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ANALYSIS OF INTEGRAL PARAMETERS IN A SINGLE-PHASE SLOTLESS AXIAL-FLUX MACHINE USED IN SMALL WIND TURBINES

ANALIZA PARAMETRÓW FUNKCJONALNYCH W JEDNOFAZOWYM BEZŻŁOBKOWYM GENERATORZE WIATROWYM O STRUMIENIU OSIOWYM

A b s t r a c t

The design of a ferrite magnet generator with trapezoidal shaped permanent magnets and coils for a wind turbine is studied. Based on the 3-D finite element analysis (FEA), the electromagnetic performances of the two generator prototypes and a simple design modification for one of the axial-flux generator prototypes are analyzed. The best generator is chosen from a range of designs, where the goal is to increase the voltage generated by the 8/8 pole and a single-phase slotless machine. Experimental results from a small size prototype machine validate the 3-D FEA models presented, and hence give confidence in their use for design.

Keywords: *axial-flux generators*, *wind turbine generators*, *efficiency*, *finite-element analysis*

S t r e s z c z e n i e

W niniejszym artykule omówiono konstrukcje jednofazowych bezżłobkowych generatorów tarczowych o 8 biegunach stojana i wirnika przeznaczonych do małych elektrowni wiatrowych. W badanych generatorach zastosowano magnesy w kształcie trapezoidalnym, a także cewki trapezoidalne. W celu zobrazowania wpływu geometrii na parametry funkcjonalne generatora oraz uzyskanie wyższej wartości napięcia rotacji w uzwojeniu dokonano modyfikacji obwodu magnetycznego jednej z analizowanych konstrukcji. Do obliczeń pola magnetycznego wykorzystano program trójwymiarowy (3D) oparty na metodzie elementów skończonych (MES). Zaprezentowano wyniki obliczeń numerycznych i wybrane wyniki badań laboratoryjnych.

Słowa kluczowe: *maszyny ze strumieniem osiowym*, *małe turbiny wiatrowe*, *sprawność*, *metoda elementów skończonych*

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1. Introduction

Axial-flux machines (AFM) with magnets for wind generator applications can be built in many configurations [7–9, 12, 13, 15]. Machines with coreless stators can potentially operate at a higher efficiency than conventional ones because of the absence of core losses. AFM-based generators can be structured as: single-rotor, single-stator; double-rotor, single--stator; single-rotor, double-stator; multi-rotor, multi-stator machines. The stator disc can be slotted or slotless. The simplified structure of AFM is a slotless single-stator disk design with winding placed or wound on the stator disk. Small size AF generators for wind turbine applications offer a promising alternative for many remote electrical uses [1–6, 10]. Their high compactness and disk-shaped profile make the axial-flux machines suitable for mechanical integration with wind turbines.

The goal of this paper is to investigate the electromagnetic field and performance of the two presented prototypes. The prototypes of generators are chosen from a range of designs based on minimizing the material cost and energy loss [14]. To demonstrate the influence of the generator, geometry changes on the generator performance, and the modification of the stator and rotor was investigated and analyzed on prototype A. A wide range of generator characteristics modeling can be found in the literature [7–9, 12–15]. The presented generator should generate sufficient output DC voltage to charge up to 4–5 batteries of 12-volt each. This generator design should be suited for charging a 48-volt battery system. The small amount of energy produced by the generators can be stored by the battery charging station and that stored energy can sufficiently improve the quality of life for such areas, giving people access to electrical lighting, TV, radio, etc. In contrast to this, the 3-D FEA approach to calculating generator characteristics and electromagnetic modeling, that uses a professional software package, has been presented in [15]. The analytical methods and the finite-element (FE) methods are, in many instances, used to investigate certain design aspects and analyse the electromagnetic field. FE models give an excellent representation of the magnetic field inside the machine.

Calcualtion of the wind generator characteristics is mainly about power-speed, efficiency--speed or torque speed characteristics. The prediction of generator performance was verified with measurements. The comparison between the measured and simulated impact of generators for the wind turbine application during normal operation is in good agreement. Testing includes both generator prototypes, the testing focuses on the DC output voltage and DC output current at various speeds. It shows that the proposed prototype B with full pitch magnets can be applied successfully to generate up to 60 V at the open-circuit operation. Future research works will be concentrated on the generators efficiency, the flux distribution in the stator and rotor core and the magnetic force between the stator and rotor.

