# Design of a Permanent Magnet Flux-Switching Machine

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# Design of a Permanent Magnet Flux-Switching Machine

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***Abstract*— In this paper a typical structure of a permanent magnet flux-switching machine (PMFSM) with 12 stator poles and 10 rotor poles is considered. The PMFSM design procedure is based on a specific analytical algorithm, which is validated by the results obtained via a two dimensions finite element method (2D-FEM). Also an optimal design procedure, based on Hooke-Jeeves method, applied to a permanent magnet flux-switching machine is implemented. Different objective functions, as maximum torque density and maximum efficiency were considered.**

***Keywords*— permanent magnet flux-switching machine, design optimization.**

## I. INTRODUCTION

The permanent magnet flux-switching machine (PMFSM) has a short history and is a relatively new category of electric machines. The basic model of PMFSM was described in [1], where Rauch and Johnson proposed a new type of motor with permanent magnets placed in the stator in order to better control their temperature, and was brought back to the scene [2] due to a multitude of reasons, including the limit of permanent magnetic materials and the necessity of sophisticated computer-aided motor design tools.

The PMFSM's have been receiving significant attention in the last two decades thanks to the advantages of high power density, mechanical robustness and torque capability [3-6]. Furthermore, it can be used with success in harsh operating environments, such as aerospace, automotive and wind energy applications [7, 8, 9].

The PMFSM is very similar to the doubly salient permanent magnet (DSPM) machine or to the flux reversal machine (FRM) [4, 5].

This paper takes into consideration a typical three phase structure of a permanent magnet flux-switching machine with 12 stator poles and 10 rotor poles. For this structure an analytical sizing-designing algorithm is developed and is validated by the results obtained via a two dimensions finite element method (2D-FEM) analysis done for a sample machine operating as a motor. In order to obtain a machine with improved performance, an optimization procedure based on Hooke-Jeves method [10, 11] is developed. The computed results for some considered optimization objectives can provide valuable information on the machine's behavior.

The conclusions and the final considerations in the case of the sample of PMFSM end the paper.

## II. PERMANENT MAGNET FLUX-SWITCHING MACHINE STRUCTURE AND DEDICATED SIZING-DESIGNING ALGORITHM

Fig.1 shows the permanent magnet flux-switching machine structure. As it can be seen, the rotor of the machine is similar to that of a switched reluctance motor, the number of rotor poles and stator poles differing by two, 10 rotor poles and 12 stator poles. Also the concentrated windings employed in the PMFSM's are similar to those in the switched reluctance motor (SRM).

The only difference compared to the SRM's consists of the configuration of the stator which contains 12 segments of ”U” shape magnetic cores, between which 12 pieces of permanent magnets are inset, the direction of magnetization being reversed from one magnet to the following.

The stator winding comprises concentrated coils, each coil being wound around a pole which contains two adjacent laminated segments and a permanent magnet. This fact leads to low copper loss due to the short end-windings.

In this paper the developed sizing-designing algorithm is introduced.

The main designing specifications for the sample PMFSM are:

- Rated output power $P_{out} = 30$ kW
- Rated phase voltage $U_f = 230$ V
- Rated speed $n = 3000$ rpm

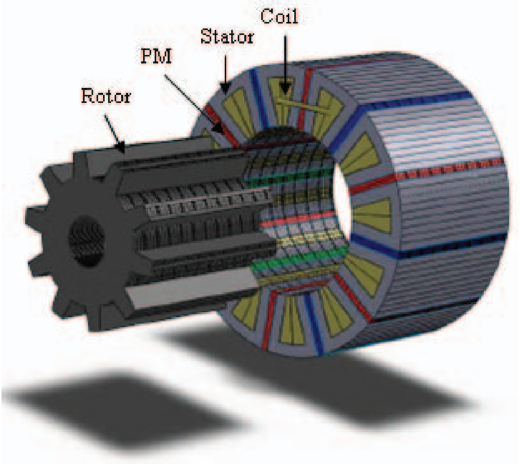

Fig. 1. A 3-phase 12/10 PMFSM prototype

The PMFSM analytical design is based on an equation which gives the machine air-gap diameter $D_g$ function of the design specifications as rated output power $P_{out}$ and speed $n$, of adopted material properties and of some sizing coefficients $k_L$, $k_E$. The performance related values, efficiency $\eta$, power factor $\cos\varphi$, maximum air-gap flux density $B_{gmax}$ and stator electrical loading $A_s$ must be chosen considering the existing data, the machine topology and the permanent magnet type.

$$D_g = \sqrt[3]{\frac{P_{out}\cdot Q_s}{\sqrt{2}.\cdot \pi^3 Q_R \eta \cdot k_L k_E \cos\phi \cdot n \cdot B_{g\max}\cdot A_S}} \tag{1}$$

where the parameters $Q_S$ and $Q_R$ are the number of stator and rotor poles.

