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A SINGLE-PHASE SLOTLESS AXIAL-FLUX LOW-POWER GENERATOR WITH FERRITE MAGNETS

BEZŻŁOBKOWY 1-FAZOWY GENERATOR MAŁEJ MOCY O STRUMIENIU OSIOWYM Z MAGNESAMI FERRYTOWYMI

A b s t r a c t

The design and development of an axial-flux ferrite magnet slotless generator for use in a small-scale wind turbine is described. The 4/4-pole single-phase machine is designed for simplicity and ease of manufacture and it consists of one slotless stator disc. The generator produces approx. 12 W at 1000 rpm with electrical efficiency of up to 46%. Because the efficiency of the machine is important, the power curve characteristics and voltage produced by the generator are investigated. The presented generator should generate sufficient output DC voltage to charge 4 to 5 batteries of 12 volt each. Finally, the finite element (FE) results are compared with measurements on a prototype. The calculated values coincide to a strong degree with the experimental results.

Keywords: *single-phase axial-flux machine*, *ferrite magnet generator*, *wind turbine application*, *efficiency*

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

Przedmiotem badań w niniejszym artykule jest prototyp generatora tarczowego, przewidzianego do zastosowania w małej elektrowni wiatrowej. Przedstawiono pomiary i obliczenia numeryczne ważniejszych parametrów funkcjonalnych, takich jak: sprawność, moc wyjściowa i moment elektromagnetyczny generatora tarczowego z magnesami ferrytowymi o strumieniu osiowym. Zbudowany prototyp generatorów o 4 biegunach stojana i wirnika posiada jednofazowe uzwojenie bezżłobkowe. W badanym generatorze zastosowano magnesy ferrytowe o przekroju prostokątnym oraz cewki owalne. Zasadniczym parametrem generatora jest napięcie rotacji, które powinno być wystarczająco wysokie do naładowania określonej liczby akumulatorów. W zamieszczonych poniżej rozważniach pominięto wpływ napięcia i rezystancji wewnętrznej baterii na parametry generatora. Analiza ta będzie kontynuowana w przyszłych badaniach. Do obliczeń pola magnetycznego zastosowano metodę trójwymiarową (3-D) opartą na metodzie elementów skończonych (MES).

Słowa kluczowe: *generatory jednofazowe ze strumieniem osiowym*, *małe turbiny wiatrowe*, *sprawność*

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1. Introduction

Permanent magnet (PM) machines offer many unique features. There are two different designs of the machine – radial and axial-flux PM motors. Axial-flux PM machines have a number of distinct advantages over radial-flux machines. They can be designed to have a higher power to weight ratio resulting in less core material. They are also smaller in size than their radial-flux concepts and have disc shaped rotor and stator structures [8–10, 12, 14–17]. Those are important features of axial-flux machines, because suitable shape and size to match the space limitation is crucial for many applications such as electric vehicles, wind turbines etc. [1–7, 11]. The end-windings are quite short which results in making the copper loss of the axial-flux machine smaller (for example, the torus non-slotted structure of the machine). The axial-flux machine can be built as the slotted or non-slotted stator core structures which consist of the stack of laminated steel. They can be constructed in single-stator-single-rotor or multiple-stator-multiple-rotor forms. The rotor can be manufactured with a surface mounted PM machine or an axial flux interior PM machine (an interior magnet structure). Possible axial flux machine structures operating as a motor or generator have been reported in the literature [8–10, 12, 14–17].

The basic and simplest axial-flux structure is the single-rotor and single-stator topology with surface mounted PMs – this machine is presented in this paper as a generator. The machine is a single-phase generator and can be used to generate power in single-phase electric power systems. It is a three-blade wind turbine for use in homes, boats, yachts, light poles, advertising signs etc. The prototype of the wind turbine is shown in Fig. 1a).

The objective of this paper is to examine the axial-flux generator and compare finite element analysis (FEA) with measurements of the electromagnetic torque, output power vs. DC output current at load operation. Additionally, the DC output voltage generated by the wind generator and the efficiency are also investigated. The required DC output voltage of the generator should be suitable to recharge 3 to 5 batteries of 12 V each.

2. Axial-flux generator prototype

The prototype presented in Fig. 1b) consists of the non-slotted stator core as a stack of laminated steel discs. The stator of the machine is made as a wound core. Coils are connected in series and placed into the disc. The space between the coils and the stator disc is filled with epoxy resin to increase robustness and provide a better heat conduction. The rotor structure is formed by surface mounted ferrite magnets, a rotor core formed from a solid steel disk and shaft.

