Transverse Flux Tubular Switched Reluctance Motor

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Abstract— **A transverse flux tubular switched reluctance motor of a particular construction is presented. The traction force equations are obtained based on two simplified models and a sizing designing procedure for the motor is developed. A two dimensions finite element method (2D-FEM) analysis is performed in order to check the analytically calculated performance and a sample motor is designed and analyzed.**

I. INTRODUCTION

Many industrial, mainly mass transit applications, require low-speed or high-speed linear displacement. Drive systems using linear, induction or synchronous motors are nowadays largely employed in such industrial applications. Linear switched reluctance motor (LSRM) can be an attractive alternative due to its specific features as: low cost, fault tolerance, modularity [1,2,3].

LSRM has usually concentrated windings, on either, stator or mover structure. This leads to a low cost manufacturing and maintenance and improves the cooling process.

Since all LSRM's phases are supplied individually, such a motor is a fault-tolerant system that can operate with a phase shorted or open.

A LSRM is a modular structure; therefore a drive system with LSRM will contain as many elementary modules of three or more phases, as necessary to obtain the required thrust. It will result a series of motors which have the homologous phase supplied in parallel from the same converter.

The tubular switched reluctance motor (TSRM) has some important advantages in comparison with the LSRM, as shorter end windings, lower leakages and shorter flux lines path. Beside all these, TSRM has larger force density ratio (thrust per volume), even than double sided LSRM.

There are some distinctive configurations of LSRM and TSRM presented in the literature, [1,2,3,4,5,6], for example, [3] being dedicated to a TSRM with a double sided longitudinal flux configuration to be used for a short stroke length.

Quite many references deal with LSRM or TSRM design, for instance [1,2,4,5], but a standard design procedure for all the possible structures has not been developed yet. In [5] a specific design procedure is presented with good results.

Attempts to develop a suitable analytical model for LSRM or TSRM were previously made [3,4]. A consistent study based on two-dimensional finite-element method (2D-FEM) of a double sided, double mover LSRM is presented in [6], the author evincing the differences existent between a 2D and a 3D approach.

This paper is dedicated to a transverse flux tubular switched reluctance motor (TSRM) with a particular structure. The motors' topology and its basic operation are described in Section II, while Section III deals with two simplified motor models which allow the traction force calculation. A sizing-designing procedure for this specific TSRM, which can be extended to other similar linear motors, is presented in Section IV. Aspects concerning the 2D-FEM analysis performed on TSRM are discussed in Section V, while Section VI is dedicated to the results obtained via analytical and 2D-FEM analysis, respectively for the sample motor considered. The conclusions are closing the paper, evincing the main results obtained.

II. TSRM CONFIGURATION

The proposed structure of the tubular SRM is given in Figs. 1 and 2. In Fig. 1 an axial section is shown, evincing the stator and the mover poles. In Fig. 2, a cross section through the stator and mover poles, in an aligned position, (XX' axis in Fig. 1), is presented.

The notations of the axial geometrical dimensions, presented in Fig. 1 are: w_{pS} – stator pole axial length, w_{sS} – stator slot axial length, τ_{pS} – stator pole pitch, w_{pM} – mover pole axial length, τ_{pM} – mover pole pitch.

The proposed tubular structure assures short end-windings, low leakages and also short flux lines topology, as seen in Fig. 2. The TSRM has only three phases per module, and as many modules as necessary, Fig. 1.The TSRM has an active stator, a passive mover and a transverse flux topology, Fig. 2. Per each stator three phase module, the mover has two pole pieces, each phase being totally independent as far as its supply and flux linkage are concerned.

