FINITE ELEMENT ANALYSIS OF THE USEFUL MAGNETIC FLUX OF A LOW SPEED PMSG

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Lucrarea de față prezintă o analiză efectuată asupra unui generator sincron cu magneți permanenți privind influența parametrilor geometrici ai secțiunii transversale a maşinii, respectiv a proprietăților de material asupra fluxului magnetic inductor util. Se au în vedere influența deschiderii crestăturii statorice, a lățimii dintelui statoric, a dimensiunilor magnetului permanent. Lucrarea include de asemenea şi o analiză a influenței proprietăților materialului feromagnetic din care sunt confecționate tolele statorice ale generatorului asupra fluxului magnetic inductor util, evidențiindu-se cel mai indicat tip de material magnetic. Calculele au la bază metoda elementului finit în aproximare 2D, rezultatele fiind utile în proiectarea optimală a maşinilor sincrone cu magneți permanenți.

This paper presents an analysis of a permanent magnet synchronous generator regarding the influence of various cross-section geometric parameters of the machine and of the material properties on the useful magnetic flux. The parameters taken into consideration in the analysis are the stator slots opening, tooth width, and permanent magnet dimensions. An influence analysis of the material properties of the magnetic core laminations on the useful magnetic flux is also carried out, to find out the most suitable type of magnetic material. The calculations are based on the Finite Element Method in 2D approach, the results being useful in the optimal design of permanent magnet synchronous machines.

Keywords: permanent magnet synchronous machine, finite element analysis

1. Introduction

Permanent Magnet Synchronous Generators (PMSGs) are widely used for wind conversion systems [1]-[4]. Among their advantages we can mention the high efficiency and power factor, the stable and reliable operation and the lack of additional DC excitation supply [5], [6]. In many cases the electric generators

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used in wind systems are mechanically coupled to the main shaft of the wind turbine eliminating the speed multiplier. The elimination of speed multiplier is justified by the fact that this component has an important size, a difficult maintenance and it is an important source of noise and faults. In this case, the generator should operate at low speeds, having many pole pairs and a large overall size and weight.

This paper presents an analysis of a PMSG regarding the influence of cross-section geometry parameters on the useful magnetic flux of the machine. The geometrical parameters taken into account are: stator slots opening and stator tooth width (by maintaining the same stator teeth pitch and slot area) and permanent magnet size (by maintaining the same magnet volume). An influence analysis of the material properties (several standardized magnetic materials are analyzed) of the stator core on the useful magnetic flux is also presented in the paper. The numerical investigations presented in the paper are based on the 2D Finite Element Method (FEM) implemented in the Flux software package.

The influence analysis detailed hereafter is useful for maximizing the inductor useful magnetic flux of the generator, (by keeping the same diameter of its rotor and stator) that may lead to an efficient use of the generator active materials [7] - [9].

2. Generator description

The machine studied in the paper is a three-phase PMSG with the following characteristics: rated power 3 kW, rated voltage 3 x 380V (stator star connection), rated speed 240 rpm, rated frequency 52 Hz.

The analyzed PMSG has 13 pole pairs on the rotor and 36 stator slots. Fig. 1 shows a cross-section of the considered generator.

The permanent magnets of the PMSG are of NdFeB type, with relative magnetic permeability μ_r = 1.1 and remnant magnetic flux density B_r = 1.044 T, unidirectionally magnetized. The ferromagnetic armatures length is 35 mm and the air-gap length is 0.5 mm.

The numbers of stator slots (Z = 36) and poles (2p = 26) of the PMSG were chosen so as to obtain a small value (2 in our case) of their greatest common divisor, Fig. 1. By this measure we ensure that the PMSG provides a very low value of the cogging torque, which is an important factor for any wind generator. Cogging torque has only negative effects on wind generators such as: noise and vibrations that lead to increased mechanical losses [10], [11], increased cut-in speed of wind turbines [12], higher harmonics in the electromotive force waveform [13], mechanical shaft unbalance [14] etc.