2. Description of the axial-flux generator

Axial-flux generators with magnets are one of the best solutions for small-scale wind generators. In this study, ferrite magnet generators with surface-magnet systems are studied and analyzed. A schematic drawing of the prototype axial-flux generators are shown in Fig. 1.

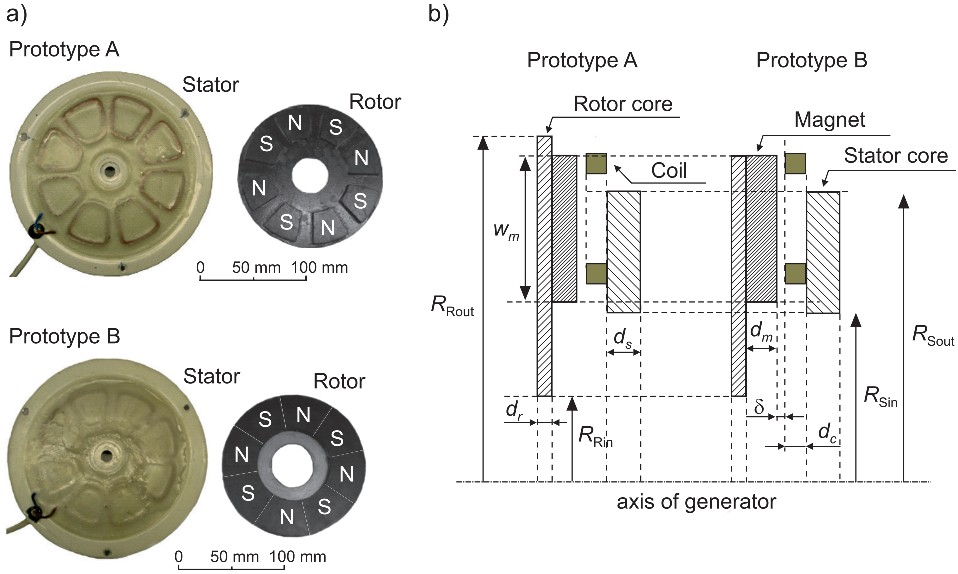

Fig. 1. Prototypes of 8-pole axial-flux generators (a) and one-stator one-rotor topology (b)

The rotors of prototype versions A and B are composed of a thin 3 mm thick steel plate, and 138.4 mm and 130.4 mm in outer diameter, respectively. Ferrite magnets are arranged in a radial pattern around the rotor plate. The initial design of prototype A of the generator includes 8 trapezoidal-shaped surface-mounted magnets with an arc of 30 mech. degrees. Prototype B consists of a rotor with 45 mech. degrees of trapezoidal-shaped magnet arc covering a full rotor pole pitch. Magnets with black epoxy coating were chosen specifically to protect them against scratching and corrosion. The slotless stator core disk for both prototypes with winding consists of a number of single-layer trapezoidal-shaped coils. These coils have the advantages of being easy to make and have a relatively short end-winding. The coils are held together and mounted on a stator disk surface by using a composite material of epoxy resin. The geometry parameters of prototypes are listed in Table 1.

Table 1

The main parameters of generator geometry and material specification

Data of generator	Version of generator prototype	
	A	B
Type of magnet	Ferrite	Ferrite
Thickness of magnet	5 mm	5 mm
High of magnet	29.5 mm	29.5 mm
Remanent magnetic flux	0.66 T	0.66 T
Outer radius of rotor core/magnet	69.2 mm	65.2 mm
Inner radius of rotor core/magnet	17.2 mm	17.2 mm
Outer radius of stator core	58 mm	58 mm

Inner radius of stator core	34 mm	34 mm
Thickness of stator core	7 mm	7 mm
Turn number per coil	124	124
Number of rotor/stator pole	8/8	8/8
Thickness of coil	4 mm	4 mm
Air-gap (stator-magnet)	1.5 mm	1.5 mm
Resistance of phase (in series)	26.9 Ω	26.9 Ω

The principal application of such wind turbines is battery charging, in which the generator is connected through a rectifier to a battery system. In order to convert the available wind power to mechanical power, the rotor should usually operate at optimal speed ratio, with its revolutions per minute varying in proportion to wind speed. In the small size wind turbine generator under study, the torque and speed control system does not need to be used regarding the application that the generators are used for.

