Study of Three-Phase Axial Flux Generators

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Abstract.- **Programming simulations by the finite element method Femm 4.2 have been made along with experimental studies of three types of especially crafted three-phase axial flux generators with rare-earth magnets. The e.m.f. and the full active power have been both calculated and measured for the three types of generators. The obtained models simulate with good precision the operation of the studied generators. Economical assessment of the generators has been carried out and it has been found that the generator with two rotors and one stator is the most appropriate for applying in wind-generating systems.**

Keywords— axial; generator; magnets; permanent; three-phase

I. INTRODUCTION

Axial flux generators with permanent magnets have found application for more than a century and a half, since they are characterized by high efficiency, simple, reliable and easy to produce construction, and high power per unit of weight [1]. The lack of excitation winding and current leads to their high efficiency in operation, while the availability of high-power Nd-Fe-B permanent magnets in their rotors additionally improves their output electrical parameters [2].

Originally single-rotor axial flux generators were used, and later on the two-rotor and multi-rotor axial flux generators were imposed, as the magnetic fluxes of dissipation in them are considerably reduced and the output power is increased [3].

Single-phase generators are used more rarely in practice, while the three-phase ones are more common, due to the fact, that the generated power is distributed among the three phases, which leads to lower phase voltages and currents [4]. When modeling these generators the Finite Element Method Magnetics (Femm) is often used, and by means of it the magnitude of the magnetic induction is defined, as well as its distribution in two-dimensional space [5].

This paper studies three types of especially crafted three-phase axial flux generators with rare-earth magnets. The first generator is a single-rotor one with one stator, the second is single-rotor with two stators, and the third has two rotors and one stator. By means of Femm the magnetic field is modeled and thus the integral magnetic induction in the stator windings is defined. Then the magnetic fluxes are found, the induced e.m.f. in the stator windings are calculated, and the phase voltages and currents are defined, together with the power at active load.

II. EXPOSITION

The considered three types of especially crafted generators consist of either one or two steel rotors 200 mm in diameter and thickness of 4 mm, with sixteen rare-earth magnets in each, measuring 20x20x10 mm. The stators are made of aluminum, they are either one or two, 240 mm in diameter and thickness of 4 mm. The stator windings are 12 in number, with 160 turns of a varnished conductor with diameter d=0,8 mm in each.

Fig. 1, Fig. 2 and Fig. 3 show the constructive schemes of the three generators with a view from the left, and the notations in them are as follows: 1 – steel or aluminum stator, 2 – stator winding, 3– steel or aluminum rotor, 4 – rare-earth magnet, and 5 – the shaft, setting the rotors in motion.

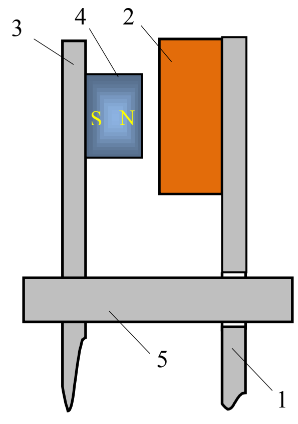

Fig. 1. Single-rotor generatpr with one stator.

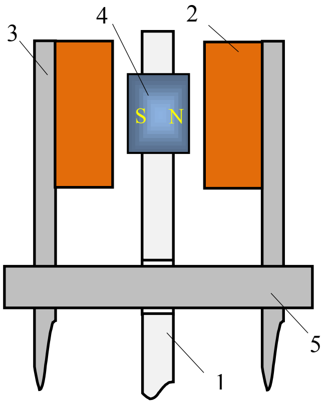

Fig. 2. Single-rotor generatpr with two stators.

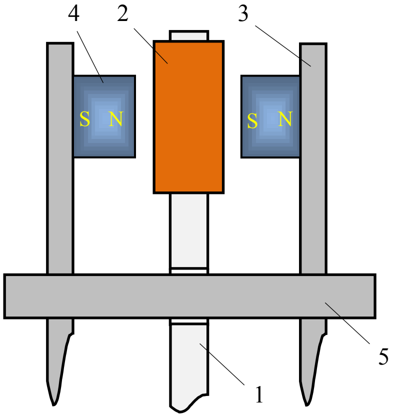

Fig. 3. Two-rotor generator with one stator.