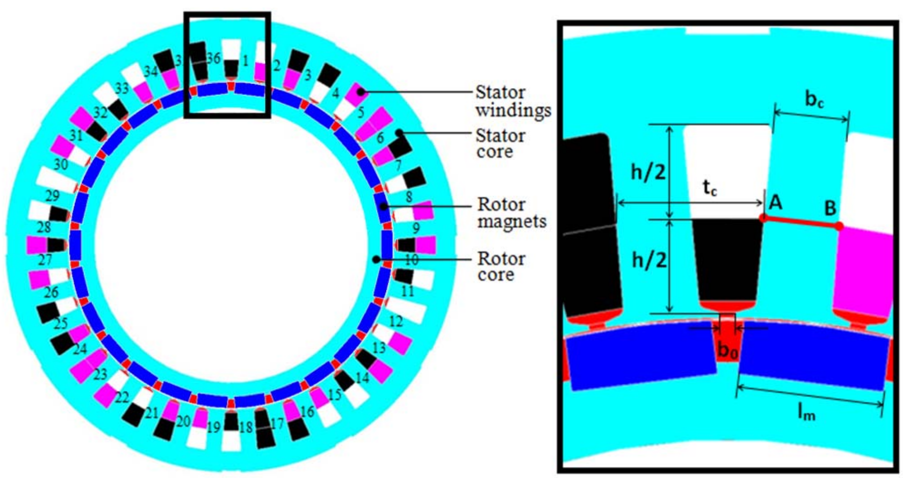
The studied PMSG have trapezoidal slots with rounded corners and stator teeth with parallel walls. The three-phase stator windings have 72 coils, 24 coils/phase. Each coil has an opening of one teeth (i.e. tooth winding) as shown in Fig. 1, in each stator slot being placed two coil sides.

The stator winding has a special structure with a fractional number of slots per pole and phase *q,* whose expression is given by:

$$q = \frac{Z}{2mp} = \frac{36}{2 \cdot 3 \cdot 13} = 0.4615 \tag{1}$$

where *Z* is the number of stator slots, *m* is the number of phases and *p* the number of generator pole pairs.

The stator magnetic core is made of magnetic steel laminations of M600-50A type and the rotor magnetic core is made of common cast steel with weaker magnetic properties than the stator laminations.



a) b)

Fig. 1. Generator geometry: a) cross section through the generator, b - notation of main dimensions of the stator slot and tooth; the tooth are numbered from 1 to 36; t_c is the tooth pitch, h is the slot height, b_c is the tooth width, b_0 is the slot opening, l_m is the magnet width.

3. FEM calculation of electromagnetic flux density

The numerical analysis of the described PMSG is based on the magnetostatic field 2D model of the machine. This electromagnetic field regime characterizes computations domains with static bodies where the source of the magnetic field is represented by the electric conduction currents with constant density J and by permanent magnets with remnant magnetic flux density B_r, invariable in time [15].

The 2D computation domain shown in Fig. 1 is composed of several regions as follows: stator magnetic core, rotor magnetic core, rotor permanent magnets, stator windings, air-gap etc.

In order to calculate the useful magnetic flux of the studied generator, the only field source in the computation domain is represented by the permanent magnets, the reaction magnetic field being neglected. In this case, the partial differential equation that characterizes the magnetostatic field model of the generator is the following [16]:

$$rot\left(\frac{1}{\mu}\cdot rotA\right)=rot\left(\frac{1}{\mu}\cdot B_r\right) \tag{2}$$

where μ is the magnetic permeability and A the magnetic vector potential, that verifies the Coulomb's gauge:

$$divA=0 \tag{3}$$

Therefore, the magnetic vector potential is a solenoidal one. After computing the magnetic vector potential A, the magnetic flux density B can be calculated using the formula [17]:

$$B=rotA \tag{4}$$

The useful inductor magnetic flux φ is determined by the equation:

$$\varphi=BS \tag{5}$$

where S is the surface through which passes the magnetic flux and B is the average value of magnetic flux density corresponding to the surface S; this surface is determined as follows:

$$S=l_{AB}\cdot l_{Fe} \tag{6}$$

where l_{AB} is the length of segment AB marked in Fig. 1, and l_{Fe} is the axial length of the stator magnetic core.

The useful magnetic flux defined in (5) can be considered practically equal to the magnetic flux passing through a stator tooth. That is why the analysis procedure used in the paper is based on the evaluation of the average magnetic flux passing through a stator tooth and all further results will refer to this flux.