3. Three dimensional FEA models of axial-flux generators

The three-dimensional magnetic field analysis was conducted during the investigation of the output voltage, efficiency and magnetic force. Two prototypes with single-phase winding are analyzed by the 3-D finite element method. Single-phase winding terminals of the generator are connected to a diode rectifier circuit with a resistive load. The 3-D FEA models of prototypes having a periodicity property (45° mech. degrees) are shown in Fig. 2.

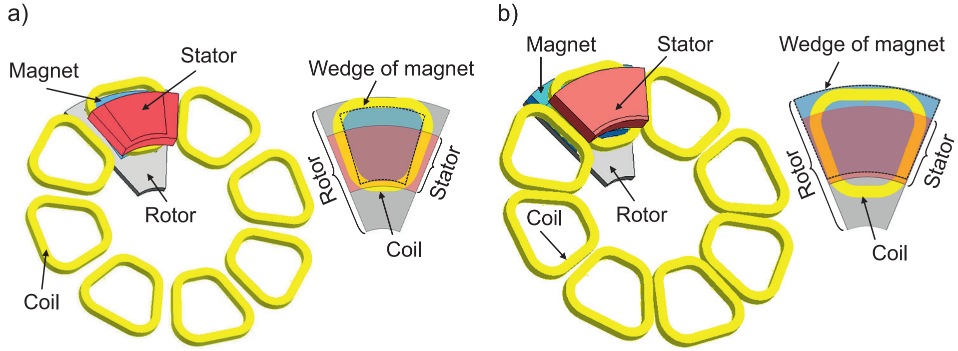

Fig. 2. 3-D FEA models of 8-pole axial-flux generator, prototype A (a), and prototype B (b)

The electrical and mechanical performance of the electric motor depend on its geometry and properties of magnetic materials. In the past, basic electromagnetic theory was used by industrial experience for preliminary motor design of the presented prototypes. 3-D FEA was used to verify the AF generators, and the results show the useful performance of the machines for wind turbine applications. However, performance of the motor can be enhanced by the modification design in terms of efficiency, torque etc. For prototype A, the geometry of the generator was redesined (Fig. 3).

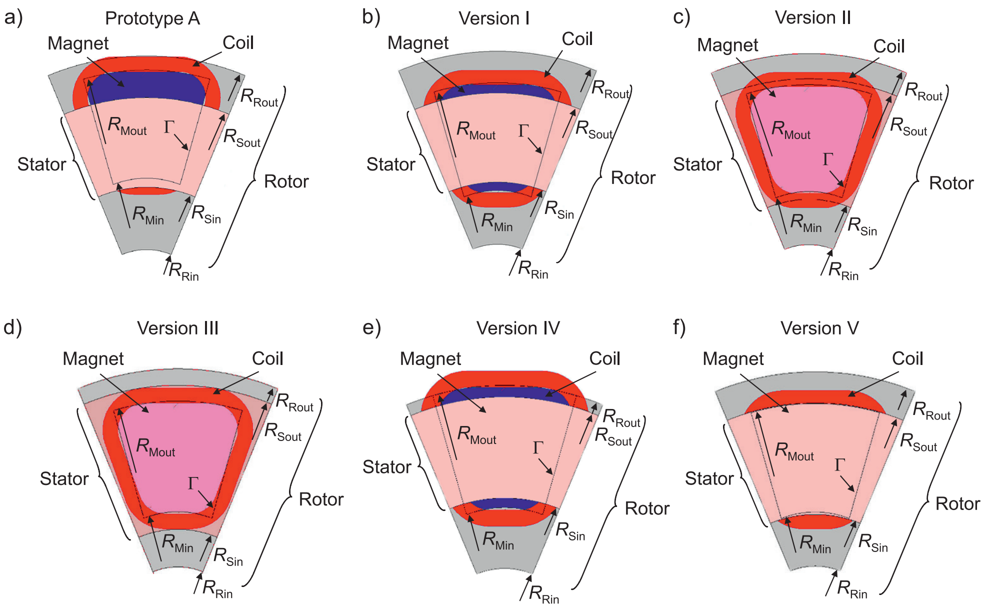

Fig. 3. The geometry of prototype A before modification (a), and several versions of prototype A after modification (b–f)