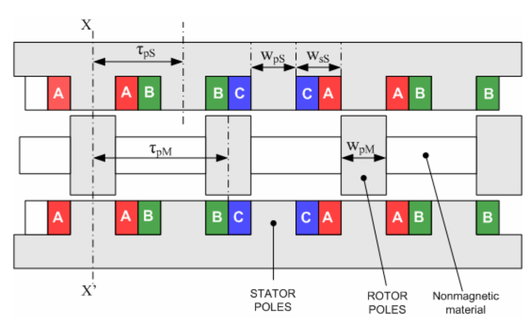

Figure 1 Tubular SRM structure, axial section

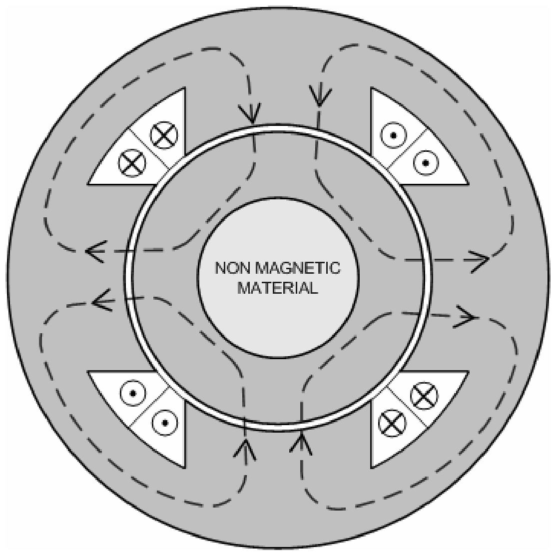

Figure 2 Tubular SRM structure, XX' cross section

The mover's poles are made of soft magnetic composite materials (SMC) cylinders placed on a shaft which may be fabricated of non magnetic material. The stator core construction can be done in different ways. For not so large motors, the stator can be obtained from four parts, each one containing a pole and the corresponding parts of the yoke cylinder. In this case, each part should be made of SMC and all four assembled in an outer case of magnetic or nonmagnetic material. The number of stator modules depends on the required thrust, specified exterior diameter and total length of the motor. The mover is built as long as necessary to assure on the entire stroke length with adequate configuration of its poles.

III. TSRM'S TRACTION FORCE CALCUALTION

The traction force is the main specification for any kind of linear motor. Consequently, a designed TSRM must produce a traction force equal or larger than the one required by the drive system. The main dimensions and excitation **mmf** strongly depend on the traction force and the designer should make the best choices in order to conform to the imposed specifications and to obtain a motor which has a good force to volume ratio.

The traction force of a linear motor, TSRM included, can be calculated analytically or by applying a specific numerical method as finite differences (FDM) or finite element (FEM). Nowadays, designing any type of electric machine consists of four compulsory stages:

i) A sizing designing stage when, based on simplified models and on existing experience, the main dimensions and performance are calculated.

ii) A second stage in which, by employing a specific numerical method, mostly FEM, the previous calculations are checked and a quasi optimal motor is obtained.

iii) The third stage is dedicated to the heating-cooling calculation via FEM or any other method which is accurate enough, as the one based on thermal equivalent circuit.

iv) Through the fourth stage, the entire drive system (supply source-motor-load) is simulated on computer to check if the dynamic and steady-state required performances are fulfilled.

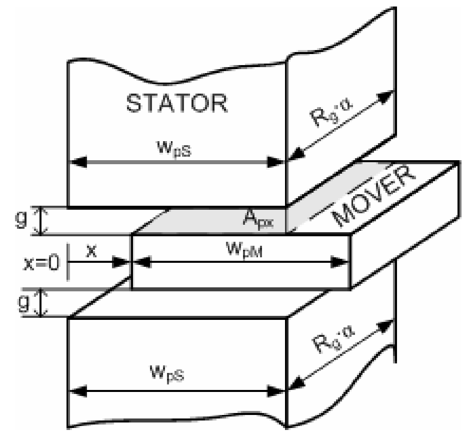

Figure 3 Traction force calculation, simplified relay-type structure

Since no specific application is considered in the paper, only the first two TSRM designing stages are discussed, more strength being put on the sizing-designing procedure which has important particularities.

Two models to calculate the TSRM traction force are used, a simplified linear one and a model based on the variable equivalent air-gap permeance method, previously applied to the rotating SRM or to the linear transverse flux reluctance motor, [7,8,9].

In the first case, a simple structure is considered, with two identical coils supplied in parallel and producing the same **mmf**, Fig. 3.

