Wind turbine permanent magnet synchronous generator magnetic field study

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Abstract. The paper shows a 2D finite element optimization method for a wind turbine permanent magnet synchronous generator (PMSG) transverse geometry. Keeping the same rotor diameter the generator's magnetic flux is maximized by changing the permanent magnets and rotoric slot opening dimensions. The studies show that for certain values of these dimensions the magnetic flux (flux linkage and mutual flux) has maximum values.

Key words

Synchronous generator, permanent magnet, simulation, optimization.

1. Introduction

From all the generators that are used in wind turbines the PMSG's have the highest advantages because they are stable and secure during normal operation and they do not need an additional DC supply for the excitation circuit (winding) [1] – [4]. Initially used only for small and medium powers the PMSG's are now used also for higher powers (because of their already mentioned advantages). The paper shows the study of the rotoric permanent magnets' magnetic flux [5] and the transverse generator's geometry influence over these fluxes. The modeling of the generator's magnetic field spectrum is done by using the finite element method and with the help of specialized software [6], [7]. The magnetic field is calculated by using the plane parallel hypothesis. This assumption influence the concluding remarks that rise from the study especially for the PMSG's that have a large (length) / (transverse diameter) ratio.

2. The generator's transverse section geometry

The studied PMSG has four poles. Its transverse section is depicted in Figure 1. The magnets are placed over a parallelepiped iron stump [5]. The spaces between the magnets (the rotoric slot opening) are filled by special shaped steel parts that create a closing path for the magnetic field. The magnetization direction of the permanent magnets is shown by the arrows that are placed inside them (Figure 1).

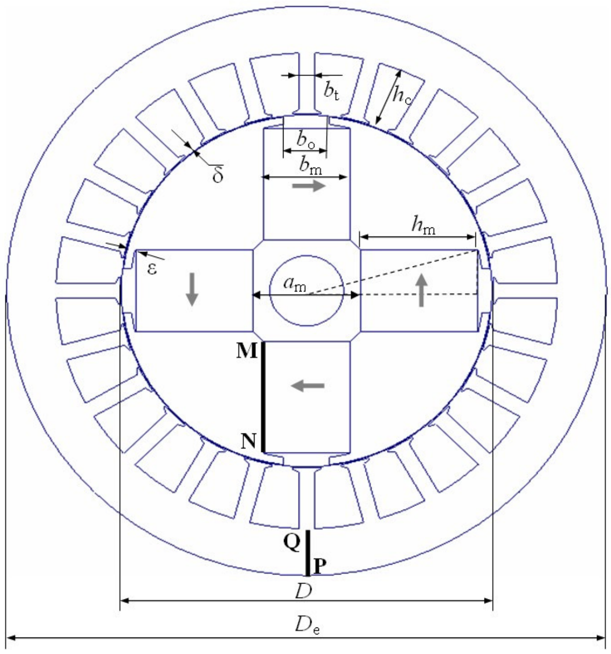

Fig.1 – The transverse section of the PMSG.

The following geometric dimensions are considered in Figure 1: b_t = 5 mm, h_c = 20 mm, D = 120 mm, D_e = 195 mm, δ = 0,5 mm, a_m =38 mm, ε = 3 mm.

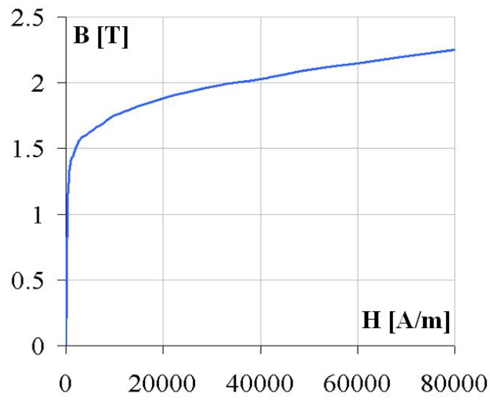

Fig.2 – The magnetic characteristic.

The magnetic characteristic of the rotor steel parts (that create a closing path for the magnetic field) and of the stator armature is depicted in Figure 2. The permanent magnets are made of NdFeB and have the following characteristics: the coercivity H_c = 979000 A/m; the relative permeability μ_r = 1.049; the maximum magnetic energy $B \cdot H_{max}$ = 40 MGOe; the electrical conductivity σ = 0,667 MS/m; The generator's stainless steel shaft has the following properties: the relative permeability μ_r = 1 and the electrical conductivity σ = 1,35 MS/m.

3. The influence of the permanent magnet length over the generator's magnetic excitation flux

In this study we have analyzed the influence of the geometrical dimensions (on the transverse section) of the rotor over the generator's magnetic flux (flux linkage, mutual flux and leakage flux). During this study the rotor's diameter D was kept constant.

