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International Journal of Energy Applications and Technologies
Vol. 3, Issue 2, pp. 50 – 54, 2016

www.academicpaper.org/index.php/IJEAT

Research Article

PERFORMANCE EVALUATION FOR A PMSG WITH INTERIOR ROTOR OF N35 AND N42 NDFEB PMs HAVING SAME GEOMETRY IN MICRO WIND TURBINES

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Received 3rd November 2016, Accepted 6th November 2016

Abstract

The aim of this paper is to compare the performance evaluation in terms of the efficiency, cogging torque and manufacturing cost for a permanent magnet synchronous generator (PMSG) with interior rotor of N35 and N42 NdFeB permanent magnets (PMs) having same geometry separately used in a micro wind turbine (MWT). Firstly N35 type PMs have been used on an interior rotor, and then its performance has been measured and calculated by a MWT setup. After that, N42 type PMs have been used on other interior rotor. According to the obtained results, the PMSG with N42 type presented better efficiency than the PMSG with N35 type. But the PMSG with N42 type has induced a bit more cogging torque than the PMSG with N35 type. When comparing in terms of efficiency, a higher efficiency has been obtained by the PMSG with N42 type.

Keywords- *PMSG, PM, efficiency, NdFeB, N42, N35.*

1. Introduction

Nowadays, the usage of renewable energy resources such as wind, geothermal, tidal and solar in electricity production is gradually increasing. Wind energy is the most popular of these renewable energy resources. In order to convert wind energy into electrical energy, wind turbines are employed [1].
Wind turbines are divided into two classes as large wind turbines (LWTs) and small wind turbines (SWTs) [2]. While LWTs usually are operated as grid-on, SWTs are utilized as both grid-on and grid-off. Furthermore, as given in Table I, SWTs are separated into three different classes [3]. According to the power of SWTs in Table I, there are SWT types employed by direct-drive and gear mechanism systems [1].
Depending on the powers of SWTs, induction generators (IGs) and permanent magnet synchronous generators (PMSGs) are widely preferred [4]. PMSGs used SWTs are more advantageous than IGs because they have more power density, higher torque and direct-drive ability [5]. Structure of PMSG is simple and their maintenance is easy [6]. There is also no copper loss on rotor. However, one of the biggest disadvantages is their cogging torque [7]. Because of the high cogging torque, they do not commence electrical energy generation at low wind speed [2].
SWTs are designed as horizontal and vertical axis. Also, PMSGs inserted in SWTs are manufactured two types as outer and interior rotors [2, 8]. Although the PMSGs with interior rotor have more size than the PMSGs with outer rotor, their power density, moment, and efficiency are high. But, when considering in terms of manufacturing cost and labor, manufacturing cost and labor of the PMSGs with interior rotor are higher than the PMSGs with outer rotor. In addition to these, PMSGs are constructed as axial and radial flux [9-10]. Output voltage and torque of the PMSGs with radial flux are greater than the axial flux [11].

2. Permanent Magnets

Permanent magnet (PM) forms and elements that are used in PMSGs have a great impact on performance of PMSGs [12-14]. PM forms, which are placed on an interior rotor with four poles, are illustrated in Fig. 1. A surface radial, a parallel, a breadloaf and a ring PM form are presented in Fig. 1. These are classified as the PMSGs with surface PM rotor. Additionally, there are

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Note: This paper has been presented at the International Conference on Advanced Technology & Sciences (ICAT'16) held in Konya (Turkey).

also the types of PMSG with PMs that are embedded in a rotor.

Magnetization profiles also are important during the PM usage. These are sine angle or sine direction, parallel, radial sine and radial profile. In addition, these are illustrated in Fig. 1 and the most popular of which is the parallel magnetization.

PMs are made up of Aluminum-Nickel-Cobalt (AlNiCo), Ferrite, Samarium-Cobalt (SmCo), and Neodymium-Iron- Boron (NdFeB) materials. Their operating temperatures and magnetic flux density-magnetic field intensity (BH_{max}) are different from each other. The values are given in Table II. When Table II is examined carefully, although NdFeB PMs have the highest BH_{max} value, their operating temperatures are lower than others. Recently, NdFeB PMs are widely preferred in PMSG design. [15-16].