The magnetic energy in the air-gap W_{mg} is:

$$W_{mg} = \frac{1}{2}\frac{B_g^2}{\mu_0}\int dv \qquad (1)$$

where the elemental volume is, function of mover's position:

$$\int dv = A_{px} g = R_g \alpha (w_{pM} - x) g \qquad (2)$$

The traction force f_{TL} results as:

$$f_{TL} = \left.\frac{\partial W_{mg}}{\partial x}\right|_{i=ct} = \frac{1}{2}\frac{B_g^2}{\mu_0} g(-R_g \alpha)$$

$$f_{TL} = -\frac{1}{2}\mu_0 F^2 \frac{R_g \alpha}{g} \qquad (3)$$

where the coil **mmf**, F is:

$$F = (1/\mu_0) \cdot g \cdot B_g \qquad (4)$$

The notations are the following: A_{px} – common stator and mover pole area, x – axial coordinate, w_{pM} – axial length of the mover pole, equal to the stator pole axial length, w_{pS}, g – air-gap length, R_g – stator interior radius in the air-gap, B_g – peak value of the air-gap flux density in aligned position, α – stator pole angular length, μ_0 – air-gap magnetic permeability.

The force f_{TL}, (3) is constant and does not depend on the mover, or stator pole axial length, but on square of the coil

mmf, pole circumferential length in air-gap ($R_g\ \alpha$) and air-gap length g.

Considering the actual structure of the TSRM, Fig. 2, the total traction force developed by a energized phase is:

$$f_{TLph} = -(\mu_0 / g) \cdot F^2 R_g \alpha \quad (5)$$

In the case of the variable equivalent permeance model, the flux linkage comes as, [7,8]

$$\lambda(x,i) = \mu_0 N^2 i \frac{R_g \alpha \cdot w_{pM}}{K_C g} \frac{1 + P_{coeff} \cos(\frac{2\pi \cdot x}{\tau_{pM}})}{K_s(x,i)} \quad (6)$$

where N is the number of series turns per phase coil, i is the phase current, g, K_C, P_{coeff}, τ_{pM} are the actual length of the air-gap, the Carter's factor, the variable equivalent air-gap permeance coefficient [7,8] and the mover axial pole pitch. The saturation function $K_S(x,i)$ can be given by a cosinusoidal function as in [3]:

$$K_S(x,i) = K_{S0}[A\cos(2\pi \frac{x}{\tau_{PM}}) + B] \quad (7)$$

where the coefficients A and B are function of phase current and should be calculated by using the aligned and unaligned flux linkage versus current characteristics.

For design purpose, in a first sizing-designing stage, the saturation function can be reduced to a saturation constant estimated in aligned position, considering the core material magnetization characteristic (B-H), Fig. 4. Accordingly, the saturation factor Ks is given by:

$$K_S = K_{S0} \cdot B_{uns} / B_{sat} \quad (8)$$

$$K_{S0} = 1 + (1/\mu_{r0}) \cdot (l_{co} / l_g) \quad (9)$$

Where B_{uns}, B_{sat} are the flux density unsaturated and saturated values, l_{co}, l_g are mean length of magnetic path in the core and in the air-gap respectively, and μ_{r0} is the initial relative permeability of the core material. The estimated magnetic field intensity H_e should be approximated initially considering that the entire **mmf** is producing magnetic field only in the air-gap.

The traction force f_{TP} developed by two opposite coils, calculated based on this model, is:

$$f_{TP} = \int_0^i \frac{\partial \lambda}{\partial x} di = = -\pi \frac{\mu_0}{g} F^2 \alpha R_g \frac{w_{pM}}{\tau_{pM}} \frac{P_{coeff}}{K_C K_S} \sin(\frac{2\pi \cdot x}{\tau_{pM}}) \quad (10)$$

