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ON THE TUBULAR TRANSVERSE FLUX RELUCTANCE MOTOR'S DESIGN

BY

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Abstract. This paper deals with a new type of tubular electrical machine which can develop high force at reduced strokes. It is a transverse flux machine in modular construction operating based on variable reluctance principle. The starting point of this modular tubular motor is a linear transverse flux reluctance machine. The design algorithm of the proposed machine is described in details, as well as an analytic approach based on the equivalent magnetic circuit to validate the correct sizing of the machine.

Key words: tubular motor; transverse flux machine; variable reluctance machine; equivalent magnetic circuit.

1. Introduction

The main studies carried out in the field of transverse flux machines focused on the rotary structures. Few analyses were dedicated to the linear variants. Among them an interesting variable reluctance machine was developed at the Technical University of Cluj-Napoca (Popa, 2008). It belongs to the transverse flux machines class, having only electromagnetic excitation. The component parts of the linear machine are the stator as the induced armature and the mover as the inductor, composed of a number of modules. The windings

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are placed on the modules of the mover, while the stator is passive. The main shortcoming of a linear machine is given by the existence of the normal force, about ten times greater than the tangential one.

Starting from this structure a tubular variant can be obtained (Popa *et al.*, 2008). This machine has the advantage of cancelling the attraction forces between the armatures, due to its cylindrical structure, and has an innovative construction. The basic operating principle of the tubular machine is the same with that of the linear variant mentioned above.

2. Tubular Transverse Flux Reluctance Motor

The inductor, usually the stator, has a modular construction (Fig. 1 *a*). The minimum number of modules, N, required in order to obtain a continuous movement, is of three (Popa *et al.*, 2007). Each module has an independent winding. The iron core of a module is built of m magnetic pieces, alternating with m – 1 non-magnetic pieces (Fig. 1 *b*). The stator pieces have the same construction like the stator of the induction machine. Each piece can be made both of steel sheets, like those used at the induction machine, or of soft magnetic composite material.

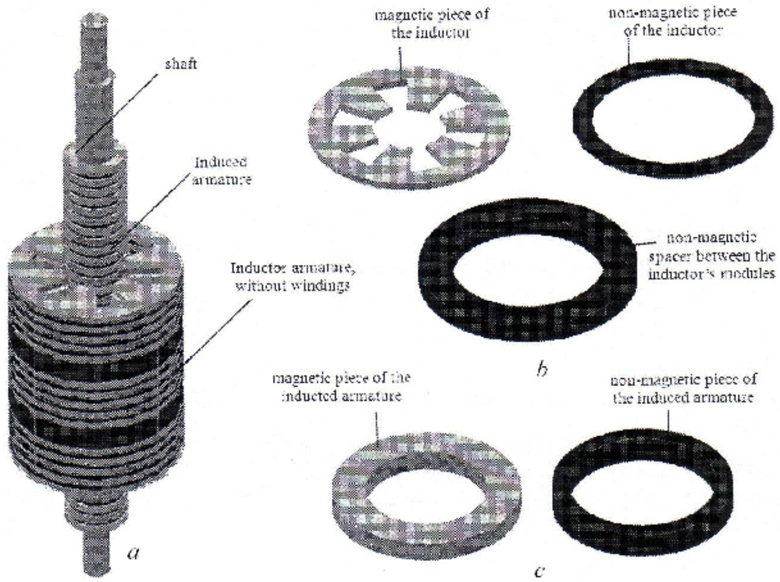

Fig. 1 – Tubular transverse flux reluctance machine: *a* – the structure; *b* – component parts of the inductor; *c* – component parts of the induced armature.

Considering that both the sheet and the module have teeth and slots, they will be defined as magnetic piece's tooth, t_p, and slot, s_p, respectively module's tooth, t_m, and slot, s_m. A module's tooth and slot form together the module tooth pitch, τ. As in the case of the linear machine, the positioning step is given by the tooth pitch and the number of modules.

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 $k\tau + s_m + \tau/N, \quad k \in \aleph$, where τ and N have the same significance like mentioned above for the tubular machine. This condition is applied also at the proposed motor. But, unlike the linear machine where the modules were placed at the construction in an aluminum case in such way that this shifting between the modules was provided, at the tubular motor the shifting is created by using non-magnetic spacers (Fig. 1 *b* (Popa *et al.*, 2010)).

The induced armature, the mover, is passive in the case of the tubular machine, too, and the toothed structure must be obtained as well, but it will be in fact a cylinder. The construction with magnetic and non-magnetic pieces can be used as in the stator. The form of the pieces is much simpler than for the other armature, just a magnetic or non-magnetic cylinder, with a place in inner part for assembling the shaft, made also of non-magnetic material (Fig. 1 *c*) (Popa *et al.*, 2010). The advantages given by this construction are, as in the case of the stator, a lower weight and cost.