The finite element discretization of the computation domain is done using second order triangular elements with smaller size in the air gap region where the most part of the magnetic energy is concentrated, Fig. 2.

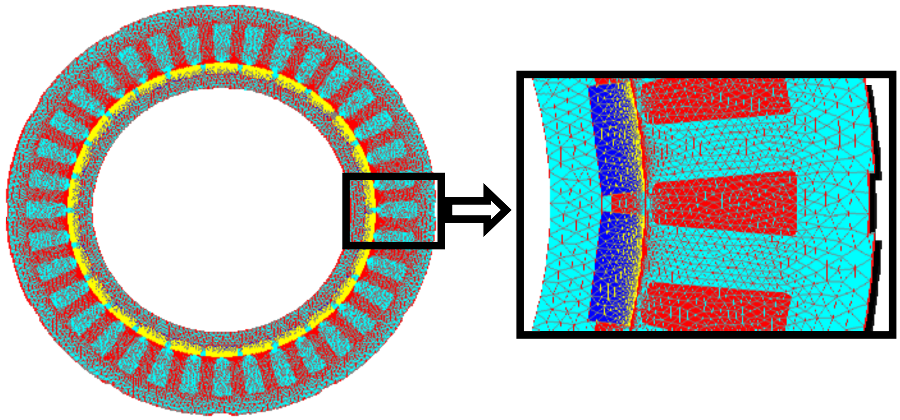


Fig. 2. Mesh on the computation domain and a detail of the mesh corresponding to the marked area

4. Influence of geometric parameters on the useful magnetic flux

The useful magnetic flux of the generator depends on its cross-section geometry and on the material characteristics of the magnetic cores of the machine. The paper analyzes the influence of slot opening, stator tooth width and permanent magnet width on the useful magnetic flux. The influence of the material properties of the stator magnetic cores on the useful magnetic flux is also analyzed. To determine their influence, the magnetic flux density is calculated for each case using the 2D FEM model of the machine.

By solving the magnetostatic field problem associated to the studied generator we obtain the magnetic flux density chart and the spectrum of magnetic field lines as shown in Fig. 3.

After solving the magnetostatic 2D problem for different relative rotor/stator positions (by rotating incrementally the rotor armature) we computed the corresponding useful magnetic flux passing through the surface bounded by AB segment.

The variation of the absolute value of useful magnetic flux versus rotor/stator angle (α) is shown in Fig. 4. The maximum value is obtained for an angle α = 1.92° that correspond to a geometrical position of the symmetry axis of the permanent magnet aligned to the symmetry axis of the tooth no. 1 in Fig. 1.

We can notice that the magnetic flux density differs from a tooth to another, its value depending on the tooth position with respect to the rotor permanent magnets, Fig. 4. For this reason the study will refer to a tooth situated in a position characterized by a maximum useful flux value (tooth no. 1 in Fig. 1).

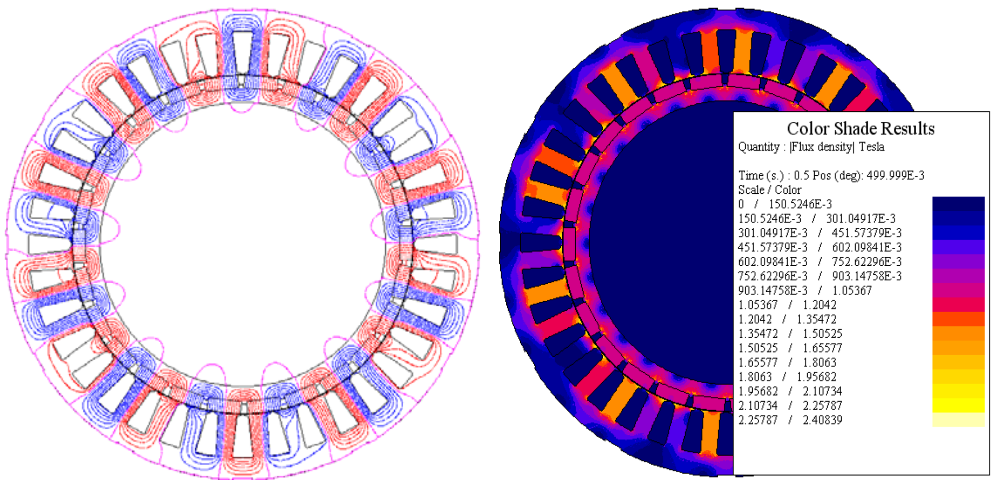


Fig. 3. Spectrum of the PMSG inductor magnetic field lines and chart of magnetic flux density