The peak and average value of f_{TP} are:

$$f_{TP\max} = 2\pi f_{TL} \cdot K_{vp} \quad (11)$$

$$f_{TPav} = 4 f_{TL} \cdot K_{vp} \quad (12)$$

where the variable permeance factor K_{vp} is:

$$K_{vp} = \frac{w_{pM}}{\tau_{pM}} \frac{P_{coeff}}{K_C K_S} \quad (13)$$

Equations (10)-(12) remain valid for a phase, by simply replacing f_{TL} *with* $f_{TLph.}$

IV. SIZING-DESIGNING PROCEDURE

The D_g^2L equation, where D_g and L are the average air-gap diameter and respectively the stack length, is the most used one to size rotating electric machines. This equation, written for motor operation, relates power output P_{out} and rotor speed n to the rotor volume, through an output general coefficient K_{siz}, which contains air-gap flux density B_g, electrical loading A, energy conversion parameters, number of pole pairs and some sizing coefficients specific to each type of motor [9,10].

In the case of linear electric machines, the sizing should start from the traction force equation, which relates the produced thrust to air-gap flux density, main dimensions and some coefficients that should be estimated based on existing experience and data collected from similar motors already built. In the specific case of TSRM, the sizing equation would be (12), which can be conveniently arranged as:

$$f_{TPav} = f = \frac{4}{\mu_0} \frac{w_{pM}}{\tau_{pM}} \frac{P_{coeff}}{K_C K_S} B_g^2 \cdot g \cdot \alpha R_g \quad (14)$$

evincing the constants and the coefficients to be estimated.

Carter's factor K_C and permeance coefficient P_{coeff} are function of the air-gap length to mover pole pitch g/τ_{pM} and mover pole axial length to mover pole pitch, w_{pM}/τ_{pM}, ratios [8,9]:

$$K_C = \frac{1}{1 - \gamma(g / \tau_{pM})} \quad (15)$$

$$P_{coeff} = \frac{4}{\pi} \beta_R \cdot K_C \cdot \sin\left(\frac{\gamma}{\beta} \cdot \frac{g}{\tau_{pM}} \cdot \frac{\pi}{2}\right) \quad (16)$$

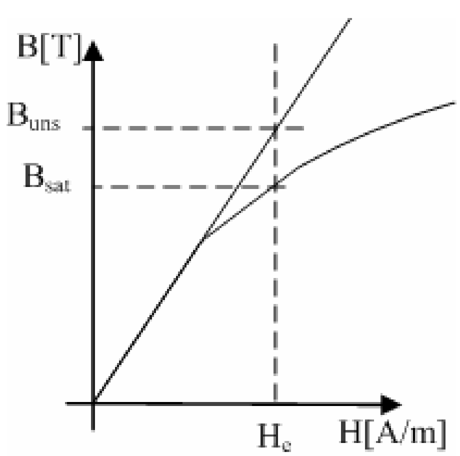

Figure 4 Saturation factor calculation

$$\left.\begin{aligned}&\gamma = \frac{4}{\pi}\left(u \cdot atn(u) - \ln\left(\sqrt{1+u^2}\right)\right)\\&\beta = \frac{(1-f)^2}{2(1+f^2)}\\&u = \frac{1-w_{pM}/\tau_{pM}}{2g/\tau_{pM}}, \quad f = u + \sqrt{1+u^2}\end{aligned}\right\} \tag{17}$$

They can be estimated initially to be introduced in (14) as will be K_S (8),(9) and should be calculated based on the motor dimensions for a second iteration in the sizing-designing procedure.

The ratio of the rotor pole axial length to rotor pole pitch is usually 1/3 since the mover pole axial length is equal to the stator pole axial length and to the stator slot axial length w_{sS}.

The peak air-gap flux density B_g value should be as large as possible, function of core material, and has to be choose initially. It results that the product $g{\cdot}Rg{\cdot}\alpha$ can be obtained from (14), where $\alpha<\pi/2$. The air-gap length value, g should be as small as possible, but its minimum is imposed in motor construction by mechanical constraints. Once a value is adopted for g, the necessary circumferential length of the stator pole will result. Since the exterior diameter of TSRM is usually limited, due to the mechanical assembly requirements, R_g will have a limit for its maximum value too.