III. Modeling and Experimental Studies

The method Femm 4.2 is used in modeling the considered axial flux generators, which are connected star-like and have a symmetric active load and thus the maximum integral magnetic induction in one stator winding is defined. Since the generators themselves are three-dimensional, while the simulation software is two-dimensional, the depth, set in it, is equal to the thickness of the magnets – 20mm. Fig. 4 illustrates the distribution of the magnetic induction in the generator with one stator and one rotor. Fig. 5 presents the integral magnetic induction per m^3 - B_c , along the x axis - B_{cx} , and along the y axis - B_{cy}, as well as the volume of the stator winding V_c. By means of these values the maximum integral magnetic induction for the volume of the stator winding B'_c is calculated.

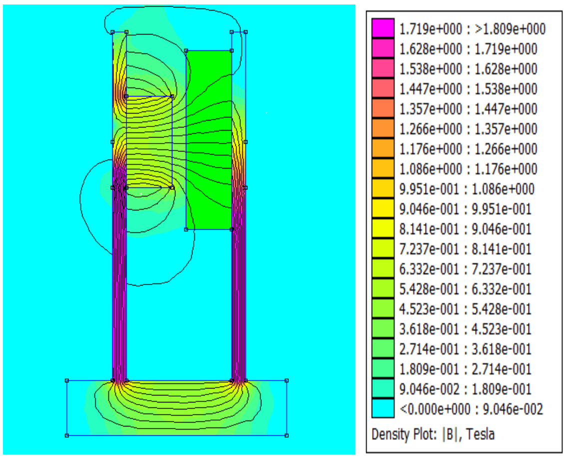

Fig. 4. The distribution of the magnetic induction in the generator with one stator and one rotor.

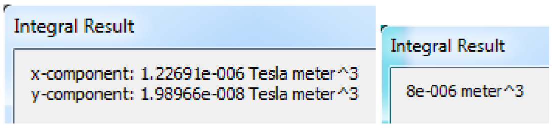

Fig. 5.

The integral magnetic induction per 1 m^3 - B_c is found from its two constituents :

$$B_c = \sqrt{B^2{}_{cx} + B^2{}_{cy}} \quad , \quad T.m^3 \quad . \tag{1}$$

Thus the maximum integral magnetic induction for the volume of the stator winding of the generator with one stator and one rotor is equal to:

$$B_c' = \frac{B_c}{V_c} = 0{,}1525 \quad , \quad T \; . \tag{2}$$

The magnetic induction and the flux for a stator winding with a cross-section A in instant form for the three generators are equal to:

$$B_c(t) = B_c \sin \omega t \; , \qquad \Phi_c(t) = B_c(t) A \quad . \tag{3}$$

The induced e.m.f. in one of the stator windings is defined by the magnetic flux, going through it, in instant form $\Phi`_c(t)$ and by the number of its turns N:

$$e'(t) = -N \frac{d\,\Phi_c'(t)}{d\,t} \quad . \tag{4}$$

From (3) and (4) the induced e.m.f. in one of the stator windings is:

$$e'(t) = -NA'\omega B_c' \cos \omega t \; . \tag{5}$$

Thus the amplitude of the induced e.m.f. in the stator winding is equal to:

$$E_{mc}' = NA'\omega B_{mc}' \quad . \tag{6}$$

The circular frequency can be expressed by the number of revolutions per minute n and the number of pole pairs p:

$$\omega = \frac{2.\pi.p}{60} n \quad . \qquad (7)$$

After substituting (7) into (6), the amplitude of the induced e.m.f. is :

$$E'_{mc} = NA'B'_{mc} \frac{\pi.p}{30} n \qquad (8)$$

Thus the r.m.s. value of the induced e.mf in one winding of the generator with one stator and one rotor is equal to:

$$E'_c = NA'B'_{mc} \frac{\pi.p}{30\sqrt{2}} n \quad . \qquad (9)$$

Fig. 6 shows the distribution of the magnetic induction for the generator with one stator and two rotors, while fig. 7 presents the integral magnetic induction per m^3 B_c and the volume of the stator winding V_c. From these values the integral magnetic induction for the volume of the stator winding is calculated - $B_c'' = 0{,}133\,,T$.

