Design of a Permanent Magnet Transverse Flux Motor for Ship Propulsion System

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Abstract* – The permanent magnet transverse flux motor (PMTFM) is characterized by power density figures larger than the conventional electric motors, and by a specific modularity, each phase being an independent module. The PMTFM has usually a complicated structure with a true three dimensional (3D) pattern. In this paper, a PMTFM with a simple structure and a quasi 2D flux pattern is proposed for a ship drive system. The PMTFM phase module design procedure is based on a specific analytical algorithm. A 3D FEM analysis is performed on the considered PMTFM. An optimization procedure based on the analytical model is implemented, the objective function considered being the maximum torque density.

***Keywords:* transverse flux machine, ship propulsion.**

I. INTRODUCTION

The concept of ships' electric propulsion is not new, the idea originated more than 100 years ago. However, with the possibility to control electrical motors with variable speed in a large power range with compact, reliable and cost competitive solutions, the use of electrical propulsion has emerged in new application areas during the 80's and 90's.

Electric propulsion with gas turbine or diesel engine driven power generation is used in hundreds of ships of various types and in a large variety of configurations.

In recent years a variety of papers have been published, providing details and promoting discussions on the diverse range of issues that make up the electric ship concept [1, 2, 3, 4, 5, 6].

The permanent magnet transverse flux motor (PMTFM) has a larger power density than the permanent magnet conventional electric machines which is an important feature in the case of a ship drive system [7]. The PMTFM has a modular structure too, each phase being an independent module, an important feature in the case of such a drive.

The propulsion power varies with the size of the vessel, from few MW for smaller ferries up to 30-40 MW for large cruise liners.

In this paper is proposed a 3 MW drive system for ships based on permanent magnet transverse flux motors with a simple structure. It is considered a set of three phase mechanically coupled permanent magnet transverse flux motors, with the same rated output power. The output power of one motor is 500 kW. The phase module is analytically designed [7] and its performance is analyzed via a three dimension (3D) magnetic field calculation by using the Cedrat FLUX 3D environment. Finally the motor is optimized to obtain the maximum torque density by using the Hooke-Jeeves algorithm.

II. PERMANENT MAGNET TRANSVERS FLUX MACHINE STRUCTURE

The PMTFM structure presented in this paper is a simple one, with a flux concentrating topology employed in the rotor as it can be seen in Fig. 1.

The stator is made of C shaped pole pieces which can be assembled from separate parts, in order to facilitate the machine manufacturing technology, even if this will lead to an extra air-gap, Fig. 2. The coil, produced separately, is placed on its room on a half of the pole piece, the magnetic circuit being completed with the second half of the pole pieces.

Such a machine may have two or more phases, each phase being a separate module. A three phase machine topology, in a linear layout, is presented in Fig. 3.

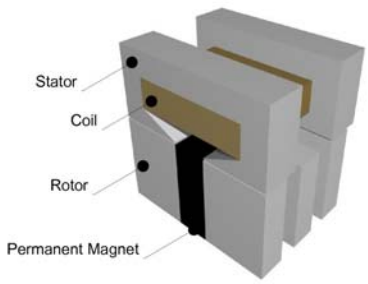

Fig. 1. A part of a PMTFM' phase linear layout

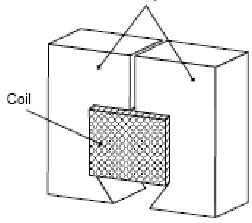

Fig. 2. Some parts of a three phase PMTFM modules in linear layout

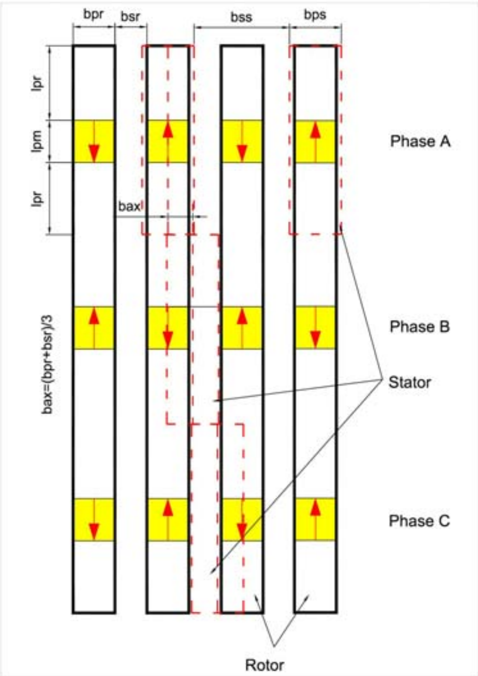

Fig. 3. Some parts of a three phase PMTFM modules in linear layout

The input data for the analytical model is: P_{out}=500 kW, U_f=4 kV, I_f=84 A, n=200 rpm, Q_S=40 and Q_R=80.