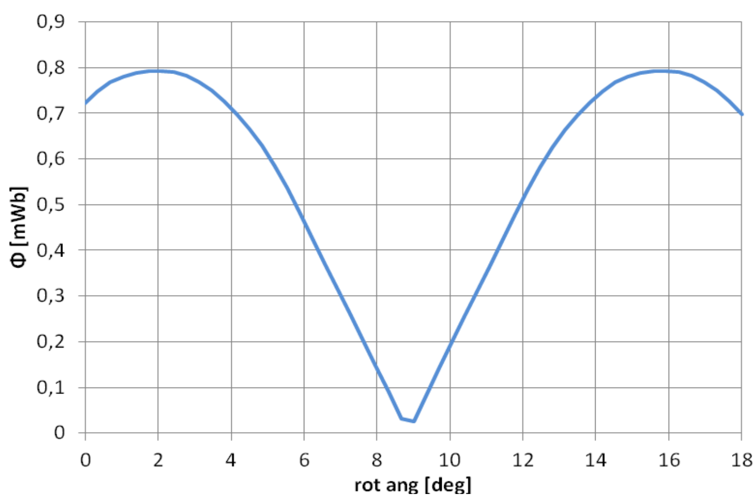


Fig. 4. Absolute value of useful magnetic flux versus rotor/stator angular position.

4.1. Influence of the stator slot opening

The stator slot opening is noted with b_0 in Fig. 1. To analyze the influence of this parameter on the useful magnetic flux φ, several values of this parameter are considered between 3.2 mm and 5.2 mm.

For each slot opening, the average magnetic flux φ is calculated along the surface bounded by the AB segment, the results being presented in Fig. 5.

We can notice that the stator slot opening has a small influence on the inductor magnetic flux value. Thus, if the slot opening varies from 3.2 mm to 5.2 mm, the useful magnetic flux decreases by approximately 0.58 %. This slight decrease of the useful magnetic flux can be justified by the fact that the increase of slot opening entails a larger leakage magnetic flux and thus a smaller useful magnetic flux.

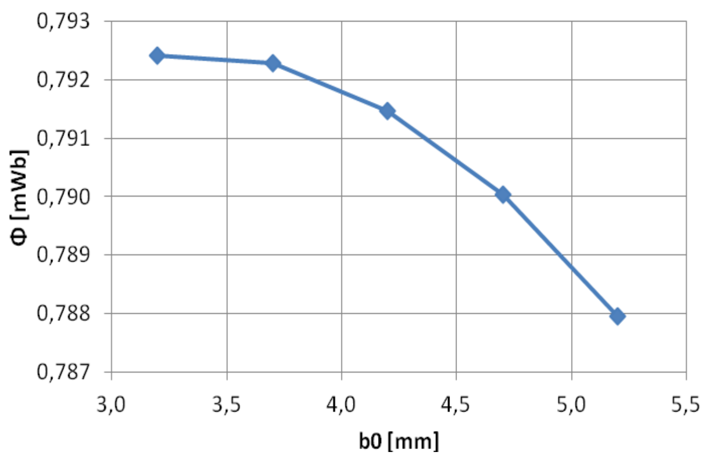


Fig. 5. Useful magnetic flux versus stator slot opening b_0.

4.2. Influence of the stator tooth width

We can see in Fig. 1 that the generator has trapezoidal slots with rounded corners and the stator teeth have constant width and parallel walls. To study the influence of the stator tooth width b_c on the useful magnetic flux, we consider the tooth pitch constant measured at half of its height (Fig. 1.b). Thus if the tooth width is reduced by a certain size the slot width will increase by the same size.

The values for b_c cannot be chosen randomly, because very narrow teeth can lead to their excessive saturation and very large teeth can lead to an excessive increase of current density in the stator windings.