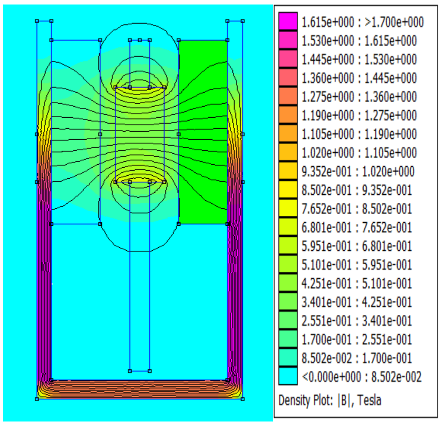

Fig. 6. The distribution of the magnetic induction for the generator with one stator and two rotors.

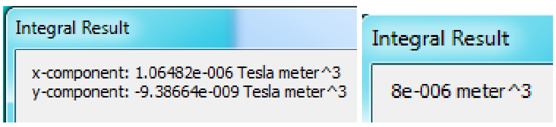

Fig. 7

By means of the expressions from (3) to (9) the r.m.s value of the induced e.m.f. in one winding of the generator with one rotor and two stators is defined.

$$E''_c = NA''B''_{mc} \frac{\pi.p}{30\sqrt{2}} n \quad . \qquad (10)$$

Fig. 8 gives the distribution of the magnetic induction in the generator with two rotors and one stator, while fig. 9 illustrates the integral magnetic induction per m^3 - $B_{c,}$, as well as the volume of the stator winding V_c., by means of which the integral magnetic induction for the volume of the stator winding is calculated - $B_c''' = 0{,}202\,,T$.

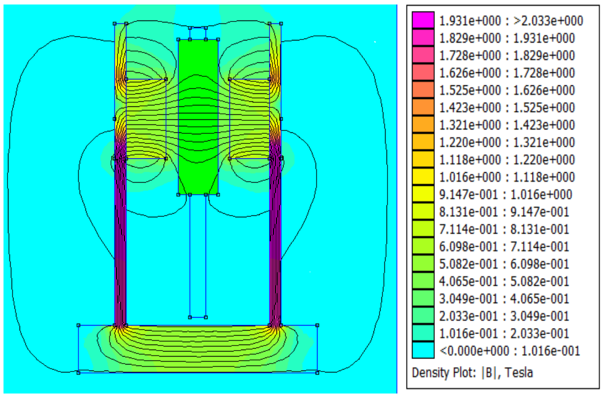

Fig. 8 The distribution of the magnetic induction in the generator with two rotors and one stator.

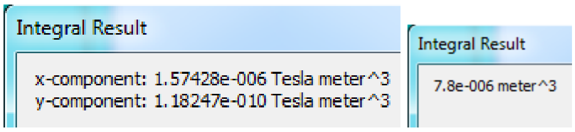

Fig. 9

Again by means of the expressions from (3) to (10) the r.m.s. value of the induced e.mf. in one winding of the generator with two rotors and one stator is defined

$$E'''_c = NA'''B'''_{mc} \frac{\pi.p}{30\sqrt{2}} n \quad . \qquad (11)$$

By means of the calculated induced e.m.f. in one stator winding (9), (10) and (11), the phase e.m.f., the currents and the power, as well as the full three-phase power at a symmetric active phase load of 5 Ω are defined.

Fig. 10 presents both the calculated during the process of modeling and the measured during the experiments values of the e.m.f. for one stator winding for the three types of generators. The calculated during the process of modeling e.m.f are higher than the experimentally obtained ones for the three generators, which is due to the asymmetries resulting from the process of their production. Fig. 11 shows both the calculated during the process of modeling and the measured during the experiments output full three-phase power for the three generators. It can be seen that the generator with two rotors and one stator has the highest full active power, followed by the one with one rotor and one stator. Table 1 gives the maximum relative errors between the models and the experimental results.

Table 2 presents the cost price, including the costs for materials and labor for the three types of generators, the electrical energy, generated by them per twenty-four-hour period of time, and their payout periods. From the table it can be seen that the price of the generator with two rotors and a stator is the highest, but it is the generator, which produces the biggest amount of electricity per day, and, in addition, its payout period is comparatively short. The generator with one rotor and one stator has the lowest cost price, generates slightly over half of the energy, produced by the generator with two rotors and one stator per twenty four hours, and it has the shortest payout period. The generator with one rotor and two stators has a comparatively low cost price, generates the smallest amount of electrical energy per twenty four hours and is paid out for the longest period of time.

TABLE I.