The modification process was performed with the following changes to stator, rotor, magnet and coil sizes: version I (Fig. 3b) consists of the coils moved about 4.8 mm to the center of the stator disc. Also, the magnets are placed to the center of the stator disk by changing the magnet inner and outer radius, magnet volume was then reduced about 0.3%. Those positions of coils and magnet are fixed in all further modifications (Fig. 3c–f). The contour profile of magnets are highlighed by the Γ symbol. Version II (Fig. 3c) concerns a modification of the stator disc width in a radial direction ($R_{Sout} - R_{Sin}$) in order to place the outer and inner edges of magnet in the middle of the coil thickness, thereby the width of stator disk is wider than the magnet width ($R_{PMout} - R_{PMin}$). The next version III (Fig. 3d) is based on further extension of the stator disc width in order to cover the whole coil. On version IV (Fig. 3e), the outer radius of the rotor disk was reduced and aligned to the outer

Table 2

Geometry parameters of generator version A after modification

Version of AFM	Parameter [mm]					
	R_{Sin}	R_{Sout}	R_{Rin}	R_{Rout}	R_{Min}	R_{Min}
Prototype A	34	58	17.2	69.2	35.8	65.2
I	34	58	17.2	69.2	31.3	60.7
II	31	62.4	17.2	69.2	31.3	60.7
III	27.1	64.9	17.2	69.2	31.3	60.7
IV	34	58	17.2	60.7	31.3	60.7
V	31	60.9	17.2	69.2	31.3	60.7

radius of magnet. After that modification, the external end-winding sticking out of the stator disc, and the rest of stator disc geometry dimentions are the same as in prototype A. The last modification (version V, Fig. 3f), is based on the same rotor disk and magnet geometry dimensions as in version I. The width of the stator disk was increased in order to cover the whole face of the magnet.

The stator, rotor, and magnet dimensions before and after the geometry modification are given in Table 2.

4. FEA results and experimental verification

Simulation and measurements of the axial-flux machine response to voltage at different speeds were performed. The machine was operated as a generator and the load level varied from no load to full load. The speed of the generator was changed from 1000 rpm down to 250 rpm. In the first stage of the experiment, the input mechanical energy was fed to the drive rotor of the proposed generators which can change mechanical energy into electrical energy. The prediction and measured voltages generated by phase caused by different speeds of the generator are presented in Fig. 4.

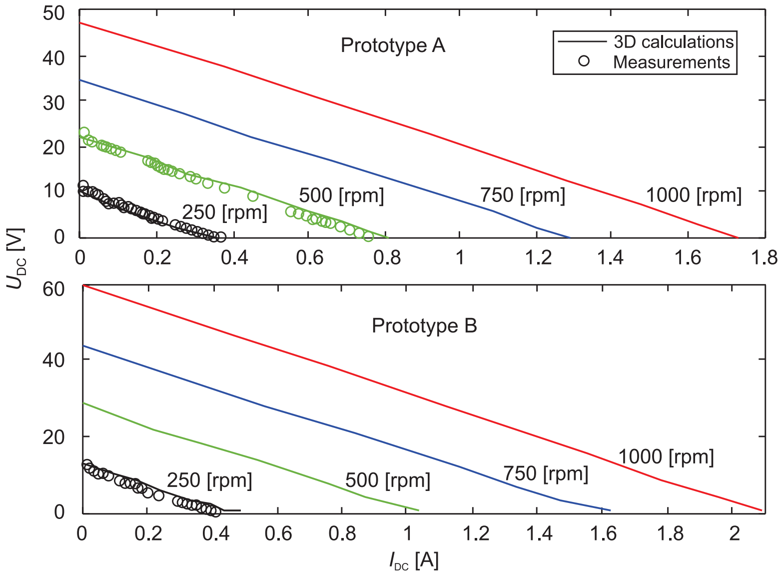

Fig. 4. DC output voltage at varied speed versus DC output current when connected to resistive load

If a higher DC load voltage is required to recharge 5 batteries of 12-volts each, the speed of operation must be high. For instance, if a DC load voltage of 60 V is required, the rotor speed has to be higher than 1000 rpm to generate this voltage within the range of peak efficiency. The prototype B seems a better solution to reach the high voltage to recharge 5 batteries than prototype A – this generates DC output voltage about 10 V lower than prototype B at a speed above 500 rpm. The line voltage in the open-circuit condition is approx. 48 V and 60 V at 1000 rpm for prototypes A and B, respectively. The open-circuit and load characteristics for different rotational shaft speeds were measured. The computed results of the DC voltage vs. the DC output current at resistive loaded operation agree strongly with the experimentally measured values. The increase of the generated voltage is directly related to the increase of the power output, and the generated voltage is proportional to the strength of the magnetic field.