The generator is designed for small outer diameters. Electromagnetic torque is a function of the outer diameter in axial-flux machines. The required torque can be achieved by using multi-stage axial-flux machine structures. This could be easier to assemble and even better torque and power densities could be obtained. The initial aim was to build the machine in such a way that it remained cheap and light. In this case, the authors decided to use thicker ferrite magnets (12.5 mm) rather than build the multi-stage axial-flux generator structure. The one-phase 4-pole stator and 4-pole rotor topology is shown in Fig. 2.

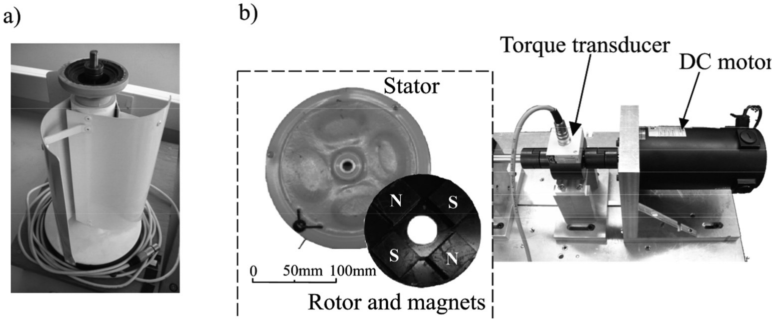


Fig. 1. 3 bladed wind turbine (a) and disassembled a one-phase 4-pole axial-flux generator with test rig (b)

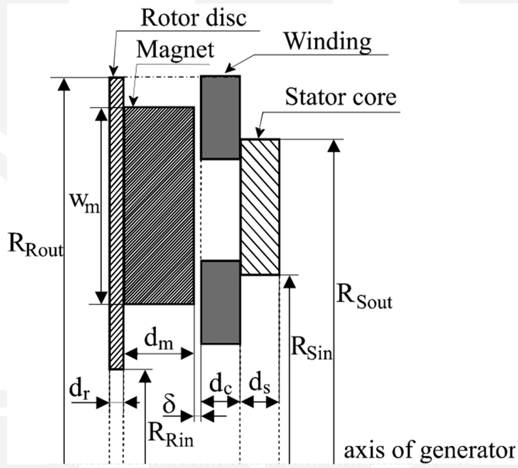


Fig. 2. Single-stator, single-rotor topology of single-phase axial-flux magnet generator

The main dimensions and material specifications of the axial-flux generator are given in Table 1.

Table 1

Dimensions and material specifications of generator

Type of magnet	**Ferrite**
Thickness of magnet (d_m)	12.5 mm
High of magnet (w_m)	35 mm
Width of magnet (l_m)	45 mm
Remanent flux density of the magnets	0.4 T
Outer radius of rotor core/magnet (R_{Rout})	69.2 mm
Inner radius of rotor core/magnet (R_{Rin})	17.2 mm
Thickness of rotor core (d_r)	2.5 mm
Outer radius of stator core (R_{Sout})	58 mm

Table 1 con.

Inner radius of stator core(R_{Sin})	34 mm
Thickness of stator core (d_s)	7 mm
Turn number per coil (n_t)	500
Number of rotor/stator pole	4/4
Thickness of coil (d_c)	7 mm
Air-gap (stator-magnet) (δ)	1.5 mm
Resistance of phase (in series)	78.6 Ω

3. FEA model of single-phase generator

A 3-D FEA model of the generator consists of 4 oval shaped coils connected in series, and 4 square shaped magnets. The 3-D model of the generator has repetitive patterns, then it is possible to model a fraction of the basis geometry such as a ¼ part of the whole generator topology as is shown in Fig. 3a). From a physical point of view, periodicity boundary conditions are set. A single-phase alternating circuit connected through the rectifier circuits produces direct voltage. The DC voltage terminals are connected to the resistive load as shown in Fig. 3b). Here, the battery voltage with internal resistance is neglected and will be investigated in future work.