The dimensions that are changed during this analysis are the permanent magnet length b_m and the rotoric slot opening b_0. Thus if b_m has a high value the special shaped steel parts that create a closing path for the magnetic field have smaller dimensions because the rotor's diameter D is kept constant. The optimum solution with respect to the permanent magnet length may be found by choosing a set of dimensions for b_m and h_m (the permanent magnet height) for which the flux linkage, mutual flux and leakage flux (that correspond to a rotor pole pair) are calculated (with the help of specialized software). It's important to mention that if the rotor's diameter D is kept constant the permanent magnets dimensions b_m and h_m lean one upon the other. For this reason only b_m is varied, the other dimension h_m being calculated with the following formula (obtained from the generator's transverse section in Figure 1):

$$h_m = \sqrt{\left(\frac{D}{2} - \varepsilon - \delta\right)^2 - \left(\frac{b_m}{2}\right)^2} - \frac{a_m}{2} \tag{1}$$

During this study the target was to maximize the generator's mutual flux and flux linkage. Because the permanent magnets' price is declining over the last years the decrease of the magnets' volume was not taken into account during the analysis.

Nevertheless the permanent magnet length has to be kept within a specific range that is given by the generator's rated power. If the magnet's volume is too small then magnetic excitation flux could be insufficient for a specific rated power (of the generator). On the other hand if the magnet's volume is too large the overall cost of the generator raises without a major effect over its energetic characteristics.

The per-unit length of the permanent magnet is given by:

$$k = \frac{b_m}{\tau} \tag{2}$$

where τ is the pitch pole measured at the air-gap level. For the analyzed generator the pitch pole is τ = 94.25 mm. It corresponds to a rotor diameter D = 120 mm. The generator's magnetic flux (flux linkage, mutual flux and leakage flux) is calculated by taking into account the per-unit length of the permanent magnet k (using (2)) and by keeping constant all the other transverse section's geometric dimensions (Figure 1): b_t, h_c, D, D_e, δ, a_m, b_0 and ε.

For the generator's transverse section geometry and material properties described in section 2 the induction map is calculated using the finite element method (with the help of specialized software).

Figure 3 shows the magnetic field spectrum (map) for b_m = 28 mm (k = 0.297) and b_0 = 15 mm. It can be seen that the portion of the statoric armature that is situated on the rotoric permanent magnets' axis is crossed by a lower value of the magnetic field.

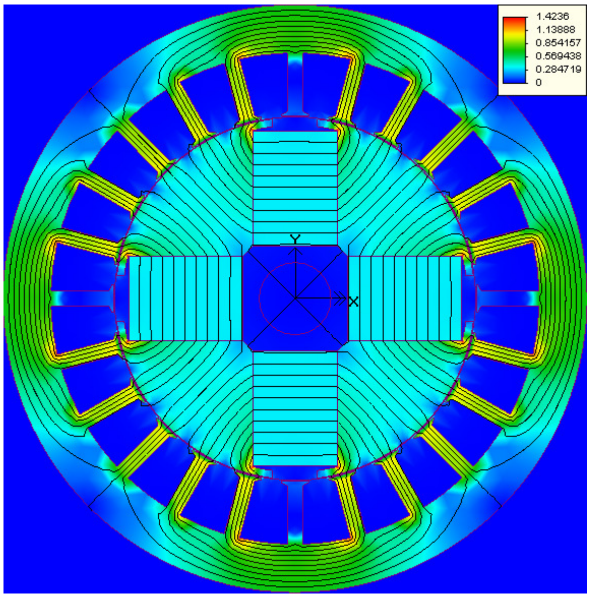

Fig.3 – The magnetic field chart for b_m = 28.3 mm (k = 0.297) and b_0 = 15 mm.

The influence of the permanent magnet's length over the generator's magnetic flux (flux linkage Φ_t (on the surface defined by the MN segment and the machine's length – see Figure 1), mutual flux Φ_u (on the surface defined by the PQ segment and the machine's length – see Figure 1) and leakage flux Φ_σ [5] was studied for the following per-unit lengths of the permanent magnets: k_1 = 0.19 (b_{m1} = 18 mm); k_2 = 0.243 (b_{m2} = 23 mm); k_3 = 0.297 (b_{m3} = 28 mm), k_4 = 0.35 (b_{m4} = 33 mm) and k_5 = 0.403 (b_{m5} = 38 mm). For each of these values the permanent magnets' height h_m, the permanent magnets' volume V_m, the flux linkage, the mutual flux and leakage flux were calculated. These results are shown in Table I.