III. PMTFM SIZING DESIGN PROCEDURE

An electric machine design procedure must follow some compulsory steps:

1) Sizing-designing procedure when the main dimensions and characteristics are estimated;

2) A 2D or 3D – FEM analysis to check the electromagnetic performances of the previously calculated machine;

3) Loss and heating calculation via 2D or 3D – FEM, or other accurate method;

4) Computer simulation of the machine behavior, embedded with its driving system.

In this paper a specific sizing-designing algorithm is introduced. It includes a heating calculation procedure based on thermal equivalent circuit [8, 9].

The PMTFM analytical design is based on an equation which gives the machine air-gap diameter function of the design specifications as rated output speed and power, of adopted material properties and of some sizing coefficients. The performance related values, efficiency, power factor, maximum air-gap flux density and stator electrical loading must be chosen considering the existing data, the machine topology and the permanent magnet type.

$$D_g = \sqrt[3]{\frac{P_{out}}{3 \cdot \eta \cdot k_l \cdot k_P \cdot k_B \cdot k_{ov} \cdot k_L \cdot k_i \cdot k_e \cdot \pi^2 \cdot B_{g\max} \cdot A_S \cdot Q_S \cdot n \cdot m}} \tag{1}$$

The stack length is determined using the following equation:

$$L = k_L \cdot D_g \tag{2}$$

where k_L is the aspect factor.

The rotor poles dimensions are determined form equations (3)-(6), the same ratios being valid for the stator poles by changing Q_R to Q_S and, adequately, all the sizing factors:

$$\tau_R = \pi \frac{D_g}{Q_R} \tag{3}$$

$$b_{pR} = k_{pR} \cdot \tau_R \tag{4}$$

$$b_{sR} = \tau_R - b_{pR} \tag{5}$$

$$l_{pR} = k_{fR} \cdot \frac{L}{2} \tag{6}$$

where Q_R – rotor pole number, τ_R – rotor pole pitch, b_{pR} – rotor pole width, k_{pR} – rotor pole coverage, b_{sR} – rotor inter-pole width, k_{fR} – geometrical sizing factor.

The permanent magnet height, h_{PM} depends on the flux concentrating factor k_{fc} which is the ratio between the adopted maximum air-gap flux density and the permanent magnet flux density B_{PM}.

$$h_{PM} = \frac{l_{pR}}{k_{fc} \cdot k_{disp}}, \tag{7}$$

The number of coil turns, N_t is computed with the following equation:

$$N_t = \frac{\sqrt{2} \cdot U_f}{\pi^2 \cdot Q_S \cdot n \cdot B_{g\max} \cdot D_g^2 \cdot k_B \cdot k_{fR} \cdot k_{pS} \cdot k_L} \tag{8}$$

The main values calculated for the 500 kW PMTFM are given in Table 1.

The PM's main characteristics are: B_r = 1.2 T, H_C = 910 kA/m.

Obviously the sizing procedure may not conduct always to a valuable machine, as in this case, but it gives quite important information for the designer.

TABLE 1: PMTFM analyticaly computed results

ITEM	UM	VALUE
Air-gap length, g	mm	1.75
Air-gap avg diameter, D_g	mm	1484
Stack length, l_{st}	mm	207
Rotor pole pitch, τ_R	mm	59
Rotor pole width, b_{pR}	mm	35
Rotor pole length, l_{pR}	mm	82
Permanent magnet height, h_{PM}	mm	89
Number of turns per phase, N_t	-	84
Electromagnetic torque, T	Nm	7367
Cogging torque, T_g	Nm	1238
Output power, P_{out}	kW	463

IV. 3D-FEM ANALYSIS

The designed motor has a circumferential periodicity, one period consisting of one stator pole piece and two rotor pole pieces, as it can be seen in Fig. 4.

In Figs. 5 and 6 is shown the flux density map for this structure in the aligned position, when the bottom rotor pole is aligned with the bottom stator pole for a **mmf** of 0 AT, respectively 7392 AT, in order to evince the parts which are more affected by saturation.

Fig. 7 presents the electromagnetic torque obtained for the rated current.