The stack length is determined by the following equation:

$$l_{st} = k_L \cdot D_g \tag{2}$$

where $k_L$ is the aspect factor.

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

$$N_t = \frac{Q_S \cdot E}{\sqrt{2}\cdot \pi^2 \cdot k_L \cdot N_R \cdot D_g{}^2 \cdot n \cdot B_{g\max}} \tag{3}$$

where the phase *rms* induced **emf** $E$ is:

$$E = N_t \cdot 2 \cdot \pi \cdot n \cdot \frac{N_R}{\sqrt{2}} \cdot l_{st} \cdot \pi \cdot \frac{D_g}{N_S} \cdot B_{g\max} \tag{4}$$

The maxium air-gap flux density $\Phi_{max}$ in aligned position is:

$$\phi_{\max} = B_{g\max\cdot} A_{coil} = B_{g\max} \cdot l_{st} \cdot \frac{\pi \cdot D_g}{N_S} \tag{5}$$

Finally, the electromagnetic torque of the PMFSM can be calculated with:

$$T = \frac{3}{2} \cdot B_{g\max} \cdot Q_R \cdot \phi_{\max} \cdot I_f \tag{6}$$

The stator poles dimensions are determined from equations (7)-(9), the same ratios being valid for the stator poles by changing $Q_S$ to $Q_R$ and, adequately, all the sizing factors:

$$\tau_s = \pi \cdot \frac{D_g}{Q_S} \tag{7}$$

$$b_{pS} = k_{pS} \cdot \tau_S \tag{8}$$

$$b_{slS} = \tau_S - b_{pS} \tag{9}$$

where $\tau_S$ is the rotor pole pitch, $b_{pS}$ is stator pole width and $k_{pS}$ is stator pole width factor.

In order to improve the torque value and to reduce the cogging torque, a suboptimal procedure was conducted via 2D-FEM. The optimal value of the stator PM width $b_{PM}$ is obtained for:

$$b_{PM} = \frac{\tau_S}{5} \tag{10}$$

TABLE I
MAIN GEOMETRIC DIMENSIONS AND PARAMETERS OF PMFSM

| | | |
|---|---|---|
| Number of rotor poles, $\mathbf{Q_R}$ | - | 10 |
| Number of stator poles, $\mathbf{Q_S}$ | - | 12 |
| Machine‘s outer diameter, $\mathbf{D_{out}}$ | m | 0,277 |
| Shaft diameter, **dax** | m | 0,045 |
| Air-gap diameter, $\mathbf{D_g}$ | m | 0,159 |
| Air-gap length, **g** | m | 0,0007 |
| Stator PM height, $\mathbf{b_{PM}}$ | m | 0,008538 |
| Rotor pole pitch, $\boldsymbol{\tau_R}$ | m | 0,0497 |
| Rotor pole width, $\mathbf{b_{pR}}$ | m | 0,01457 |
| Stator pole pitch, $\boldsymbol{\tau_S}$ | m | 0,041832 |
| Stator pole width, $\mathbf{b_{pS}}$ | m | 0,011418 |
| Stator slot height, $\mathbf{h_{slS}}$ | m | 0,04612 |
| Rotor yoke height, $\mathbf{h_{yR}}$ | m | 0,03475 |
| Stack length, $\mathbf{l_{st}}$ | m | 0,159 |
| Stator yoke height, $\mathbf{h_{yS}}$ | m | 0,01249 |
| Number of turns per phase, $\mathbf{N_t}$ | - | 36 |
| Phase current, $\mathbf{I_f}$ | A | 58 |

The initial peak air-gap flux density was taken $B_{gmax}$ = 1.55 T while the PM of NdFeB type has residual flux density $B_r$ = 1.2T and coercive field intensity $H_C$ = 910 kA/m.

The main dimensions of the flux switching machine calculated using the algorithm presented here are evinced in table I.

Obviously, the sizing procedure may not conduct always to the best results, but it gives quite important information for the designer.

## III. 2D-FEM ANALYSIS

The 2D-FEM analysis, by using the Cedrat FLUX 2D environment, was employed in order to check the analytically results obtained via the sizing-designing calculation.

Fig. 2 shows the open-circuit air-gap field distributions for the whole structure and obviously, the flux distribution is far from sinusoidal and exhibits significant harmonics, similar to that of switched reluctance machines due to doubly salient structure. It can be seen that due to the flux focusing, the stator tooth in the PMFSM is quite saturated.

The 2D-FEM calculated radial-component of the air-gap flux density is shown in Fig. 3. As it is seen, the maximum air-gap flux density exceeds 2 T and the air-gap field distribution of a PMFSM is non-sinusoidal.

