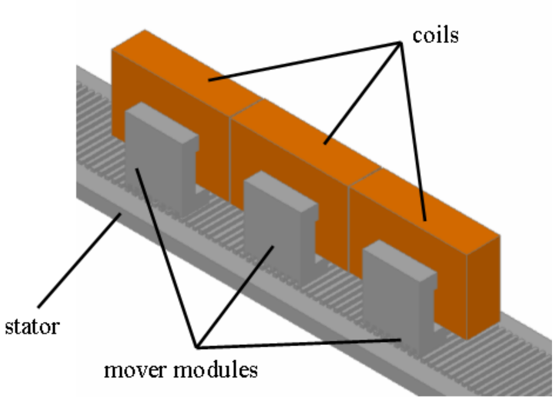


Figure 1. Linear transverse flux reluctance machine, without permanent magnets and enlarged teeth surface.

The main shortcoming of a flat linear machine is the existence of a huge normal force, of about ten times greater than the useful tangential one. By unfolding the linear machine given in Fig. 1 in the direction of movement, a tubular variant is obtained.

2 The Tubular Transverse Flux Reluctance Machine

The inductor, usually the stator, has a modular construction, as shown in Fig. 2.

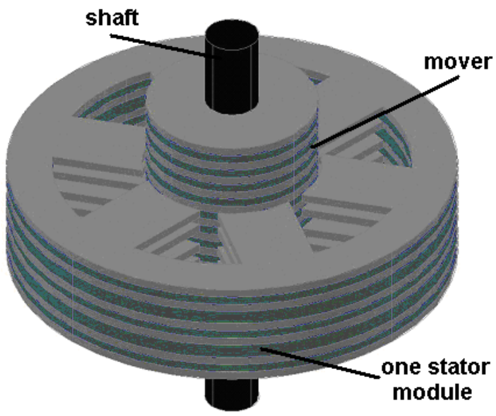


Figure 2. The structure of the proposed tubular machine.

The minimum number of modules N required in order to obtain a continuous movement is three [2, 3]. Each module has an independent winding. The iron core of a module is built of m magnetic pieces, Fig. 3a, alternating with $m-1$ non magnetic pieces, Fig. 3b, which form the teeth, respectively the slots of the machine.

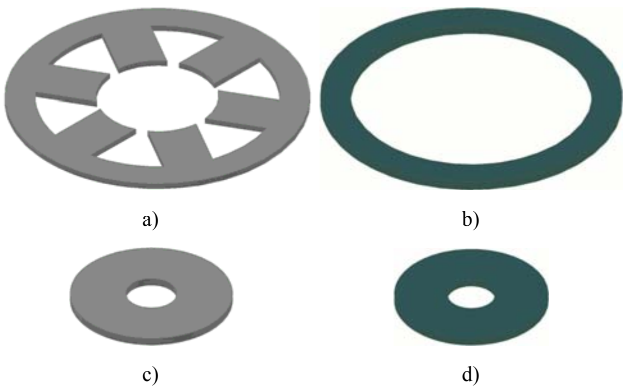


Figure 3. Parts of the stator and mover: a) stator's magnetic piece, b) stator's non-magnetic piece, c) mover's magnetic piece, d) mover's non-magnetic piece.

The length of the stator teeth t_s must be equal with that of the mover t_m, both being given by the axial length of a stator's magnetic piece. The spacers separating the magnetic pieces (the teeth) have the same length on both armatures $s_s = s_m$.

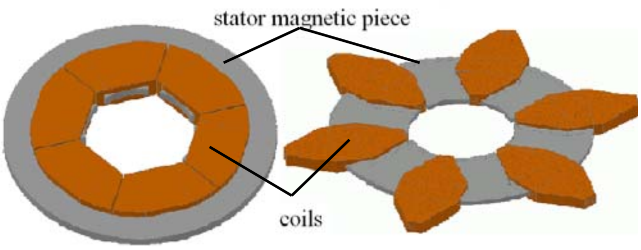
The sum of the length of a tooth and of a spacer is the module's tooth pitch τ. The step of the motor depends on the tooth pitch and the number of modules.