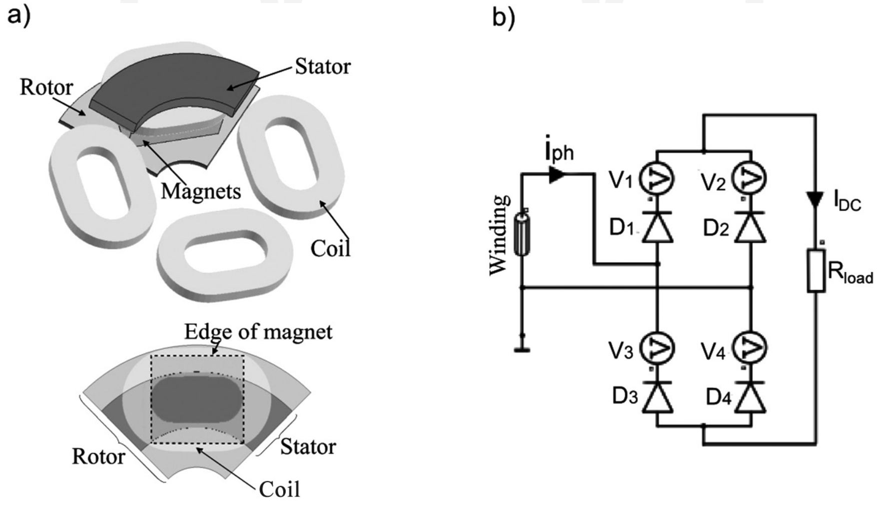
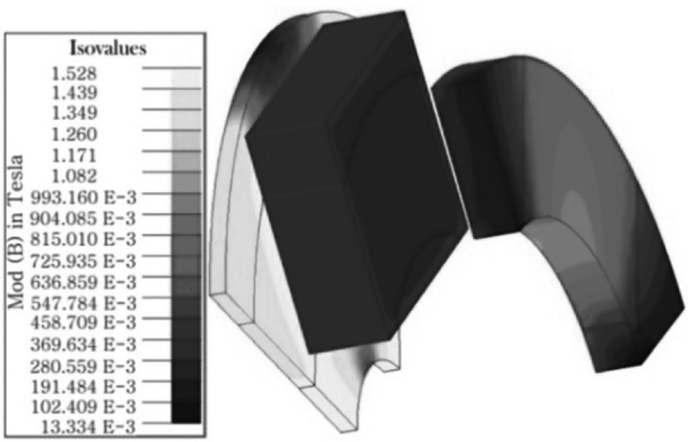


Fig. 3. 3-D FEA model of 1-phase, 4-pole axial-flux generator (a) and the electric circuit producing direct voltage for the wind turbine application with resistive load (b)

4. FEA results and experimental study of the permanent magnet generators

The localized maximum flux distribution in the axial-flux generator is found to be greater in the rotor disk area of the core at approximately 150% of that in the stator disc. The peak value of the flux density at the rotor core is 1.5 T. In this case, at high speed operation the magnet temperature can increase rapidly. The remanent flux density (B_r) of the magnet will then decrease and that will decrease the torque, and consequently, the power and efficiency of the machine. To lower the risk of demagnetization, the size/shape of magnets should be redesigned and/or the thickness of the rotor disc should be increased. Furthermore, the flux density distribution in the air-gap is also shown in Fig. 4.



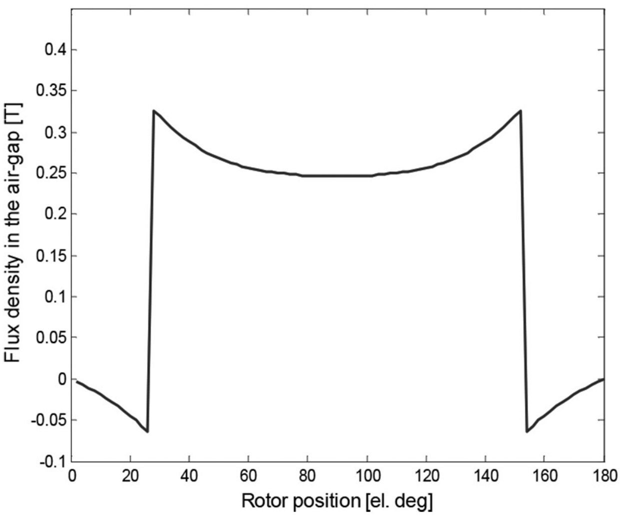


Fig. 4. Flux density distribution in the wind generator and in the air-gap at 1000 rpm under no-load operation

The open-circuit and load characteristics for different rotational speeds are measured. The single-phase load as a diode rectifier with resistive load is connected to the terminal of the generator (Fig. 3). The electromagnetic torque calculated and measured at open-circuit line voltage and the load operation at 1000 rpm is shown in Fig. 5.