The 2D-FEM computed electromagnetic torque and cogging torque are displayed in Figs. 4 and 5 versus rotor position. The rotor was moved over a complete electrical period with an increment of 1 mechanical degree, one electrical period corresponding to 36 mechanical degrees.

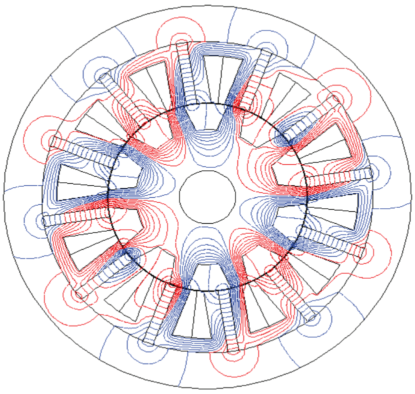

Fig. 2 Map of flux distribution

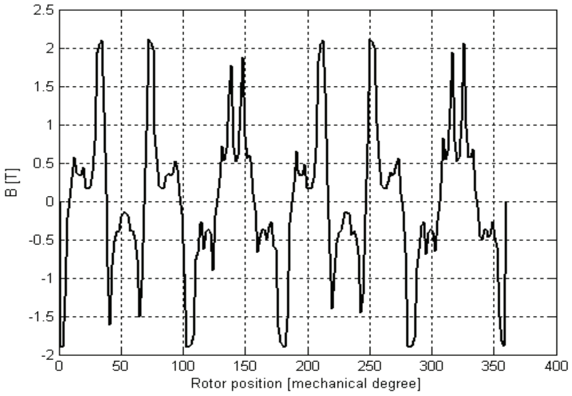

Fig. 3 Air-gap field distribution of the PMFSM.

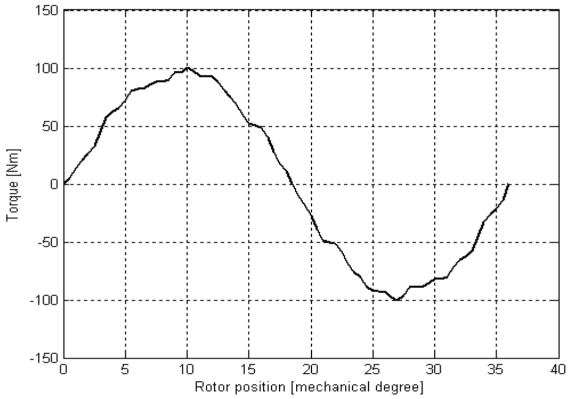

Fig. 4 Electromagnetic torque of the PMFSM.

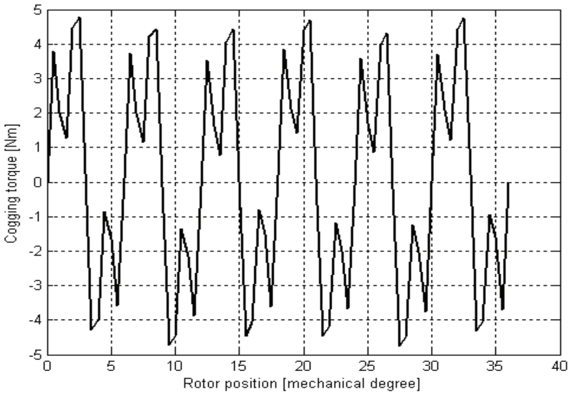

Fig. 5 Cogging torque of the PMFSM.

## IV. DESIGN OPTIMIZATION

Even if the results provided by 2D-FEM are accurate, this approach to optimize the geometry proved to be highly time consuming and inefficient. 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.

In this case, the Hooke-Jeeves method was selected. It is a 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. 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.

In the case of the proposed PMFSM design, a set of six optimization variables were selected: air-gap diameter, $D_g$, permanent magnet width $b_{PM}$, stator and rotor pole width factor, $k_{pS}$, $k_{pR}$, stator pole axial length factor, $k_{fS}$, and aspect ratio $k_L$.

For the optimization program, the objective functions, as maximum torque density and maximum efficiency were considered.

The variation of optimized variables and the objective functions are given in Figs. 6-11.

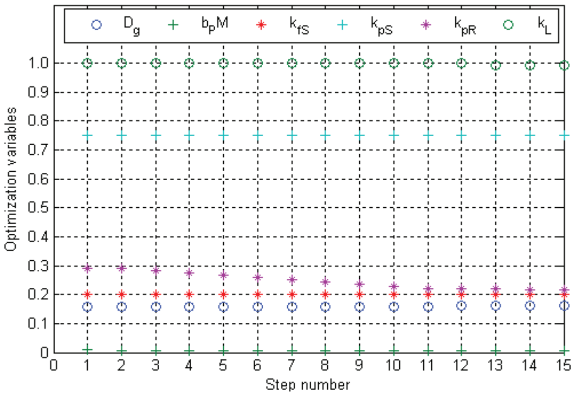

Fig. 6 Optimization variable evolution.