For a pole pitch measured at the middle of the slot height t_c = 29 mm, a variation of tooth width b_c in the range (12 mm ... 15 mm) is acceptable.

By solving successive 2D magnetostatic applications for various teeth widths we obtain the dependence of the useful magnetic flux on this parameter, Fig. 6.

By studying the results we can see that the useful magnetic flux increases significantly, with about 9.6 %, with the increase of the tooth width from 12 mm to 15 mm.

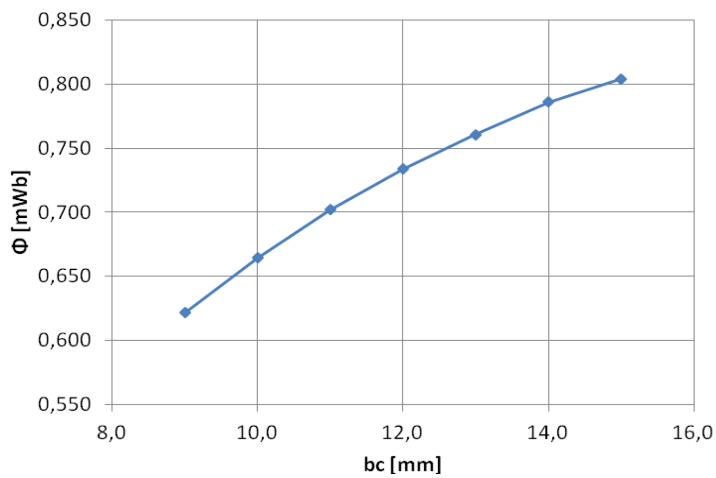


Fig. 6. Useful magnetic flux versus stator teeth width b_c.

4.3. The influence of the permanent magnet width

To obtain concluding results, the variation of the permanent magnet width was made by keeping constant the magnet cross-section area, i.e. by keeping constant the magnet volume. Thus if the magnet width decreases its thickness increases so as to keep unchanged the magnet cross-section area. The permanent magnet has the following characteristics: permanent magnet width is variable in the range (27 mm ... 31 mm), material NdFeB, unidirectionally magnetized. By successive numerical simulations for various values of the magnet widths we obtained the results shown in Fig. 7. By studying these results we can see that the useful magnetic flux increases with the permanent magnet width l_m (Fig. 7).

Thus, if the magnet width increases from 27 mm to 31 mm, the inductor magnetic flux increases by about 0.52 %. The reason for this weak increase is related to the magnetic flux path that in case of large width magnets it will be split on two or three teeth.

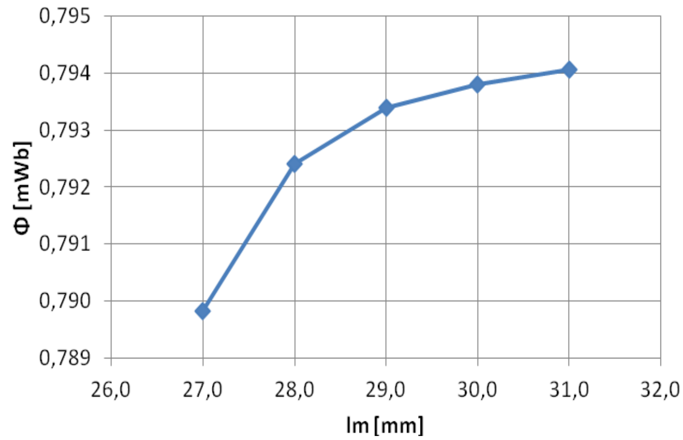


Fig. 7. Average useful magnetic flux versus permanent magnet width l_m.

5. Influence of magnetic characteristics of the generator armatures

The main magnetic characteristics of the stator ferromagnetic core are the initial relative magnetic permeability μ_r and the saturation magnetic flux density B_s. The computation algorithm based on FEM allows us to take into account the magnetic nonlinearities of the material used to build the generator armatures.

In Fig. 8 are presented three magnetization characteristics $B = f(H)$ of the magnetic armatures, corresponding to three different standardized magnetic steel laminations, M600-50A (reference material for this study), M400-50A, M800-50A. For all three cases the value of the magnetic flux density at saturation B_s is around 1.9T - 2T. The shapes of the magnetization characteristics are generated by the software package Flux, the three materials belonging to the software material database.