The speed range is limited by the maximum power that can be dissipated in the rotor resistances. The results presented in the following plots correspond to 250 rpm, 500 rpm, 750 rpm and 1000 rpm of the rotor speed at various generator loads. The efficiency of prototype A and B increases to about 58% and 64% at high speed, respectively (Fig. 5).

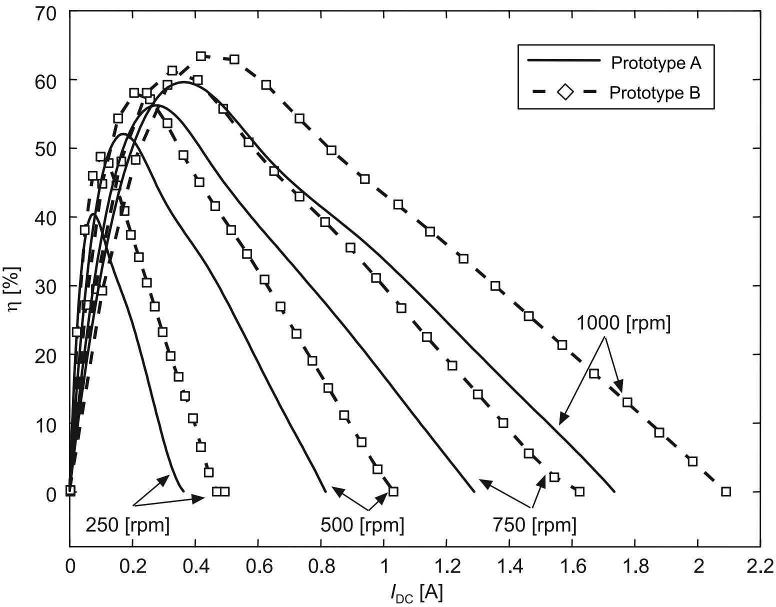

Fig. 5. Efficiency of AFM versus DC output current at varied speed when connected to resistive load

Figure 6 shows the magnetic flux distribution in the air-gap of the investigated machines obtained by FEA as a function of one mechanical period, during the open-circuit operation condition. It is clearly demonstrated that the prototype B of the generator has a higher volume of magnets realized by the use of a wider arc of the magnet as compared with prototype A, therefore, the strength of the magnetic field increased.

All the versions of modified prototype A have a lower saturation effect observed in the stator or rotor cores. Table 3 presents a list of peak values for the calculated flux density in the stator core under open-circuit operation conditions.

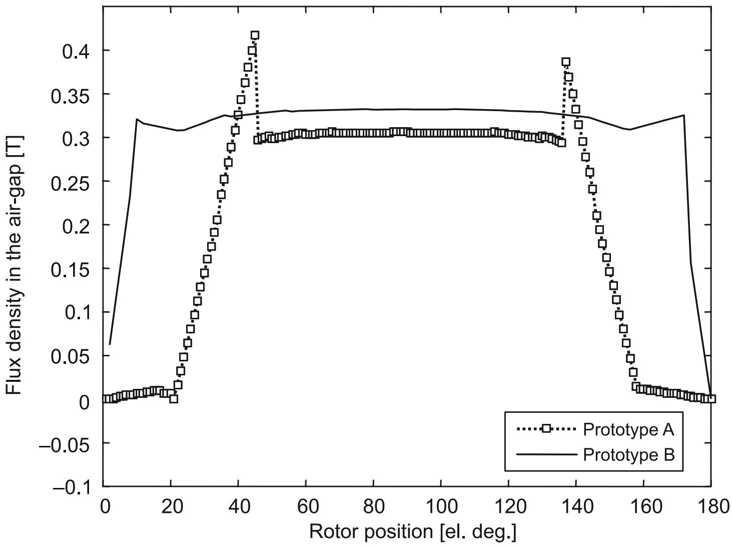

Fig. 6. Magnetic flux density distribution in the air-gap of prototype A and prototype B

The right choice of the ratio of the inner stator disc diameter to the outer diameter has a crucial influence on back-EMF voltage, which is the induced voltage when the current is zero. The results of the obtained DC output voltage after the modified stator/rotor geometry of prototype A are listed in Table 3. It clearly demonstrates that changing the diameter ratio of the stator disc has an influence on the induced voltage by the coils. Induced voltage (e) is a function of the flux-linkage of the winding ($d\psi/dt$).