All the results shown in Table I were calculated for the same rotoric slot opening b_0 = 15 mm. It can be seen that both the flux linkage and the mutual flux reach a maximum value. These maximum values are not simultaneous but they are reached for close values of the permanent magnet length b_m. The mutual flux has a greater importance because it induces electromotive forces (e.m.f.) in the stator windings. Seeing the results from Table I we can conclude that the optimum functioning regime of the generator is reached if the per-unit length of the permanent magnet varies between 0.25 and 0.35 ($k \in (0.25 \ ... \ 0.35)$).

TABLE I.

b_m [mm]	h_m [mm]	V_m [mm^3]	Φ_t [Wb]	Φ_u [Wb]	Φ_σ [Wb]
18	37.5	81000	$1.415\cdot10^{-3}$	$1.312\cdot10^{-3}$	$1.031\cdot10^{-4}$
23	37	102120	$1.445\cdot10^{-3}$	$1.326\cdot10^{-3}$	$1.181\cdot10^{-4}$
28	36.5	122640	$1.457\cdot10^{-3}$	$1.329\cdot10^{-3}$	$1.274\cdot10^{-4}$
33	36	142560	$1.459\cdot10^{-3}$	$1.326\cdot10^{-3}$	$1.333\cdot10^{-4}$
38	35	159600	$1.433\cdot10^{-3}$	$1.301\cdot10^{-3}$	$1.317\cdot10^{-4}$

Figure 4 depicts the mutual flux variation with the permanent magnet length b_m.

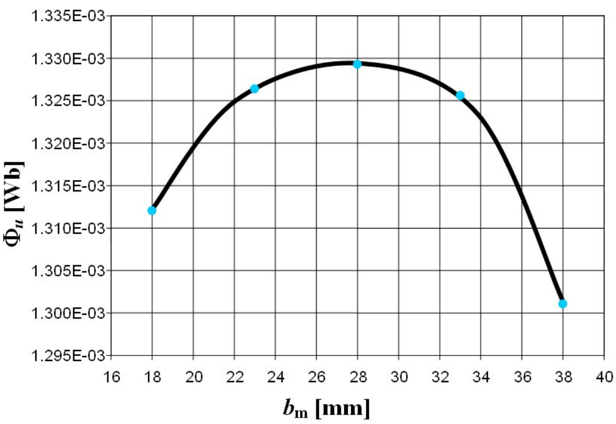

Fig.4 – The mutual flux variation with the permanent magnet length.

4. The influence of the rotoric slot opening over the generator's magnetic excitation flux

This study was realized for the same geometry of the generator's transverse section (as the one defined in chapter 2) and by choosing the per-unit length of the permanent magnet $k = 0.297$ ($b_m = 28$ mm) (for this value the mutual flux reaches it's maximum – see Table I and Figure 4). For this analysis we have chosen four values for the rotoric slot opening: $b_0 = 5$ mm, $b_0 = 10$ mm, $b_0 = 15$ mm and $b_0 = 20$ mm. For each of these values the flux linkage, the mutual flux and leakage flux were calculated. These results are shown in Table II.

TABLE II.

b_0 [mm]	Φ_t [Wb]	Φ_u [Wb]	Φ_σ [Wb]
5	$1.4679\cdot10^{-3}$	$1.1902\cdot10^{-3}$	$2.7771\cdot10^{-4}$
10	$1.4586\cdot10^{-3}$	$1.2905\cdot10^{-3}$	$1.6806\cdot10^{-4}$
15	$1.4532\cdot10^{-3}$	$1.3283\cdot10^{-3}$	$1.2489\cdot10^{-4}$
20	$1.4474\cdot10^{-3}$	$1.3468\cdot10^{-3}$	$1.0059\cdot10^{-4}$

It can be seen that when the rotoric slot opening grows the flux linkage drops with about 1.4% while the mutual flux grows with 12.5%. This phenomenon happens due to the fact that the rotoric slot is filled with air and the equivalent reluctance of this air-space grows (while the rotoric slot opening grows) leading to a decrease of the leakage flux [5]. The greatest increase of the mutual flux (about 8.4%) takes place when the rotoric slot opening grows from 5 mm to 10 mm.
Figure 5 shows the mutual flux variation with the rotoric slot opening dimension b_0. It's recommended to build a generator that has a larger rotoric slot opening (at the same permanent magnet length b_m) because the increase of the mutual flux leads to an increase of the electromotive forces (e.m.f.) in the stator windings.

