PERMANENT MAGNET TRANSVERSE FLUX MOTOR (PMTFM) FOR A SHIP PROPULSION DRIVE SYSTEM

Emil PADURARIU  
Technical University of Cluj-Napoca

Kay HAMEYER  
RWTH Aachen University

Ioan Adrian VIOREL  
Technical University of Cluj-Napoca

Liviu SOMESAN  
Technical University of Cluj-Napoca

REZUMAT. Motorul cu magneti permanenti si flux transversal (PMTFM) comparativ cu motoarele electrice conventionale este caracterizat printr-o densitate de putere mare si constructie modulara specifica. PMTFM de obicei, are o constructie complicata, este un adevarat model tridimensional. In această lucrare, un PMTFM cu o structură simplă este propus pentru un sistem de propulsie a navelor iar performantele sale sunt verificate printr-o analiză FEM 3D. Rezultatele obținute sunt în cele din urmă comentate.

Cuvinte cheie: design, motor cu flux transversal, propulsie navală.

ABSTRACT. The permanent magnet transverse flux motor (PMTFM) is characterized by power densities figures larger than the conventional electric motors and by a specific modularity. The PMTFM has usually a complicated structure with a true three dimensional (3D) pattern. In this paper, a PMTFM with a simple structure is proposed for a ship drive system and its performance checked via a three dimensions finite element method (3D-FEM) analysis. The obtained results are finally commented.

Keywords: transverse flux motor, ship propulsion, optimal design.

1. 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, as [1, 2, 3]. The propulsion power varies with the size of the vessel, from some few MW for smaller ferries up to 30-40 MW for large cruise liners.

The permanent magnet transverse flux motor (PMTFM) has two important advantages: larger power density than the conventional machines and a modular construction [4, 5, 6]. Usually the PMTFM has a complicated structure and a large leakage flux due to its armature homopolar pattern, which means a low power...
factor value. If the leakage flux cannot be drastically reduced, the construction can be simplified and an example is constituted by the sample PMTFM topology considered here and previously presented in [6, 7]. For this particular PMTFM an analytical sizing-dimensioning algorithm was developed [6, 7, 8, 9] and it was fully validated by the results obtained via a three dimensions finite element method (3D-FEM) analysis done for a sample machine operating as motor [6].

The influence of the permanent magnet (PM) dimensions on the machine performance and the influence of the rotor pole shape and dimensions on the leakage flux were studied, by employing a 3D-FEM analysis in [6] and respectively [6, 7]. In both cases few simulations could be done by changing each dimension on every new calculation due to the very large computer time involved. The results show that an advanced design optimization, based on a numerical algorithm would be necessary to obtain a machine with improved performance. The 3D-FEM analysis is useful only in checking the results obtained via the optimization procedure. Consequently, by using the sizing-design algorithm given in [6], an optimization procedure, based on Hooke-Jeeves method [10, 11, 12] is developed and the obtained results for different optimization objectives are presented in this paper.

In the second part of the paper, a particular sample PMTFM is described briefly and some hints on the machine simplified model and its sizing-designing algorithm are given. In the third part the basics of the optimization procedure, for the considered sample PMTFM, is presented, evincing the optimization algorithm structure, the optimization variables and the imposed constrains. The conclusions and the final considerations end the paper.

2. PMTFM STRUCTURE AND DEDICATED SIZING ALGORITHM

The quite novel rotating PMTFM topology discussed here was introduced in [6]. This topology assures a construction very simple with a quite large enough power density and an improved power factor. The structure of the proposed PMTFM, Fig. 1, one phase module, is derived from a transverse flux reluctance machine [4], the only important change being made in the rotor where axially magnetized PMs with alternating polarity as seen in Fig.1, are placed in a flux concentrating topology, between rotor poles.

In Fig. 1 is presented only a part of one phase, containing a ring-shaped coil, two stator pole pieces and three rotor pole pieces.

The stator core is made of C shaped pole pieces which are assembled from separate parts. The phase coil, of circular type, is placed in its room on a part of the stator pole piece, the second part completing the stator pole piece assemble. The stator and the rotor case have special holes where are introduced the poles to facilitate the machine assemble and consolidate the whole mechanical structure.

The developed sizing-design procedure [6] is presented fully in the flow chart given in Fig. 2. The basic flux calculation is done by employing simplified magnetic equivalent circuits.

In order to avoid the PMs’ demagnetization process the air-gap flux produced by PMs in aligned position must be larger than the air-gap flux produced by stator mmf , rotor in the same aligned position.