The interaction between the permanent magnets on the rotor and the stator slotted structure is creating a cogging torque component. The cogging torque is usually undesirable, as it produces noise and vibrations, its influence being more prominent at lower current values. Its value can be calculated when the coil is not energized, Fig. 8.

The torque values obtained were interpolated using cubic spline method, in order to obtain smoother curve lines.

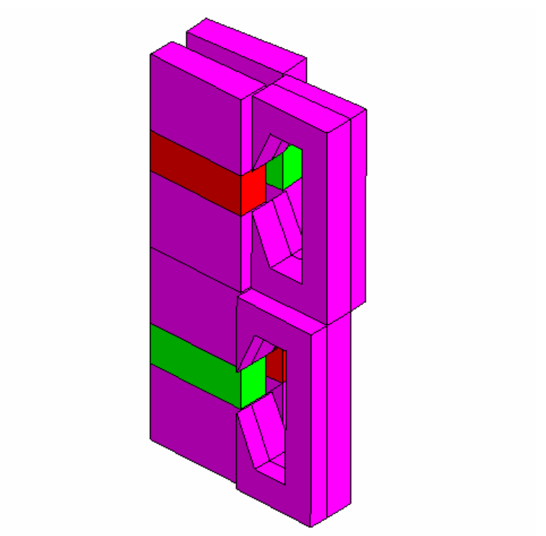

Fig. 4. Two phase modules of a three phase PMTFM

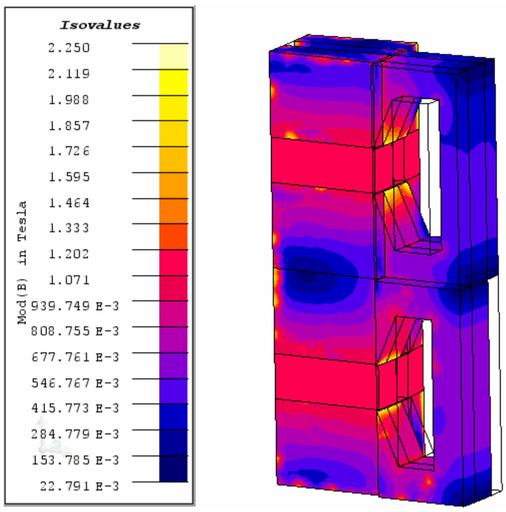

Fig. 5. Flux density isovalues at 0AT, aligned rotor position

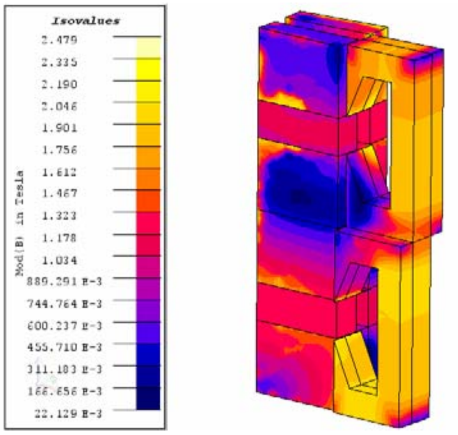

Fig. 6. Flux density isovalues at 7392 AT, aligned rotor position

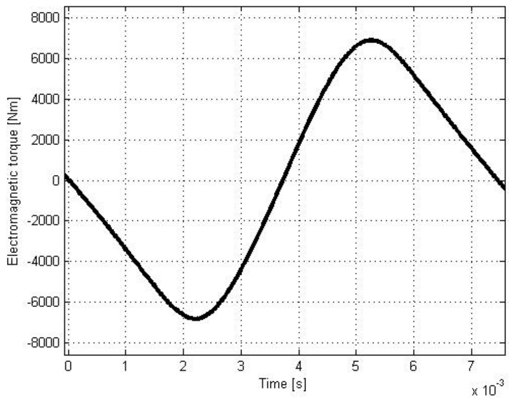

Fig. 7. Electomagnetic torque at 7392 AT

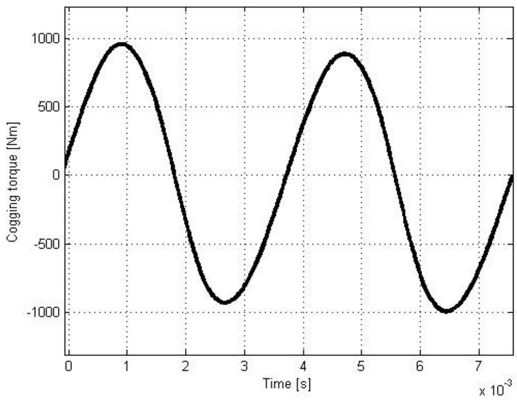

Fig. 8. Cogging torque

In each case the rotor was moved over a complete electrical period with an increment of 0.45 mechanical degrees, one electrical period coresponding to 9 mechanical degrees.