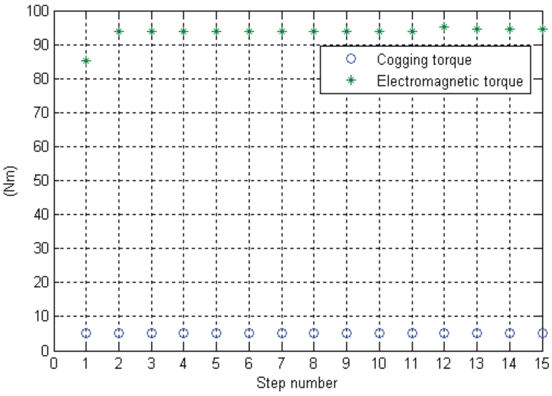

Fig. 7 Electromagnetic and cogging torque evolution.

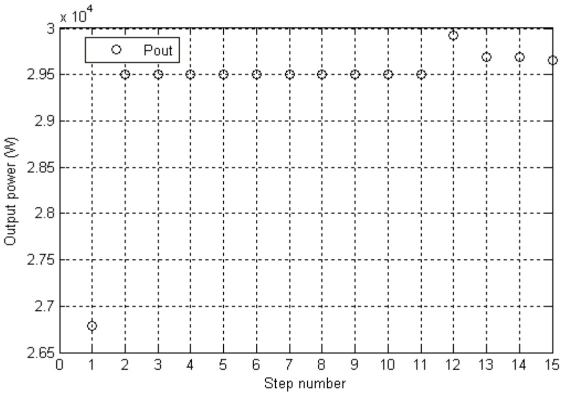

Fig. 8 Output power evolution.

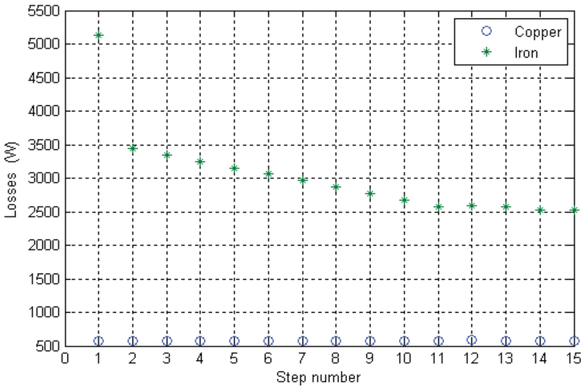

Fig. 9 Losses evolution

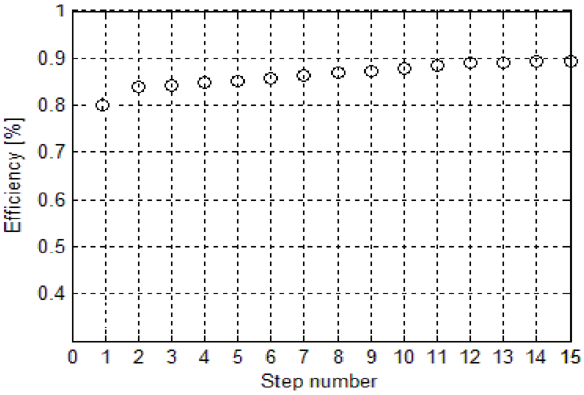

Fig. 10 Efficiency objective function.

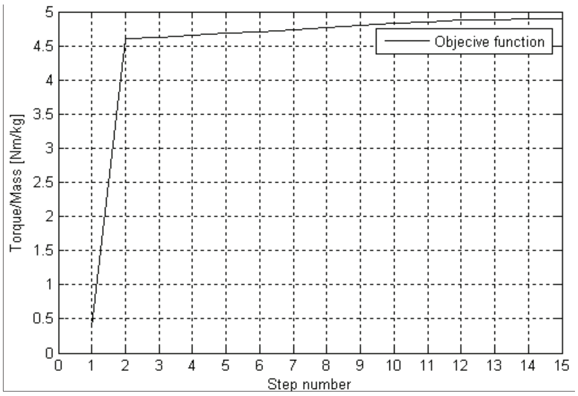

Fig. 11 Maximum torque density objective function.

## V. CONCLUSIONS

In this paper a typical structure of permanent magnet flux-switching machine (PMFSM) with 12 stator poles and 10 rotor poles was proposed. The PMFSM design procedure is based on a specific analytical algorithm and it was validated by the results obtained via a two dimension magnetic field calculation (2D-FEM) by using the Cedrat FLUX 2D environment.

In order to obtain a machine with improved performance, an optimization procedure based on Hooke-Jeves method was developed and different objective functions were considered.

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.

In conclusion, the optimizing method can be considered a reliable one in reaching its objectives.

## ACKNOWLEDGMENT

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