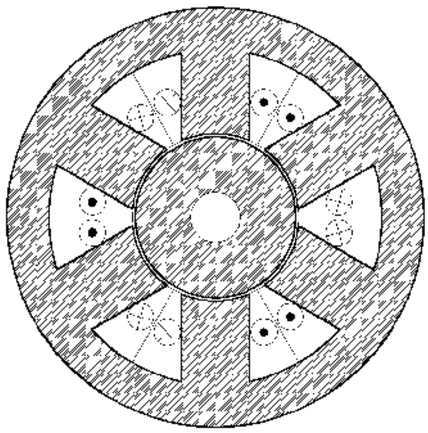

Fig. 2 – Cross section through the transverse flux tubular machine.

The disposal of the windings of the tubular machine is shown in a cross section of the machine (Fig. 2). The variant with concentrated windings around each tooth of the stator, connected in series, is presented. Another possible solution would be with coils wound around the yoke.

3. Design Principles

The most important characteristic of the linear transverse flux reluctance machine is the developed tangential force. The normal force is about ten times bigger than the tangential one, and this is one of the major shortcomings of all linear machines (Boldea, 2001). As stated before, the existence of only the traction force due to the compensation of all the attraction forces is one of the most important advantages of the tubular variant. The force is given, like in the case of the linear structure, by a single module with energized winding. The main dimensions and excitation magneto-motive force (mmf) strongly depend on the required traction force. This motor has the particularity that the iron core of the two armatures is not homogenous. Considering that this introduces major difficulties from the first steps of the design stages, one can start from the hypothesis that the whole structure is made of magnetic material, the error being relatively small.

The traction force of any linear motor can be calculated analytically or by finite element analysis. In this paper, the basic aspects of an analytic approach shall be covered. The principle used to compute the developed forces at any linear variable reluctance machine is the variation of the magnetic energy in the air-gap *versus* the linear displacement (Strete & Viorel, 2008). The expression of the magnetic energy, where the elemental volume is function of mover's position, is

$$W_m = \frac{1}{2}\cdot\frac{B_g^2}{\mu_0}\int \mathrm{d}v = \frac{1}{2}\cdot\frac{B_g^2}{\mu_0}A_p g = \frac{1}{2}\cdot\frac{B_g^2}{\mu_0}R\alpha g(t_m - x). \tag{1}$$

The traction force, f_T , and the coil mmf, F, are, respectively,

$$f_T = \frac{\partial W_m}{\partial x} = \frac{1}{2}\cdot\frac{B_g^2}{\mu_0}g(-R\alpha) = -\frac{1}{2}\mu_0 F^2\frac{R\alpha}{g}, \tag{2}$$

$$F = \frac{1}{\mu_0}gB_g, \tag{3}$$

where the notations are: A_p – common armatures area, g – air-gap length, R – stator interior radius in the air-gap, α – stator pole angular length, x – axial coordinate, B_g – peak value of the air-gap flux density in aligned position, μ_0 – air-gap magnetic permeability.

The force, f_T (rel. (3)), is constant and does not depends on the axial length of the armatures, but on the square of the coil's mmf, pole circumferential length in air-gap ($R\alpha$) and air-gap length, g. Considering the structure of the tubular motor proposed here, the traction force developed by an energized phase is

$$f_{T\mathrm{ph}} = \mu_0 F^2\frac{R\alpha}{g}. \tag{4}$$

Starting from these relationships, a connection between the force and the magnetic and geometric dimension of the machine can be established namely

$$R = \frac{\mu_0}{4}\cdot\frac{K_C K_S}{r}\cdot\frac{f_t}{C_r B_g^2 g\alpha m Z}, \tag{5}$$

where K_C, K_S are the Carter's and saturation coefficient, respectively, r is the ratio between the common axial length of the stator and mover pole and the polar pitch, C_r – the air-gap equivalent reluctance coefficient, Z – the number of poles of a magnetic piece. One must take into account that K_C and C_r coefficients are functions of the air-gap length to mover pole pitch, g/τ, and mover pole axial length to mover pole pitch, l_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

$$A_s = \frac{2gB_g}{\mu_0 J_1 K_{\text{fill}}}, \quad (6)$$

one can obtain the height of the pole

$$h_p = \frac{\sqrt{2A_s \sin\alpha + \left(\frac{2\pi}{Z} - \alpha\right)\frac{1+\cos\alpha}{2}\left[R^2\left(\frac{2\pi}{Z} - \alpha\right) + 2A_s\right]} - \left(\frac{2\pi}{Z} - \alpha\right)R\cos\frac{\alpha}{2}}{\left(\frac{2\pi}{Z} - \alpha\right)\frac{1+\cos\alpha}{2}}. \quad (7)$$

All the other geometric dimensions result easily. The exterior radius of the stator is computed considering the flux that closes through the yoke at a typical switched reluctance machine (SRM).