The remanence magnetization value (B_r) of AlNiCo magnets among them is quite high. Due to the fact that they are expensive and also can easily lose their magnetization property, they are not preferred lately.

Ferrite magnets being another type of PMs that are relatively lower cost and more commonly usage than AlNiCo PMs. They are resistant to the loss of remanence magnetization. BH_{max} values of both AlNiCo and Ferrite PMs are lower than SmCo and NdFeB PMs.

SmCo and NdFeB PMs are known as rare-earth magnets. Their BH_{max} values are quite high compared the AlNiCo and Ferrite PMs. One of their biggest disadvantages is that they are fragile. The remanence and demagnetization values are high.

In recent years, the remanence values of the sintered NdFeB PMs are increased above 1.0 T. In Table III, properties of N35 and N45 type NdFeB PMs that are sintered at different grade are listed. Their performance analysis two type PMs were carried out in a micro wind turbine (MWT). The sintered PMs offer up to 150°C operation temperatures. After the operation temperatures, SmCo PMs are preferred. SmCo PMs also have different temperatures. Their operation temperatures rise at 250°C. Studies continue to increase the operation temperatures of NdFeB and SmCo PMs.

Table 1. Generation powers of SWTs

Category	Power (kW)	Annual energy production (kWh)	Tower height (m)
Micro wind turbine	< 1.5	< 1,000	10–18
Small wind turbine	1.5-50	< 200,000	15–35
Small–medium wind turbine	50-500	< 1,800,000	25–55

3. Application

Two rotors with surface magnet having N35 and N42 NdFeB PMs were designed and manufactured. The dimension of PMs was sized as 20 × 20 × 6 mm. The usage of the rotor together with a PMSG stator is demonstrated in Fig. 2. A designed MWT, the stator and the rotor dimensions are presented in Table IV. To reduce the cogging torque, the used PMs were selected in a breadloaf form. Moreover, to reduce the cogging torque, their placement was fulfilled according to a pole shifting method [7].

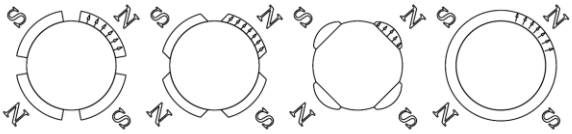

Fig. 1. PM forms with magnetization profiles: (a) Surface radial magnets with sine angle or sine direction magnetization profile, (b) Surface parallel magnets with parallel magnetization profile, (c) Breadloaf magnets with radial sine magnetization profile and (d) Ring magnets with radial profile.

Table 2. PM properties.

Permanent Magnet	Operating Temperature (°C)	BH_{max} (kJ/m^3)
NdFeB	150	470
SmCo	250	350
AlNiCo	500	80
Ferrite	300	40

Table 3. Properties of N35 and N42 type neodymium-ferrite-boron PM

Properties	N42	N35
Maximum energy production, BH_{max} (kJ/m^3)	318-342	263-287
Maximum work temperature, T_m (°C)	≤80	≤80
Remanence (residual induction), B_r (T)	1.28-1.32	1.17-1.22
Coercive force, H_c (kA/m)	≥915	≥868
Curie temperature, T_c (°C)	310	310
Intrinsic coercive force, H_{ci} (kA/m)	≥955	≥955
Temperature coefficient, βH_{ci} (% / °C)	-0.6	-0.6

After the rotors that manufactured two prototypes had inserted in the PMSGs, they were mounted in the MWT, as given in Fig. 3. Lastly, their performance tests were carried out by means of a truck test [2]. During the truck test, the generated power from the MWT was transferred to a battery group, which was consisted of four batteries of 12 V and 60 Ah. The battery group was charged until 13.5 V. After the charge, two load resistances of 600 W were used to discharge to the battery group. In order to measure the generated power from the MWT with PMSGs used N35 and N42 NdFeB PMs, a data acquisition system, which was described and embedded formulas in detail

[2], was operated. The measurement of input power of the MWT was realized by two different calibrated anemometers – one was Prova AVM-03, the other was Kestrel 3000 model. In addition to these measurements, wind speed was also checked by the truck display. The ambient temperature was registered by both the data acquisition system and Extect HD200 measurement instrument. To define the cogging torque, Crane Electronics/UTA-451-0020-OP 5 Nm brand/model transmitter and Crane Electronics/TO-890-01CR-0-EUR brand/model display, which was described in detail [7], were utilized.