By solving the magnetostatic field problem for the three different magnetic materials we obtain the variation of the useful magnetic flux versus stator-rotor angle, as shown in Fig. 9.

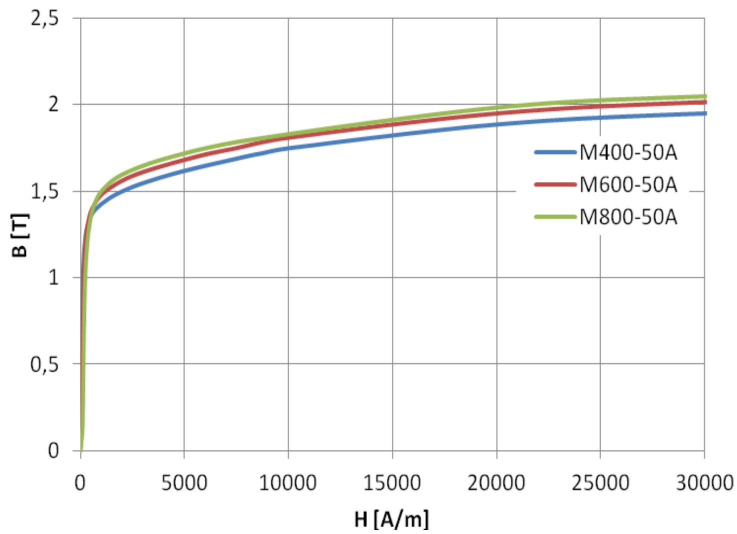


Fig. 8. Magnetization characteristics of stator magnetic cores laminations; M400-50A; M600-50A; M800-50A.

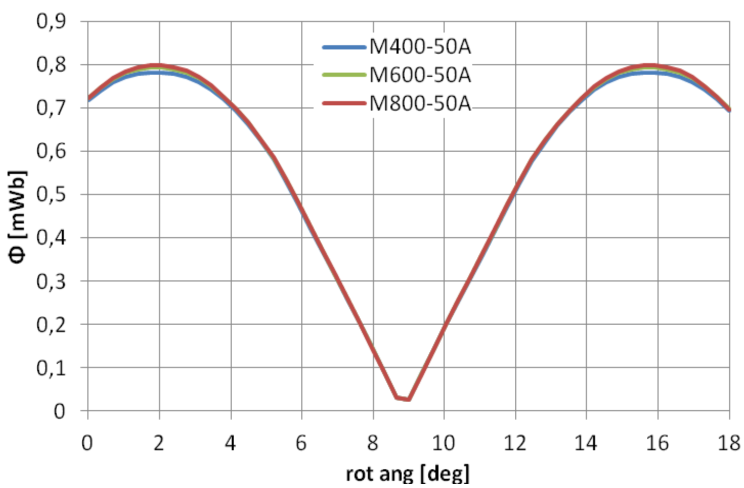


Fig. 9. Useful magnetic flux versus rotor/stator angular position for three electric steel types; M400-50A, M600-50A, M800-50.

The results emphasize a relative maximum difference between the results of about 1.28 %. This difference corresponds to the point characterized by maximum useful magnetic flux in the three cases. Therefore, the change of the magnetic material affects the useful magnetic flux of the PMSG but not in a very significant manner.

7. Conclusions

The FEM analysis carried out in this paper referred to a PMSG with a large number of poles that can used as electrical generator in direct drive wind power systems.

The research presented in the paper was focused on the influence analysis of several geometrical parameters of the machine (stator slots opening, stator tooth width for the same stator tooth pitch and slot area, permanent magnet width for the same magnet volume) and of the material properties (three standardized magnetic steel laminations types) of stator core on the useful inductor magnetic flux.

From construction point of view the studied PMSG has a larger useful inductor magnetic flux in case of smaller slots openings, of larger teeth width (for the same tooth pitch) and of wider permanent magnets (for the same magnet volume).

The paper shows also the optimal ranges of these parameters for which the useful inductor magnetic flux is maximized. The maximization of the inductor magnetic flux leads to a more efficient use of the generator active materials making it more competitive on the market. The numerical results presented in the paper are useful for the optimal design of PMSG.

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