4. The Magnetic Equivalent Circuit

In order to check the validity of the proposed design algorithm, an equivalent magnetic circuit for the proposed structure was built up (Fig. 3, (Ruba, 2008)). The circuit corresponds to two poles, the yoke and the slot between them and the corresponding part of the mover. Besides the mmf of a coil, F, it is known, using the determined geometric dimensions, the reluctance 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, respectively, to the air between two neighbored coils and to the air-gap.

By solving the equation system obtained applying Kirchhoff laws for the presented circuit, the fluxes through each branch of the circuit result. Consequently, 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.

In order to prove the validity of the proposed algorithm and the analytic approach, a machine developing a tangential force of 800 N was considered. The chosen values are: peak air-gap flux density, B_g = 1.3 T, current density, $J = 5 \times 10^6$ 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_{rc}= 1.3, mover pole axial length per pole pitch, r = 1/3.

For the proposed machine, Z = 6 poles were considered, and the number, m, of magnetic pieces of a module is two. The angle, α, of a pole was considered to be of 50^{o}.

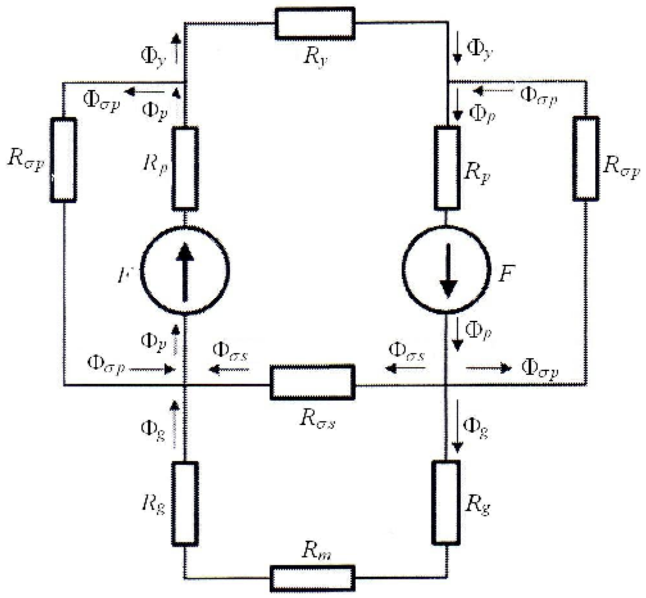

Fig. 3 – Equivalent magnetic circuit of the tubular machine.

The necessary area of the stator slot is (s. (6)) $A_s = 0.19 \times 10^{-2}$ m^2 and the required mmf per coil is (s. (3)) F = 1,900 Aturns. In this case the height of the pole was computed with relation (7) obtaining h_p = 50 mm, the exterior radius being R_{ex} = 130 mm.

The analytic computation was done for a shifting of half of mover piece from the stator one. As it results from the magnetic circuit, the biggest value of the flux is in the poles. Considering this as the reference value, the percentage value of 83.89% is obtained for the flux in the yoke, 72.7% for the air-gap flux, and 11.2%, respectively 16.1%, for the two leakage fluxes. The mean value of the air-gap flux density is of 1.27 T, in very good accordance with the chosen one in the design process.

5. Conclusions

This paper deals with a new type of tubular machine, belonging to the transverse flux machines class and operating based on the variable reluctance principle. The design algorithm which is proposed for this structure was verified using an analytical method based on the equivalent magnetic circuit of the machine. The machine is suitable for applications requiring precise positioning step or high forces at low speed, with reduced strokes.

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ASUPRA PROIECTĂRII MOTORULUI TUBULAR CU FLUX TRANSVERSAL ŞI RELUCTANŢĂ VARIABILĂ

(Rezumat)

Se prezintă o structură nouă de maşină tubulară, cu flux transversal şi reluctanţă variabilă. Este detaliată structura propusă, având o topologie inovativă prin folosirea materialelor magnetice şi nemagnetice la construcţia miezului. Pentru realizarea înfăşurărilor există varianta folosirii bobinelor concentrate în jurul polilor sau a jugului şi conectate în serie sau în paralel. Este abordat algoritmul de proiectare în urma căruia să rezulte toate dimensiunile geometrice, electrice şi magnetice caracteristice maşinii. Circuitul magnetic echivalent realizat are scopul validării pe cale analitică a algoritmului propus.