In order to work properly the modules, like in the case of the linear transverse flux reluctance machine, have to be shifted one from each other by $k\tau + s_m + \tau/N, \quad k \in \aleph$. But, unlike the linear machine where the modules were placed in an aluminum case in such a way as to assure the required shifting between the modules [5], in this case the shifting is assured by using non-magnetic spacers between the stator's modules, as shown in Fig. 2b.

The stator magnetic pieces are manufactured as those of the induction machine: by punching out of steel sheets. These pieces can be made also of soft magnetic composites.

The mover is passive. It is built, like the stator's core, of magnetic, Fig. 3c, and non-magnetic pieces, Fig. 3d. However, they are much simpler, being of cylindrical form. The length of the axial pole of the mover is the same with the stator's one.

The windings of the tubular machine are relatively different from other machines. Two types of windings can be applied: with concentrated coils around each pole of a magnetic piece, Fig. 4a, or around the yoke of each magnetic piece, Fig. 4b.



a) b)

Figure 4. Winding variants for the tubular transverse flux reluctance machine a) concentrated coils around poles b) coils wound on yoke.

In the first situation, the winding disposal is similar to a classic SRM [6]. The coils belonging to a single module can be connected or in series or in parallel, because all of them are supplied simultaneously. The number of coils can be reduced by using windings that are wound around all the poles of a module and not around each pole. The shortcoming in this case is that the leakage fluxes are greater. For the second case, Fig. 4b, the main advantage is the possibility that there is bigger space to place the coils as in the case of the first variant. But also the leakage fluxes are greater.

3 Design Algorithm of The Tubular Transverse Flux Reluctance Motor

One of the major shortcomings of all linear machines is that the attracting force between the two armatures is about ten times bigger than the pulling tangential one [2]. In the case of the tubular machine the attraction forces acting around all the circumference of the air-gap are totally balanced due to the machine's radial symmetry.

In the case of the machine in study at each time the pulling force is given by a single module, that with the energized coil. The main dimensions and the excitation magneto-motive force (mmf) strongly depend on the required pulling force [7]. The main objective of the analytical design is to obtain the dimensions of a module in order to develop the imposed traction force.

The traction force of any linear motor can be calculated analytically or by finite element analysis. In the paper, both of these methods shall be used to validate the design procedure to be presented next.

The analytical computation takes into consideration that the developed force at any linear variable reluctance machine is the variation of the magnetic energy in the air-gap versus the linear displacement [7, 8]. The expression of the magnetic energy, where the elemental volume is function of mover's position, is:

$$W_m = \frac{1}{2} \cdot \frac{B_g^2}{\mu_0} \cdot \int dv = \frac{1}{2} \cdot \frac{B_g^2}{\mu_0} \cdot R \cdot \alpha \cdot g \cdot (t_m - x) \qquad (1)$$

Like in the case of other types of variable reluctance machines, the force can be computed from the variation of the magnetic energy and it can be written as [7]:

$$f = \frac{\partial W_m}{\partial x} = -\frac{1}{2} \cdot \mu_0 \cdot F^2 \cdot \frac{R \cdot \alpha}{g} \qquad (2)$$

where A_p is the common armatures' area, g is the air-gap length, R is stator interior radius in the air-gap, α is the stator pole angular length, x is the axial coordinate B_g is the peak value of the air-gap flux density in aligned position, μ_0 is the air-gap magnetic permeability. The mmf F can be written just function of the air-gap and the flux density in the air-gap:

$$F = \frac{1}{\mu_0} \cdot g \cdot B_g \qquad (3)$$

Starting from these relationships, a connection between the force and the magnetic and geometric dimension of the machine can be established as [8]:

$$R = \frac{\mu_0}{4} \frac{K_C K_S}{r} \frac{C_r \cdot f_t}{B_g^2 \cdot g \cdot \alpha \cdot m \cdot Z} \qquad (4)$$

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_r is the air-gap equivalent reluctance coefficient, Z is the number of poles of a magnetic piece. One must take into account that K_C and C_r coefficients are function of the air-gap length to mover pole pitch g/τ and mover pole axial length to mover pole pitch, t_p/τ ratios, and also that the value of α 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.