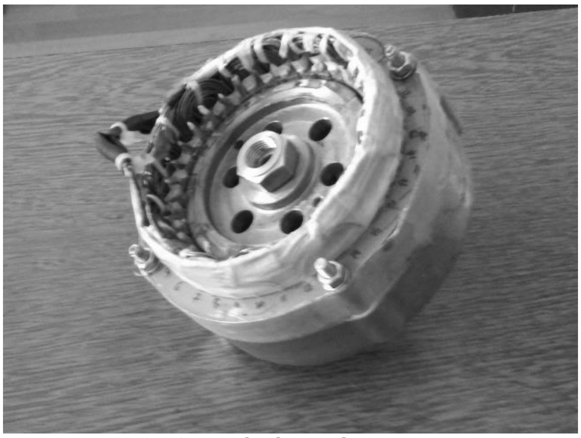

Fig. 2. The designed PMSG.

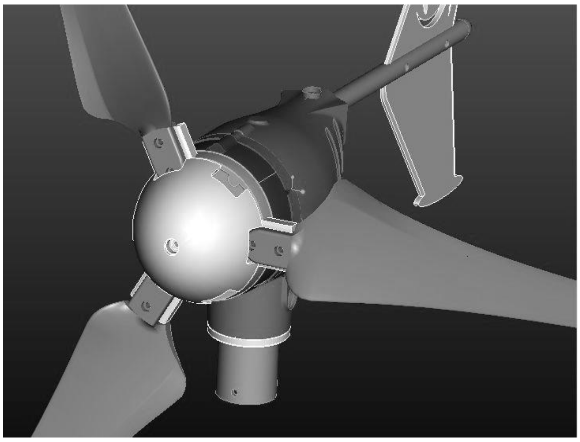

Fig. 3. The designed and constructed MWT.

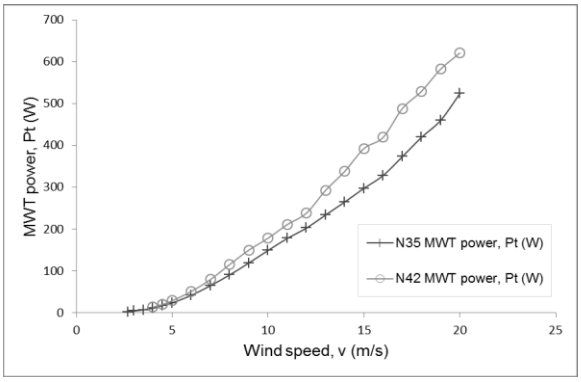

Fig. 4. The obtained powers as a function of wind speed.

Table 4. The designed MWT, stator and rotor dimensions and properties.

MWT	
Properties	**Value**
Number of blades	3
Body material	Aluminum
Axis type	HAWT
Blade swept area	1.207 m^2
Breaking	Electrical
Rotation	Clock wise
Stator	
Properties	**Value**
Inner diameter	99 mm
Length	20 mm
Groove width	7 mm
Outer diameter	150 mm
Slot height	11 mm
Slot opening width	3 mm
Rotor	
Properties	**Value**
Number of poles	12 poles
Material	1040 steel
Air gap	1 mm
Shaft length	110 mm
Bearing outside diameter	40 mm
Bearing inside diameter	20 mm

4. Results and Discussion

The truck test was carried out by using of the PMSGs having two rotors with surface magnet separately used N35 and N42 NdFeB PMs in the MWT. The air pressure was taken as 1020 hPa to calculate the input power of the MWT. The air density was obtained 1.221 kg/m^3.

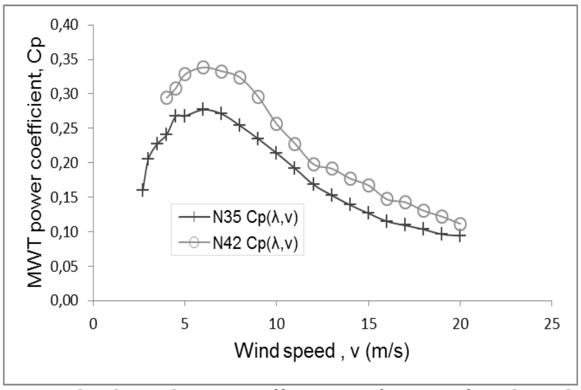

Fig. 5. The obtained power coefficient as a function of wind speed.