Table 3

The maximum value of flux density and voltage generated at 1000 rpm observed in prototype A and its modified versions

Generator version	Open-circuit operation condition	
	B_{max} [T]	U_{DC} [V]
Prototype A	1.19	46.66
I	1.21	48.84
II	1.23	50.09
III	1.23	49.86
IV	1.38	48.19
V	1.23	50.13

Since we have postulated that there is no current, it is the flux-linkage produced in the winding by the magnet. The rotation magnet causes the flux-linkage of the winding to alternate and generate an alternating EMF. If the flux waveform in the air-gap is given by a sinusoidal function such as $\psi = \phi \cdot \sin(\theta)$ (where θ – angular position of the coil in electric degree) then the induced EMF voltage by the coil with the number of turn N_t can be expressed as:

$$e = -\frac{d\psi}{dt} = -N_t \phi \cos\left(\theta \frac{d\theta}{dt}\right) \tag{1}$$

where $d\theta/dt$ is the angular frequency of the coil (ω). The eq. (1) can be expressed as:

$$e = -N_t \phi \omega \cos(\omega \cdot t) = -N_t B S_{Fe} \cos(\omega \cdot t) \tag{2}$$

The maximum value of the induced voltage (U_{DC}) of one coil (one pole of the stator) for the maximum value of the flux density (B) in the air-gap is given by:

$$U_{DC} = N_t \cdot \phi \cdot p \cdot \omega_m = N_t \cdot B \cdot S_{Fe} \cdot p \frac{2\pi}{60} n \tag{3}$$

where:

- p – the number of rotor pole,
- n – the speed of the rotor,
- ω_m – angular velocity in mechanical degree.

Equation (3) shows that the induced voltage is a function of the angular velocity and cross-section of the stator disc (S_{Fe}). According to the results listed in Table 3, the maximum voltage induced by winding occurs at ratios 0.5, 0.42, 0.56 of the stator inner to outer diameter, respectively, for the generator versions II, III and V. According to literature [2, 12] the optimal ratio for the idealized axial-flux machine is 0.58.

In axial-flux magnet machines, there is an axial force between the rotor magnets and the stator disc. The period of force fluctuations is equal to the angular distance between two identical magnets. The average axial force from one period was calculated. Figure 7 shows the average axial force between stator and magnet vs. rotor speed at varied resistive load.

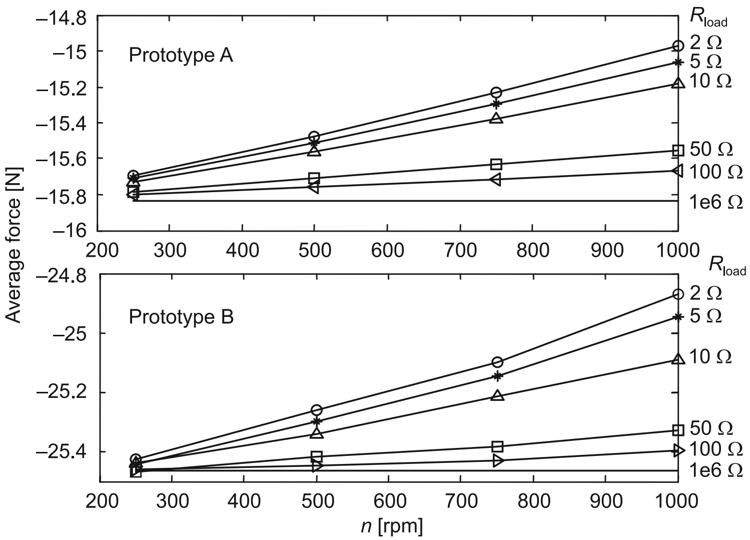

Fig. 7. Axial force between stator and rotor vs. rotor speed at varied load from open-circuit to 2 Ω

5. Conclusion

In this paper, we have presented the design of an axial-flux magnet generator which has the capability to be manufactured in a small workshop. Two prototype concepts of wind generator have been presented. The generators have been chosen from a range of designs based on minimizing the material cost and energy loss.