In order to design a stator pole module, Fig. 2, a compromise should be made between the pole circumferential length and the cross section area of the slot, where the excitation coils are placed. The peak air-gap flux density B_g requires a certain coil **mmf**, and consequently, for an adequately considered current density J and slot fill factor K_{fill}, the slot area results as:

$$A_{sl} = \frac{2g \cdot B_g}{\mu_0 J \cdot K_{fill}} \tag{18}$$

Let now consider the cross section through TSRM half of the stator, Fig. 5, where the notations are: R_g – stator interior radius in the air-gap, R_p – stator pole base radius, R_{ex} – stator exterior radius, y – stator pole height, α - stator pole angular length, β - auxiliary angle characterizing the stator pole height.

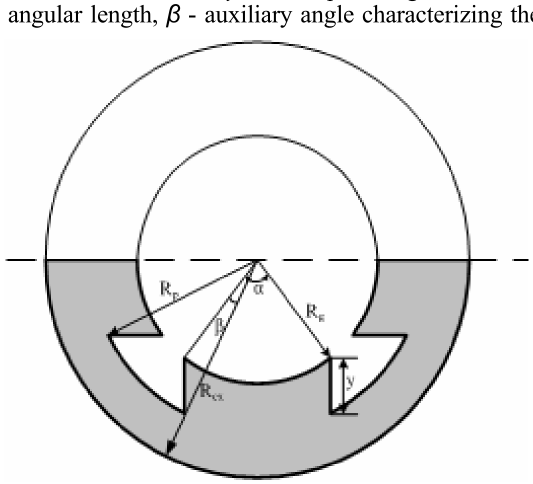

Figure 5 TSRM parameterized dimensions

The slot and pole cross section area, A_{sl}, A_p are:

$$A_{slot} = \frac{\pi \cdot R_g^2}{4}\left(\frac{\sin^2(\alpha/2)}{\sin^2\beta} - 1\right) - A_{pol} \tag{19}$$

$$A_{pol} = R_g^2 (2\frac{y}{R_g}\sin\frac{\alpha}{2} + \left(\beta\frac{\sin^2(\alpha/2)}{\sin^2\beta} - \frac{1}{2}\sin\alpha - \frac{y}{R_g}\sin\frac{\alpha}{2}\right) - \left(\alpha - \sin\frac{\alpha}{2}\cos\frac{\alpha}{2}\right)) \tag{20}$$

The auxiliary angle β is:

$$\beta = \operatorname{atan}\frac{\sin(\alpha/2)}{\cos(\alpha/2) + y/R_g} \tag{21}$$

Two more issues concerning TSRM sizing-design procedure should be discussed.

Firstly, one has to answer to an important question: how many phases? This question refers to the motor modules number too.

It is obviously clear that the minimum number of phases for a symmetrical conventional SRM is three and there is practically no upper limit. There are some particular structures with one or two phases [9], but their performances are not that good. Basically, by taking a number of phases larger than three, the force ripple can be reduced and, by supplying adequately more than one phase in the same time, the traction force can be increased. In fact, since the exterior diameter is imposed in most cases, the designer must consider TSRM with more than one module, but with minimum number of phases. It means that a module will be the shortest possible and the converter the cheapest one, since there will be no need for a more sophisticated control to overlap the phases' conduction period.

The steps to be followed in a sizing design procedure, when the specifications impose the total traction force and the maximum exterior diameter are:

i) Take initial values for K_C, K_S, P_{coeff}, g, B_g, J, K_{fill} and for the w_{pM}/τ_{pM} ratio
ii) Calculate the necessary slot area A_{sl} (18) and the product $R_g{\cdot}\alpha$ (14). If R_g results larger than half of the exterior radius, for a reasonable $\alpha<\pi/2$, then a motor with more than one three phase module should be considered.
iii) By using equation (14), (19), (20) and with already known necessary slot area, quasi optimal calculation will give the values for the main dimensions, R_g, , y, R_{ex} and w_{sS} w_{pS} w_{pM}.
iv) Having a first motor draft, calculate K_C, K_S, P_{coeff} using (8),(9),(15),(16),(17) and the tangential force produced by one phase of TSRM module. If the obtained force is greater than the required one for one module, then the sizing procedure is over and the designer will go on to calculate the parameters and performances. If the force produced is smaller than the required one, then there are two possibilities. First is to increase the number of modules if the difference is important and second to try to increase the force produced by one module if the difference is small.

v) With data obtained through the sizing step, the parameters and performances can now be calculated.