Considering that the area of a slot is given by

$$A_s = \frac{2g \cdot B_g}{\mu_0 \cdot J \cdot K_{fill}} \qquad (5)$$

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 interior radius of the stator R_i and the radius of the mover result easily. The stator pole height h_p can be obtained, using all the known geometric dimension:

$$h_p = \frac{\sqrt{2 \cdot A_s \cdot \sin\alpha + \left(\frac{2\pi}{Z} - \alpha\right) \cdot \frac{(1+\cos\alpha)}{2} \cdot \left[R^2 \cdot \left(\frac{2\pi}{Z} - \alpha\right) + 2 \cdot A_s\right]} - \left(\frac{2\pi}{Z} - \alpha\right) \cdot R \cdot \cos\frac{\alpha}{2}}{\left(\frac{2\pi}{Z} - \alpha\right) \cdot \frac{(1+\cos\alpha)}{2}} \qquad (6)$$

The exterior radius of the stator is computed in a similar manner as of classic SRMs [6, 9]. The section of the yoke must be equal to 0.8 of the pole section, so:

$$R_e = \left(R + \frac{g}{2}\right) \cdot \left(1 + 0{,}8 \cdot \frac{\alpha}{2}\right) + h_p \cdot \cos\frac{\alpha}{2} \qquad (7)$$

The geometric dimensions led to an easy computation of the volume and then of the mass.

In order to prove the validity of the proposed algorithm, a machine developing a tangential force $f = 1000$ N was designed. The chosen values are: peak air-gap flux density in the aligned position $B_g = 1.45$ T, current density $J = 5\cdot 10^6$ A/m^2, air-gap length $g = 1.5$ mm, slot fill factor $K_{fill} = 0.4$, saturation coefficient $K_S = 1.4$, Carter's factor $K_C = 1.6$, air-gap equivalent reluctance coefficient $C_r = 0.75$, mover pole axial length per pole pitch $r = 1/3$. 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 $\alpha = 50^o$. 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 area of the stator slot is (6) $A_s = 0.19\cdot 10^{-2}$ m^2 and the required mmf per coil is (3) $F = 1900$ Aturns. The height of the pole was computed (7) $h_p = 50$ mm, the exterior radius being (8) $R_e = 125$ mm. In brackets are the numbers of the equations upon which the quantities were computed.

The shaft of the tubular structure was considered to have a diameter of 20 mm. The total mass is 31.68 kg, and the force / mass ratio is of 31.56 N/kg.

4 THE ANALYTICAL ANALYSIS

The validity of the proposed design algorithm was checked, at first, by analytical means. An equivalent magnetic circuit for the proposed motor structure was used, Fig. 5 [10]. The magnetic equivalent circuit is built up for two poles, the yoke and the slot between them, and the corresponding part of the mover. The mmf of a coil F can be computed (3). The known geometric dimensions of all the parts of the motor's magnetic circuit allow the computation of all the reluctances: of the yoke R_y, of the pole R_p, of the air-gap R_g and of the mover R_m. The leakage reluctances $R_{\sigma p}$ and $R_{\sigma s}$ are due to the air between two neighbored coils and to the air-gap. For this circuit, a constant value of the relative magnetic permeability was considered in each of the sections of the magnetic piece: yoke, pole and mover. By solving the equation system obtained via applying Kirchhoff's laws, the fluxes through each branch of the circuit can be computed.