V. DESIGN OPTIMIZATION OF THE PMTFM

In the third chapter, a specific analytical design algorithm was discused for the proposed PMTFM structure. Since the electro-mechanical system is described by a very large number of variables, some of them had to be initially chosen in order to reduce the complexity of the problem.

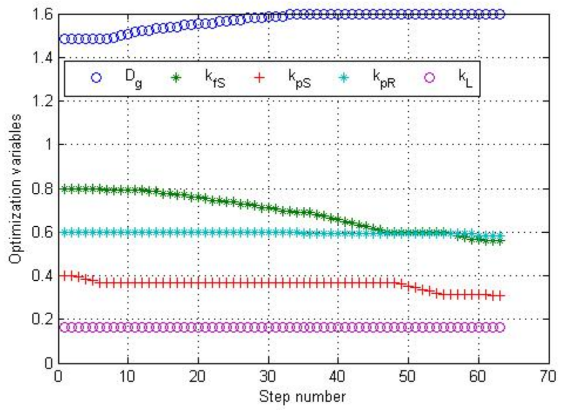

Fig. 9. Optimization variables

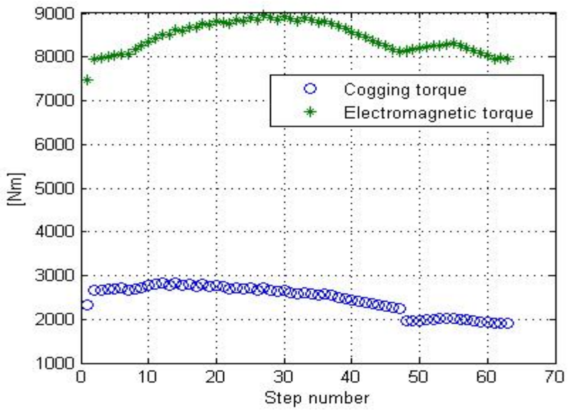

Fig. 10. Electromagnetic and cogging torque per phase evolution

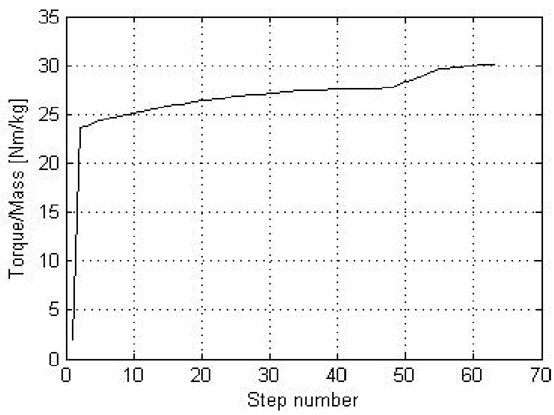

Fig. 11. Maximum Torque/Mass objective function evolution

Taking all these into account, it is clear that an advanced design optimization based on numerical algorithms has to be used in order to improve the system's performance.

Hooke-Jeeves method was selected for the present application. It is a so called pattern search method [10, 11], which, for each iteration, initially defines a pattern of points by moving each parameter one by one, so as to optimize the objective function. The entire pattern of points is then shifted or moved to a new location determined by extrapolating the line from the old base point in the *m* dimensional parameter space to the new base point.

For the optimization program, the objective function is represented by the ratio of torque versus mass, torque density.

In Figs. 9, 10 and 11, the evolution of the most important parameters is presented. It can be seen that the electromagnetic torque increased from 7367 Nm to 7960 Nm giving a torque per mass ratio of about 30 Nm/kg.

VI. Conclusions

In this paper, a PMTFM with a simple structure and a quasi 2D flux pattern is proposed for a ship drive system. The PMTFM phase module design procedure is based on a specific analytical algorithm.

A 3 MW drive system for ships based on permanent magnet transverse flux motors with a simple structure is proposed. Its performance are analyzed via a three dimension (3D) magnetic field calculation by using the Cedrat FLUX 3D environment.

An optimization procedure based on the analytical model is implemented, the objective function considered being the maximum torque density.

In conclusion it can be said that the PMTFM can be a good solution in a ship propulsion drive system, thanks to its high torque density.

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