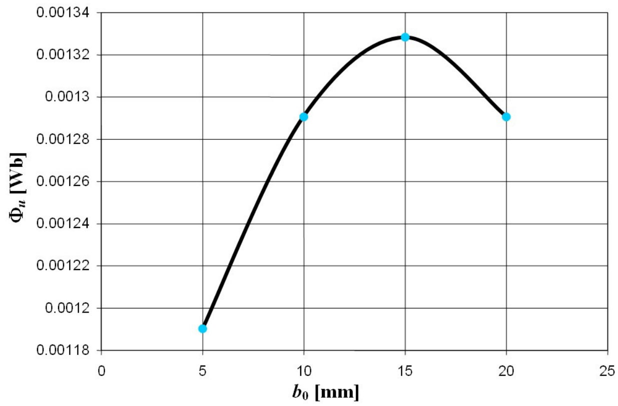

Fig.5 – The mutual flux variation with the rotoric slot opening dimension.

As it was already mentioned the leakage flux decreases with the increase of the rotoric slot opening. Figure 6 shows this variation. It can be seen (as it was expected) that the greatest decrease of the leakage flux takes place when the rotoric slot opening grows from 5 mm to 10 mm.

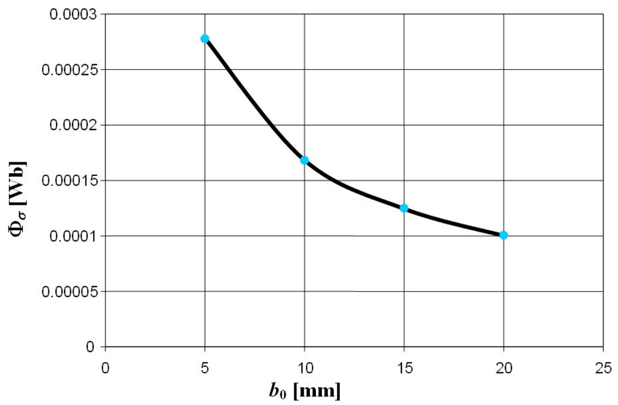

Fig.6 – The leakage flux variation with the rotoric slot opening dimension.

5. Concluding remarks

The permanent magnet synchronous generators (PMSGs) will be used in wind turbines all over the world because of their main advantages: they are stable and secure during normal operation, they have smaller overall dimensions than wound rotor synchronous generators (WRSGs) and they do not need an additional DC supply for the excitation (circuit).

The optimization of the generator's transverse section geometry (keeping constant the rotor's diameter D) can be done by changing the permanent magnets length b_m and the rotoric slot opening b_0.

In our analysis we show that the generator's mutual flux has maximum values that depend both on the permanent magnets length b_m and the rotoric slot opening b_0.

These values were calculated by using a 2D finite element method with the help of a specialized software called MagNet 6.24.1 (developed by Infolytica) [6], [7]. Thus, the optimized transverse section geometry has to have a per-unit length of the permanent magnet between 0.25 and 0.35 ($k \in (0.25\ \dots\ 0.35)$) and a large enough rotoric slot opening (in our case between 10 and 20 mm – $b_0 \in$ [10 ... 20] mm) that leads to an increased mutual flux (with about 8.4 % in our case).

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References

[1] J. Vergauwe, A. Martinez and A. Ribas, "Optimization of a wind turbine using permanent magnet synchronous generator (PMSG)", in Proc. ICREPQ'06, http://www.icrepq.com/icrepq06/214-vergauwe.pdf.
[2] C. Ghiță, A.– I. Chirilă, I. – D. Deaconu, and D. I. Ilina, "The magnetizing field of a linear generator used to obtain electrical energy from waves energy", in Proc. ICREPQ'07, pp. 207-208.
[3] K. Shinji, I. Yoshitaka, M. Masakazu and T. Akira, "A Low-Cost Wind Generator System with a permanent Magnet Synchronous Generator and Diode Rectifiers", in Proc. ICREPQ'07, http://www.icrepq.com/icrepq07/212-kato.pdf.
[4] M. Predescu, A. Crăciunescu, A. Bejinariu, O. Mitroi, A. Nedelcu, "Impact of the design method of permanent magnets synchronous generator for small direct drive wind turbines for battery operation", in Proc. ICREPQ'07, http://www.icrepq.com/icrepq07/240-Predescu.pdf.
[5] R. Măgureanu, N. Vasile, "Motoare sincrone cu magneți permanenți", Editura Tehnică, Bucureşti, 1982.
[6] Infolytica Corporation, MagNet Documentation Center, www.infolytica.com.
[7] G. Mîndru, M.M., Rădulescu, "Numerical Analysis of Electromagnetic Field", Editura Dacia, Cluj-Napoca, 1986.