The torque, power, losses, efficiency are calculated in usual manner [6], while the power factor is obtained by using (1).

\[
\cos(\varphi) = \frac{P_{\text{out}} + P_{\text{loss}}}{U_{\text{ph}} I_{\text{ph}}}
\]

(1)

\(P_{\text{out}}\) and \(P_{\text{loss}}\) are the output power and respectively the total losses while \(U_{\text{ph}}, I_{\text{ph}}\) are the phase voltage and current. The heating is calculated by using thermal equivalent circuit as explained in [6].
3. OPTIMIZATION BASICS

3D FEM can be used to study the influence of the PM’s dimensions or other geometry data on the machine’s performances. The sizes had to be modified one by one and the simulation repeated for each resulted structure. Even if the results provided by FEM are accurate, this approach to optimize the geometry proved to be highly time consuming and inefficient. Therefore, it is clear that an advanced design optimization based on numerical algorithms has to be used in order to improve the machine’s performance. A large number of such optimization techniques exist in the literature and choosing the right method depends on the nature of the problem, the number of variables, constraints or objectives.

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 n dimensional parameter space to the new base point.

The modified Hooke-Jeeves algorithm [11] has the following structure:

i) Choose the set of variables that will be modified in the process and for each variable define a starting value, a minimum and maximum limit and an increment coefficient.

ii) Set special limitations of other variables that can be altered during the optimization process.

iii) Define the objective function.

iv) Set the initial and final value of the global increment. The given values will be initially modified with a larger increment, which will be further decreased in order to refine the search space.

v) Compute the dimensions and the magnetic and electric values, following the analytical procedure, and evaluate the objective function.

vi) Make a movement along to each optimized variable in positive and negative direction, (grid search), using the initial step. Compute the objective function and its gradient and use the partial derivative to find the worse and the track points.

vii) Make an optimized variable movement with a step until the objective function is decreasing.

viii) Repeat the movement and use the gradient to find the better direction to the new point.

ix) Reduce the variation step and repeat the previous steps. The algorithm stops when the research movement cannot find better points even with the smallest variation step. The found value represents a local minimum and different values may be found by changing the initial starting points.

In the case of the proposed PMTFM design, a set of six optimization variables were selected: (air-gap diameter, $D_g$, stator pole pieces number, $Q_s$, stator and rotor pole width factor, $k_{ps}$, $k_{pr}$, stator pole axial length factor, $k_{as}$, and aspect ratio $k_L$). Excepting the air-gap diameter, which is calculated, all other variables values were taken based on experience so it’s important to change their value in order to improve the machine’s
Inferior and superior limits are set for each variable to keep the structure functional, for example the pole width to pole pitch ratio $k_{ph}$, $k_{ph}$, cannot be greater than 0.8 since it will lead to large leakage flux values. The search step varies for each optimizing variable, so a specific increment is introduced and is multiplied by the global increment to give the search step. For example, since the search step for the stator number of pole pieces has to be an integer, the specific increment is set to 1000, while the minimum value of the global increment is 0.001. The specific increment of the other optimizing variables will be much smaller in order to obtain a lower search step. The global increment is initially set to 0.008 and will decrease to 0.004, 0.002 and to a minimum value of 0.001.

The following constrains are set, and a penalty coefficient is asserted to each and included in the objective function:

- The output power has to be greater than the design specified value;
- PM’s demagnetization has to be prevented by assuring the adequate length of the permanent magnets;
- The flux density in the air-gap has to be smaller than the maximum specified value;
- The flux density in the stator teeth has to be lower than the maximum imposed value;
- The machine should not overheat.

4. PMTFM FOR SHIP PROPULSION

The sizing-designing algorithm developed and applied in the case of a low power sample PMTFM can be easily extended for large power PMTFM as are that used for ship propulsion. Before to estimate the dimensions and the characteristics of the motor, must be chosen the drive solution from the many possible variants. To use only one three or six-phase motor it is not a good idea since it will have a very large air-gap diameter and consequently poor performance. It means that the entire drive system should be obtained by employing a certain number of small motors mounted on the same shaft and supplied and controlled in parallel. The six phase motor would be favorable due to the reduced cogging torque, but the inverter is more complicated and it costs more than a three phase one. Consequently the adopted solution was a set of three phase motors, each having an air-gap diameter smaller than one meter in order to assure the adequate parameters and performance. The three phase basic layout of the PMTFM is given in Fig. 3.

![Fig. 3. Basic three phase PMTFM layout](image)

The scaling procedure can be applied to obtain a first draft for a new motor once one basic motor is known by its dimensions and performance [6]. The original machine is the one calculated in [6], having the rated data: $P_{out}=1.2$ kW, $m=2$ phases, 15 stator poles, 30 rotor poles and the rated speed of 200 rpm.