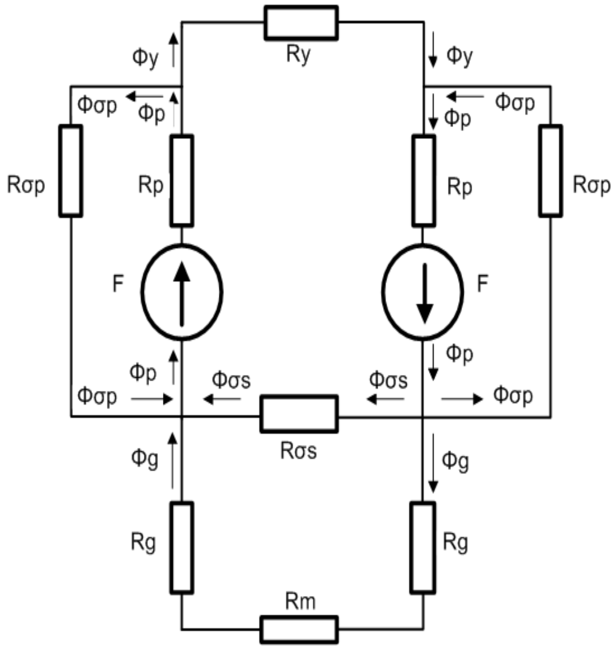


Figure 5. Magnetic equivalent circuit of the tubular machine

One can compute the percentage value of each flux from the greatest one in the circuit (in this case, the one in the poles) and the flux density value in the poles, yoke, mover and air-gap.

The analytic computation was done considering the aligned position of a stator's module with the mover. As it results from the magnetic circuit, the biggest value of the flux is in the poles. 83.89% of this reference flux is obtained the yoke, 72.7% in the air-gap. The two leakage fluxes are of 11.2%, respectively 16.1% of the reference flux. The mean value of the air-gap flux density is of 1.31 T, in good accordance with the chosen one in the design process.

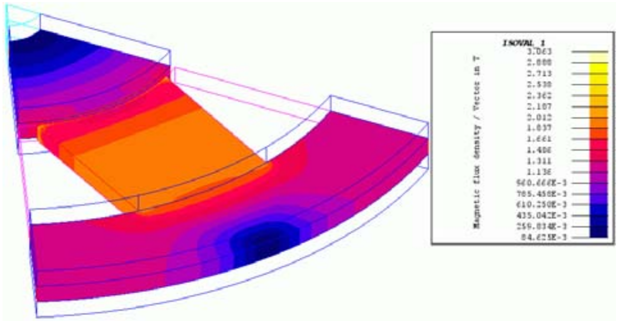
5 THE 3D FEM ANALYSIS

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 [11].

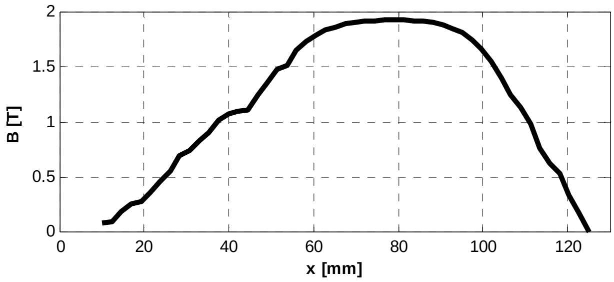
Since only the coils of a single module are supplied any time, it is enough to analyze only a single module and the corresponding part of the mover [3, 4, 5]. Due to the symmetry of the module, the analysis was carried out on a single pole of a module's magnetic piece. To emphasize the maximum flux densities in the motor the analysis was performed for the aligned position of the mover relatively to the mover.

The flux density map in the iron parts of a stator pole and the corresponding part of the mover is given in Fig. 6a.

Upon the magnetic field computations also the flux density could be plotted along a radial line, from the center of the machine to the exterior, Fig. 6b.



a)



b)

Figure 6. FEM analysis results:
a) flux density distribution in a pole of the magnetic piece and the corresponding mover part
b) flux density variation from inside to exterior.

The air-gap flux density is around 1.4 T close to the value considered in the design procedure. The numerical analysis emphasizes the actual values of the flux density values in the machine. Hence a comparison is possible with the results obtained analytically, where the flux densities were considered constants for each zone of the machine corresponding to a magnetic reluctance.

As expected, the traction force in the aligned position is nil.

All the results obtained via numerical field computations are in good accordance with the analytical ones.

6 CONCLUSIONS

The paper deals with a new type of tubular linear machine. It has a novel transverse flux structure and it is operating upon the variable reluctance principle.

The innovative construction, by alternating magnetic and non-magnetic pieces, has two major advantages: a lower weight and price than using the classical iron core, and very good performances.

The validity of the proposed design algorithm was proven both by analytic computation and by FEM analysis. The results were in good accordance with the initial estimations.

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

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