Another interesting curve is the one shown in Fig. 6 which depicts the power extracted from the generator as a function of DC current at varied rotor speeds. The dashed red line connects the peak points of all the power curves, and represents the maximum power extraction curve. It clearly shows that the curve rises very quickly as the speed of the generator increases by spinning machine representing a wind.

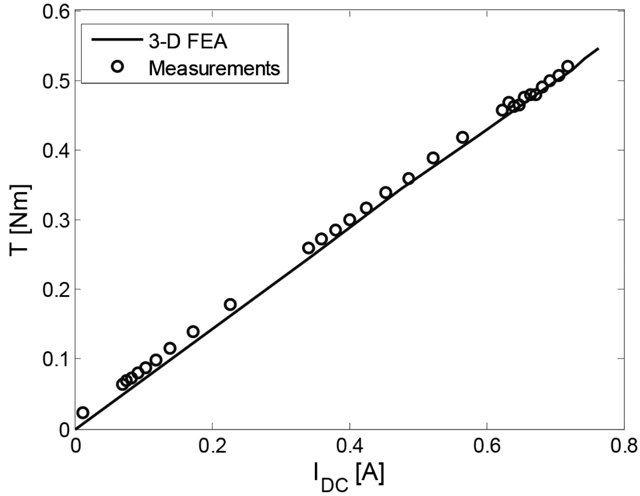


Fig. 5. Measurements and finite element analysis of electromagnetic torque vs. DC output current

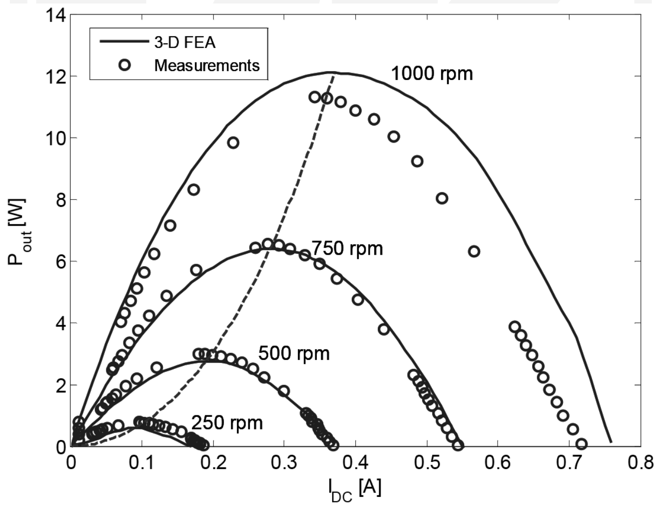


Fig. 6. Measurements and finite element analysis of wind generator output power vs. DC current at varied rotor speed

In the case of the resistive load, the measured voltage of the prototype ferrite magnet generator is about 66 V, the calculated value is 62 V at high speed. The computed data strongly agree with the experimental measurements. The difference may be caused by the magnet temperatures, which differ from those predicted. The calculated line voltages and the output power tended to differ from experimentally measured values by 0.5–20%. This is caused mainly by the fact that the experiment starts from a low speed at the open-circuit operation to the high load operation, therefore, experimental temperatures of the magnets are relatively lower than the temperature set in the FEA model at the first stage of tests. At 1000 rpm, the magnet was already preheated, so the measured power is relatively lower than the predicted values during the test. The working temperature of the load operation is neglected in the finite element analysis and the temperature is set to 25°C.

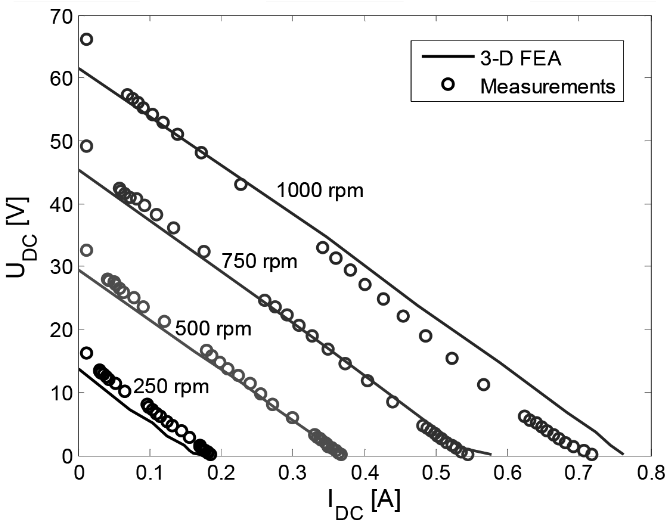


Fig. 7. Measurements and calculations of DC output voltage at varied speed versus DC output current when the terminals of the wind generator are connected to the resistive load

The stiffness characteristic of the presented generator depicted in Fig. 7 is low, owing to the high winding resistance being (R_{ph} = 78.6 Ω) of the small size generator.