Maximum Relative Errors	***One rotor one stator***	***One rotor two stators***	***Two rotors one stator***
For the e.m.f.	δ=6,22%	δ=7,97%	δ=6,89%
For the full three-phase power	δ=6,76%	δ=8,74%	δ=7,19%

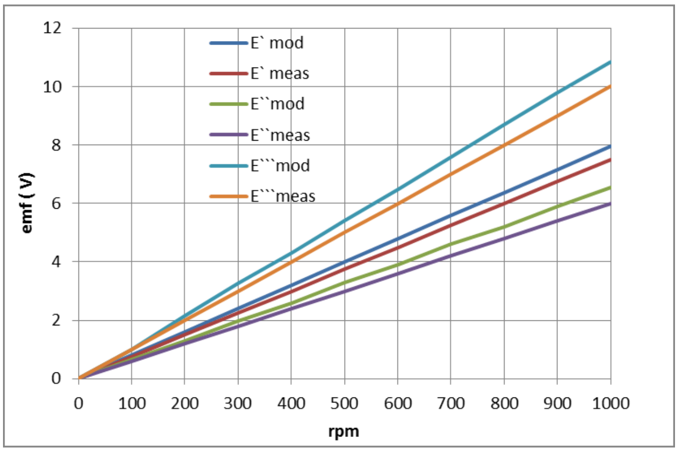

Fig. 10

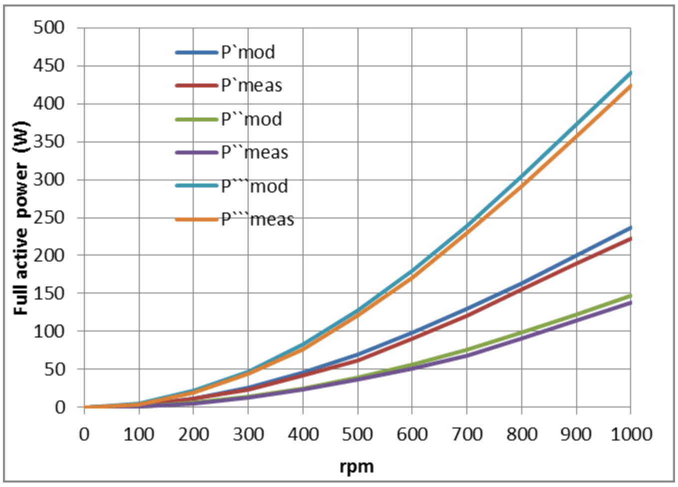

Fig. 11

TABLE II.

	One rotor one stator	***One rotor two stators***	***Two rotors one stator***
Cost price, €	59	65	111
Produced energy per day, kW/day	2,4	1,5	4,4
Period of repayment, days	189	333	194

IV. CONCLUSIONS

Theoretical derivations, programming simulations and experimental studies of the considered especially crafted three types of three-phase axial flux generators have been carried out. By means of the finite element method Femm 4.2 the distribution of the magnetic field for the considered axial flux generators has been obtained. The calculated during the process of modeling e.m.f. and full active power of the generators are higher than the experimentally obtained ones, which is due to the asymmetries, resulting from the process of their production. The maximum relative errors between the models and the experimental results for the three types of generators are below 8% for the e.m.f and below 9% for the full power. The generator with two rotors and one stator has the highest cost price, though it generates the biggest amount of electricity per twenty-four-hour period of time, has a relatively short period of repayment and is the most appropriate for applying in wind-generating systems.

REFERENCES

[1] J. Gieras, R. Wang and M. Kamper, "Axial flux permanent magnet brushless machines," Dordrecht Netherlands: Kluwer Academic Publishers, 2004.

[2] E. Aritz, "Overview of Axial flux Flux Machines," Electric Energy Magazine – Spain, vol. 4, pp. 3-7, 2013.

[3] M. Mohammad and S. Widyan, "Optimization, Construction and Test of Rare-Earth Permanent-Magnet Electrical Machines with New Topology for Wind Energy Applications," Fakultät IV–Elektrotechnik und Informatik der Technischen Universität, Berlin, pp. 17-22, 2006.

[4] R.Wang and M. Kamper, "Optimal Design of a Coreless Stator Axial Flux Permanent-Magnet Generator," IEEE Transactions on magnetics, vol. 41, 2005.

[5] D. Meeker, "Finite Element Method Magnetics – Version 4.0," User's Manual, 2006.