Considering that a one phase module has 45 kW, than the scaling factor results:

$$k^3_{sc} = \frac{P_{out}^*}{P_{out}} = 4.217$$  \hspace{2cm} (2)

where the basic motor, the one previously analyzed has 0.6 kW per module at a phase voltage and current of 230 V and 5 A. The input voltage, current and power for the scaled motor are:

$$V_{ph}^* = k^{2.5}_{sc} \cdot V_{ph} = 4009 \text{ V}$$  \hspace{2cm} (3)

$$I_{ph}^* = k_{sc} \cdot I_{ph} = 21.086 \text{ A}$$  \hspace{2cm} (4)

$$S_{ph}^* = V_{ph}^* \cdot I_{ph}^* = 86.25 \text{ kVA}$$  \hspace{2cm} (5)

which leads to a power factor $p.f.=0.53$ that is quite reasonable.

Since the pole number must be increased in the case of large power PMTFM to be used for ship propulsion, and consequently the phase number of turns is changed to, the large power PMTFM must be designed adequately, the scaled values being only informative.

The dimensions and main input/output values for the PMTFM resulted as: $Q_s=40$ poles, $Q_R=80$ poles,
$D_g=0.927\text{m}$, $l_{st}=0.130\text{m}$, $\tau_S=0.073\text{m}$, $\tau_R=0.036\text{m}$, $b_{ps}=0.026\text{m}$, $b_{pr}=0.021\text{m}$, $l_{PM}=0.027\text{m}$, $h_{PM}=0.070\text{m}$, $V_{ph}=4000\text{V}$, $I_{ph}=25\text{A}$, $T=1942\text{Nm}$, $P_{out}=45\text{kw}$, $\eta=0.83$, p.f.=0.53, $n=200\text{rpm}$ where $Q_{S/R}$ – number of stator/rotor poles, $D_g$ – air-gap average diameter, $l_{st}$ – module’s stack length, $\tau_S$, $\tau_R$ – stator and rotor pole pitch, $b_{ps}$, $b_{pr}$ – stator and rotor pole width, $l_{PM}$ – permanent magnet length, $h_{PM}$ – permanent magnet height, $T$ – output torque, $P_{out}$ – output power, $\eta$ – efficiency, p.f. – power factor, $n$ – rated speed.

The dimensions were obtained after an optimizing process, considering as objective the function of maximum torque per mass ratio. The variation of the objective function and of the optimizing variables is given in Fig. 4 and Fig. 5 respectively.

The 3D-FEM analysis was performed on a one pole symmetrical part, as seen in Fig. 6 where a flux density map is given too.

The results obtained after the optimizing process were checked via a 3D-FEM analysis, the torque and the cogging torque per module being presented in Fig. 7 and Fig. 8.

The comparison between the 3D-FEM calculated values, $T_{FEM}=2400\text{Nm}$ $T_{cFEM}=300\text{Nm}$ with the values resulted after the optimizing process $T_o=2154\text{Nm}$ $T_{cgo}=474\text{Nm}$ shows quite a good agreement.
5. CONCLUSIONS

The idea of the ships’ electric propulsion originated about one hundred years ago but only in the last decades electric propulsion of the ships took an important impetus. For the ships’ propulsion are employed almost all conventional electric motors and some special ones. The PMTFM, as a competitor in the domain of the electric ships propulsion, has two important advantages: larger power density than the conventional electric machines and a modular construction. Two important back points should be evinced: a quite small value of the power factor which means large rate of kilovoltamperes per kilowatts and a limited air-gap diameter. For the PMTFMs a too large air-gap diameter, as for all permanent magnets excited electric machines, means a decrease of their performance and an increase of the leakage flux.

The solution, proposed in the paper, consists of a PMTFM with reduced air-gap diameter. For such a motor, with quite a small power, a design was adequately done and an optimizing process based on Hooke-Jeeves method was applied too. The final resulted dimensions were checked via a 3D-FEM calculation to obtain the final values.

A weak point of the Hooke-Jeeves method might be that it finds local minimum solutions. For the case presented here, the size of the objective function was not that large (only 6 variables) and their limits were well set, the dimensions of the searching space are not large and consequently the solution reached is pretty close to global minimum.

The most important aspects in order to get accurate results with the optimizing procedure, are actually the initial steps, when the problem is defined. In consequence, it is vital to select the best optimizing variable set, the right constrains and to have a correct sizing-designing algorithm. The PMTFM design presented here was based on the analytical design which was validated by the 3D FEM results. In conclusion, the optimizing method can be considered a reliable one in reaching its objectives.

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REFERENCE