The main aim of this paper has been to design the wind generator producing the required DC output voltage at the resistance load operation. This generator design is suitable for charging a 3 to 5, 12 V battery system with the rectified generator output voltage. As FEA results show the generators are able to reach the required DC load voltage at speeds in the range of 750 to 1000 rpm. According to Fig. 4, prototype B generates approx. 10 V more than prototype A. Generator prototype B has a higher volume of magnets realized by use of a wider arc of magnet, therefore the strength of the magnetic field is increased (Fig. 6). There is a further possibility to increase the output DC voltage by decreasing the air-gap between the magnets and the stator core. The generated voltage is proportional to the strength of the magnetic field, which depends on the axial length between the stator and magnets.

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References

[1] Parviainen A., Pyrhonen J., Kontkanen P., *Axial flux PM generator with concentrated winding for small wind power applications*, Electric Machines and Drives, IEEE, 2005, 1187-1191.

[2] Vansompel H., Sergeant P., Dupre L., *Optimized design considering the mass influence of an axial flux permanent-magnet synchronous generator with concentrated pole windings*, IEEE Transactions on Magnetics, December 2010, Vol. 46(12), 4101-4107.

[3] Khan M.A., Pillay P., Batane N.R., Morrison D.J., *FPGA Prototyping a composite SMC/steel axial-flux PM wind generator*, Industry Applications Conference, 41st IAS Annual Meeting, IEEE, October 2006, Vol. 5, 2374-2381.

[4] Ani S.O., Polinder H., Ferreira J.A., *Energy yield of two generator system for small wind turbine application*, IEEE International Electric Machines and Drives Conference, IEMDC, May 2011, 735-740.

[5] Louie H., *Experiences in the construction of open source low technology off-grid wind turbines*, Power and Energy Society General Meeting, IEEE, July 2011, 1-7.

[6] Andriollo M., Bertoli M., Martinelli G., Morini A., Torella A., *Permanent magnet axial flux disc generator for small wind turbines*, Electrical Machines, ICEM, IEEE, September 2008, 1-6.

[7] Gerlando A., Foglia G., IacchettiM., Perini R., *Axial-flux PM machines with concentrated armature windings: Design analysis and test validation of wind energy generators*, IEEE Transactions on Industrial Electronics, September 2011, Vol. 58(9), 3795-3805.

[8] Yicheng C., Pragasen P., *Axial-flux PM wind generator with a soft magnetic composite core*, Industry Applications Conference, Fortieth IAS Annual Meeting, IEEE, October 2005, Vol. 1, 231-237.

[9] Javadi S., Mirsalim M., *Design and analysis of 42-V coreless axial-flux permanent-magnet generators for automotive applications*, IEEE Transactions on Magnetics, April 2010, Vol. 46(4), 1015-1023.
[10] Bumby J.R., Stannard N., Dominy J., McLeod N., *A permanent magnet generator for small scale wind and water turbines*, IEEE, September 2008, 1-6.
[11] Glinka T., Wolnik T., Król E., *Silnik tarczowy z wirnikiem wewnętrznym – obliczenia obwodu elektromagnetycznego*, Zeszyty Problemowe – Maszyny Elektryczne, 2011, Nr 92, 23-28.
[12] Glinka T., Jakubiec M., *Rozwiązania silników tarczowych*, Zeszyty Problemowe – Maszyny Elektryczne, 2007, Nr 77, 243-249.
[13] Glinka T., Król E., Białas A., Wolnik T., *Silniki tarczowe z magnesami trwałymi*, Zeszyty Problemowe – Maszyny Elektryczne, 2010, Nr 87, 63-68.
[14] Hosseini S.M., Agha-Mirsalim M., Mizaei M., *Design, prototyping and analysis of a low-cost disk permanent magnet generator with rectangular flat-shaped magnets*, Iranian Journal of Science and Technology, Transaction B, Engineering, 2008, No. B3, 191-203.
[15] Giangrande P., Cupertino F., Pellegrino G., Ronchetto D., Gerada C., Sumner M., *Analysis of two-part rotor, axial flux permanent magnet machines*, Energy Conversion Congress and Exposition (ECCE), IEEE, September 2011, 1576-1581.