The efficiency of the axial flux generator can be calculated as:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \cdot 100\% \tag{1}$$

where:
P_{out}, P_{in} – the output and input power.

The input power P_{in} is calculated as the sum of mechanical power on the shaft and mechanical losses. Mechanical power of the rotating machine can be expressed as $P_{\text{mech}} = T \cdot \omega$, where T – average electromagnetic torque (Nm), ω – angular velocity (rad/s), and mechanical losses are assumed to be dependent upon speed. The losses of winding and losses in the rectifier circuit are also taken into account. Because the axial-flux generator operates at a low electrical frequency, the iron losses are very small and can be neglected.

The results of the efficiency vs. DC current at various speeds in the range 250 rpm to 1000 rpm are presented in Fig. 8. It is shown that at 1000 rpm, the efficiency of the investigated generator is $\eta = 45\%$.

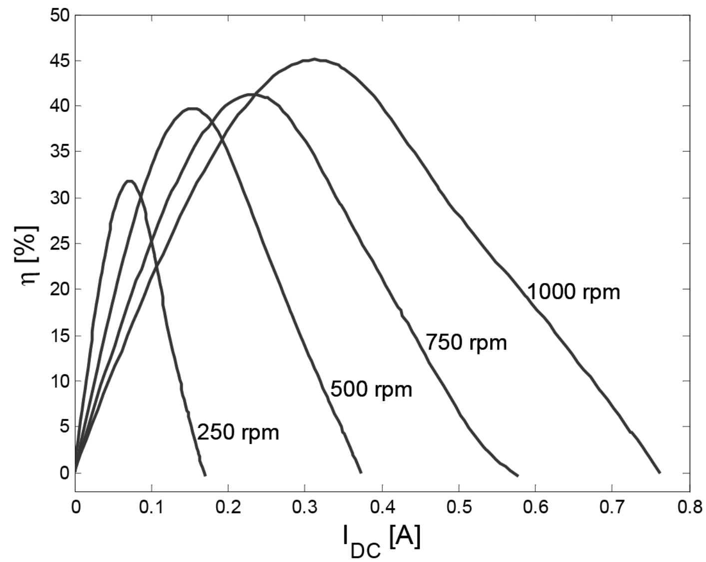


Fig. 8. Efficiency of the axial-flux generator vs. DC current at varied speed

From Figs. 6 and 8, it can be seen that the peaks of the output power and the peaks of the efficiency are roughly at the same DC load currents.

5. Conclusion and future work

This paper has presented the design of a small power axial-flux generator with permanent magnets for small-size wind turbine applications. The concept has comprised a very simple design such as simple wind blades, a disc generator and an electric rectifier circuit. The whole small-scale wind power application has the capability to be manufactured in a small workshop. To calculate the efficiency, mechanical characteristics and output voltage vs. loaded DC current at varied rotor speeds were carried out by using the 3-D software package based on a finite element analysis. The FEA calculation of the electromagnetic torque and output power were verified with measurements to be in strong agreement. The differences between FEA and measurements may be caused by the magnet temperatures.

In the first stage of the experimental tests, the input mechanical energy was fed to drive the rotor of the investigated generator which can change mechanical energy into electrical energy. The results show that the rotor speed of 1000 rpm while the wind generator terminals were connected to the resistivity load, produce a direct current voltage equal to 62 V at a very low resistivity load, with the efficiency of the generator equal to $\eta = 45\%$, the output DC current equal to 0.34 A, and the power output equal to 12 W.

The most common application of wind turbines is battery charging through a diode rectifier. In this research, the balance of power across the AC and DC sides was investigated without a battery connection. Here, the power supplied to the battery and the DC current to the battery was neglected. The battery voltage and internal resistance can affect current I_{DC} during charging and affect the torque [6, 10]. In future work, the battery internal resistance and battery voltage will be connected to the terminals of the diode rectifier system to investigate the power to the battery.

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