In the MWT having the PMSG with the surface magnet rotor used N35 NdFeB PMs, the cut-in was measured 2.7 m/s. In other, which was the MWT having the PMSG with the surface magnet rotor used N42 NdFeB PMs, the cut-in was taken 4.1 m/s.

Depending on wind speed, the generated powers from the MWTs and their power coefficients are presented in Fig. 4 and 5. When Fig. 4 was examined, the nominal power of the MWT that has N35 NdFeB PMs at 11 m/s wind speed was 177 W. Also, the nominal power of the MWT that has N42 NdFeB PMs at 11 m/s wind speed was 210 W. In Fig. 5, the power coefficients of the MWTs having N35 and N42

NdFeB PMs were defined 0.277 and 0.388, respectively.

The highest cogging torques of the MWTs having N35 and N42 NdFeB PMs were measured as 0.1 Nm and 0.17 Nm, respectively, as shown in Fig. 6. In the MWT with N42 NdFeB PMs, the cogging torque was occurred a quite high value. In order to reduce the value, it is necessary that other cogging torque reduction methods have to be used together with the pole shifting method.

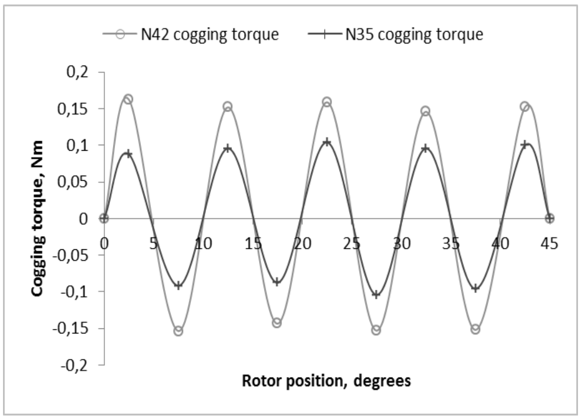

Fig. 6. The obtained cogging torque as a function of rotor position.

When examining the literature regarding the study, Lee *et al.* [8] executed a study with outer rotor PMSG. The cogging torque of about 0.18 Nm was measured in their application used PMs of Br 0.43 T. Also, Jang *et al.* [10] manufactured an MWT of 1.5 kW employed both NdFeB of 1.26 T and Ferrite type PMs. They tried on the usability of Ferrite PM instead of NdFeB PM. Although the PMSGs generated same power, the PMSG with Ferrite type PM had larger volume than the PMSG with NdFeB PM in reference to their results. They saw an increase of manufacturing cost. At low speed conditions, Ani *et al.* [17] compared six different SWT in terms of the energy yield and the generated electricity cost. Their cut-in speeds were observed between 2.5 and 4.0 m/s. The manufactured MWT with N35 type PM was compared with regard to cut in, manufacturing cost, energy yield and generated electricity cost in [2] in detail. Because of the usage of N42 type PMs, a small increase of 20 € occurred in the manufacturing cost of MWT. The value was below 1%. According these obtained results, these were quite acceptable when the carried out study was compared the other studies in literature.

5. Conclusions

In this study, the performance analyses of both N35 and N42 type PMs for interior rotor PMSGs were carried out. For this purpose, two surface-mounted rotors that had N35 and N42 NdFeB PMs were designed and manufactured. These were tried on an MWT with PMSG inserted in the rotors separately. According to the obtained data, the generated nominal power of the MWT having N35 NdFeB PMs was obtained 177 W. For the other MWT having N42 NdFeB PMs, the generated nominal power was measured 210 W. When compared their power coefficients, an improvement of 18% was calculated in the MWT having N42 NdFeB PMs in reference to the MWT having N35 NdFeB PMs. However, the cogging torque increased 1.7 times in the MWT having N42 NdFeB PMs. On the other hand, the usage N42 NdFeB PMs increased only 1% in the manufacturing cost of MWT.

Acknowledgment

The author would like to acknowledge that this work was supported by TUBITAK under No. 114E419.

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