The final dimensions and main data will be fixed only after a FEM analysis, when the force versus mover position and stator mmf is calculated and the flux density through different parts of TSRM iron core checked.

V. 2D-FEM ANALYSIS

The TSRM magnetic field has a true 3D pattern, but it can be calculated by combining two 2D structures. Since there is not any problem concerning the 3D-FEM analysis for the TSRM, here will be further discussed only the combination which should be made in order to obtain the adequate solution of the 3D problem by employing two 2D configurations.

The first 2D-FEM analysis is performed through a cross section of TSRM in aligned position, Fig. 2, all four coils being energized. This is a natural structure and allows for the peak flux density values calculation in the air-gap and in the stator and rotor iron core. That is an important calculation since it gives information about the level of saturation obtained in the iron core.

The second 2D structure considered is presented in Fig. 6. It consists of two stator pole pieces and two rotor poles, all in a rectangular form. An exterior structure, for closing the flux lines is considered too. The stator and mover poles have the same axial pole length and pitch as the actual motor. The stator pole thickness on the *z* direction is equal with the actual motor poles circumferential width and this is kept the same for rotor poles and for the stator frame that closes the flux path.

An equivalent coil **mmf** is taken in order to obtain in the aligned position the same air-gap flux density value, as the one calculated via 2D-FEM in a cross section with only two opposite coils energized.

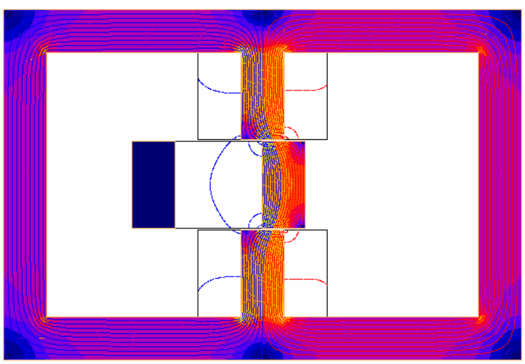

Figure 6 TSRM, axial 2D structure and FEM obtained flux lines

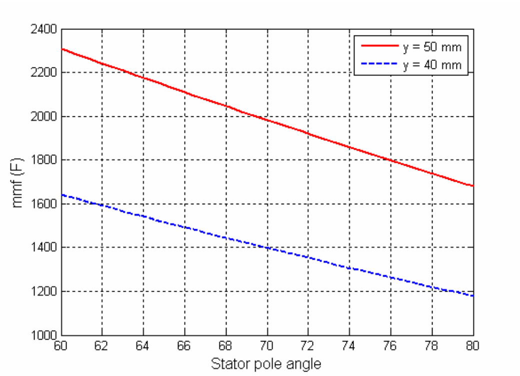

Figure 7 Sample TSRM, **mmf** per coil

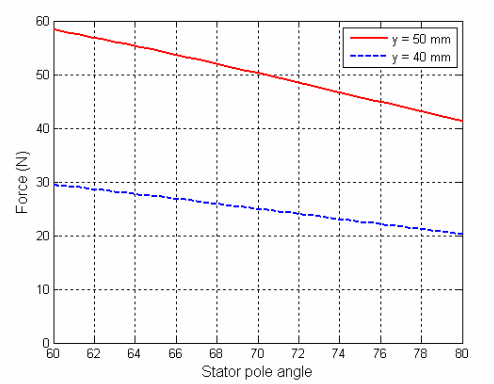

Figure 8 Sample TSRM, tangential force per pair of coils

VI. CALCULATED RESULTS

In the following, typical results for the quasi optimal calculation in the case of a sample TSRM are given. The traction force per module is 100N and the chosen values are: peak air-gap flux density B_g = 1.6T, current density *J*

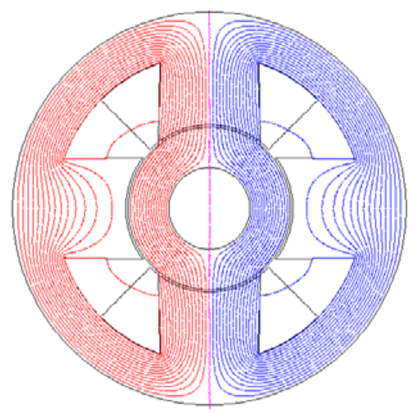

Figure 9 Sample TSRM,2D-FEM analysis in a cross section

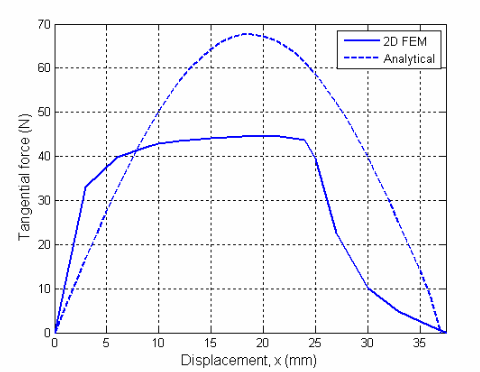

Figure 10 Sample TSRM, tangential force

$= 5\cdot10^6$ A/m^2, air-gap total 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 permeance coefficient P_{coeff}=1.3, mover pole axial length per pole pitch w_{pM}/τ_{pM}=1/3.

The necessary area of the stator slot (18) is A_{sl} = $0.19\cdot10^{-2}$m^2 and the required **mmf** per coil (4) is F=1900A.

From (14) comes the pole circumferential length $Rg\cdot\alpha$=$4.22\cdot10^{-2}$m·rad. If R_g = 0.05m, then the minimum α value results 48.46 deg.

Considering now α as variable and y as parameter, for the given sample TSRM, the coil **mmf** and the tangential force variation characteristics are given in Figs. 7 and 8.

In this case, if y = 50mm, the exterior radius is R_{ex} = 125mm, the stator yoke height being 25mm.

The force density results:

$$f_{den} = \frac{f_{Tph}}{Vol} = \frac{84}{2.945\cdot10^{-3}} = 28.52\cdot10^3\,N/m^3 \quad (22)$$

where the total force per phase f_{Tph} is calculated via 2D-FEM analysis and Vol is the phase volume. Even for a first draft, as it is the designed TSRM, the force density is quite impressive.

The computational process should stop when the required force is obtained with the minimum volume, which means in fact the minimum value of R_g. An adequate program can be developed and a lot of variants calculated in extremely short time.

In Fig. 9, the 2D-FEM results obtained in a cross section, with R_g=0.05m and y=0.05m are given. In Fig. 10 is given the traction force calculated via 2D-FEM simplified model, Fig. 6, in comparison with the values calculated by using the variable equivalent permeance method.

As can be seen from the characteristics presented in Fig. 10, the simplified model based on variable equivalent air-gap permeance covers quite well the phenomena. The differences that exist are caused by the saturation effect which is not entirely considered in the model.

VII. Conclusions

A transverse flux tubular switched reluctance motor of a particular construction is introduced. Such a motor can be a good solution for short track transfer system drives due to its good performance and high thrust to volume ratio.

A novel sizing-design procedure is developed for TSRM based on traction force equation and simplified magnetic equivalent circuit calculations. The 2D-FEM analysis is employed to check the analytical calculated values. The 2D-FEM analysis is performed on two models, a cross section through an aligned natural position and an axial section specially defined to calculate the trust versus mover displacement at different values of the phase **mmf**.

The sizing-design procedure is applied on a sample TSRM. The motor traction force is calculated via 2D-FEM, as are calculated the flux density values in the air-gap and stator and mover core for aligned position and different phase **mmf**.

A quasi optimal TSRM, concerning the best thrust to volume ratio can be obtained via the proposed algorithm too.

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