Design and Experimental Analysis for Reduction of Cogging Torque by Pole Shifting in Permanent Magnet Synchronous Generator

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***Abstract*—This paper presents an application of the pole shifting technique used for reducing the cogging torque of permanent magnet synchronous generators (PMSGs) that employs in micro wind turbines (MWTs). The effectiveness of the pole shifting technique on the cogging torque reduction of the PMSG has been tested by the cogging torque measurement system that has been connected with a MWT. In order to evaluate the performance of the proposed technique, two internal rotors for the PMSG on the measurement system, namely internal rotor with the pole shifting and internal rotor without the pole shifting, have been designed and fabricated. The measurement results and analyses have showed that the PMSG with the pole shifting has a very low cogging torque when comparing to the PMSG without the pole shifting.**

***Index Terms*—Permanent magnet machines, renewable energy sources, torque measurement, wind energy generation.**

I. INTRODUCTION

In some rural regions, in which there is not an electricity network, electricity generation by wind energy has become more efficient and inexpensive than other renewable energy resources. Therefore, many countries support the usage of wind turbine in such regions [1]. Before the installation of a wind energy system, it is a necessity to do analyses related to the wind power in the regions where the system is installed and the expected investment cost. In literature, many methods have been developed for these analyses [2]. However, such analyses for micro wind turbines (MWTs) are not required to be fulfilled due to the low cost of installation [3].

Two types of generators are usually employed in the MWTs: Induction generators (IGs) and permanent magnet synchronous generators (PMSGs). The PMSGs are manufactured as internal and external rotor [4]. Recently, in the MWTs, the PMSGs have been more widely utilized than the IGs because of direct drive and high efficiency [5]. Additionally, the PMSGs have the high torque density and the power factor characteristics [6]. One of the biggest disadvantages of the PMSGs is the high cogging torque which negatively effects the electricity production of the MWT at low wind speeds [7].

The electrical energy amount per rotor swept area (kWh/m^2) of the MWT is high, which starts the electricity production at low wind speeds. Also the energy per cost (€/kWh) is low. In this situation, the MWT with low cogging torque is more advantageous than other MWTs [8]. For this purpose, some cogging torque reduction techniques such as the fractional number of slot per pole and phase, the skewing, the magnet optimization and the changing stator slot width have been executed in PMSGs [9]. The reduction techniques of the cogging torque are simulated by finite element analyses (FEA) on the computer programs. Some of these techniques cause additional costs to manufacturers [7].

The skewing technique, which is one of the most widely used techniques for reducing cogging torque, has been applied in a PMSG. The high production cost and the reduction of the maximum obtained torque have been seen in tests [10]. So as to reduce the cogging torque, a flux barrier technique has been executed and the cogging torque has been reduced from 35 % to 5 % [11]. A study which focused on the hybrid technique consisting of the magnet shifting and the magnet pole-arc optimization has been conducted [12]. When the technique is implemented on small PMSGs, the result of the slight production defects that could be required at high machine tolerance has been reached. For a PMSG with an eleven-slot stator and a four-pole, a study has been carried out by FEA. An effective pole-arc to pole-pitch has been defined for reduction of cogging torque [13]. In another study, the cogging torque has been reduced by auxiliary slots inserted into pole face of the magnetizing yoke [14]. For use at low hydroelectric speeds, a PMSG of about 4 kW has been simulated and the cogging torque has been realized about 6 Nm [15]. A new pole shifting calculation technique also has been analytically proposed [16]. Moreover, the cogging torque has been decreased based on Fourier series by the way pole shifting [17].

In this study, the implementation for the reduction of the cogging torque of PMSGs has been carried out by employing the pole shifting technique. Two type PMSG

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rotors have been used on the PMSG. One of them has had the high cogging torque rotor without the pole shifting and the other has had the low cogging torque rotor with the pole shifting. They have been both examined on a single PMSG separately. Then, the PMSG with these rotors has been tested on a MWT. In the study, the application results have been discussed rather than the simulation results of the pole shifting. Presentation of the study has been organized as follows: the implemented material and method, the obtained results and discussion and ultimately conclusions.

II. MATERIAL AND METHOD

A. *Cogging Torque*

The cogging torque stems from the interaction between the rotor permanent magnets (PMs) and the stator teeth [6]. The cogging torque on a PMSG is constant and produces zero work [7]. For this reason, the cogging torque causes noise and vibration in PMSGs especially at low speeds and the direct drives applications. It is given as the below equation

$$\tau_{cog} = -\frac{dW_m}{d\theta_m}, \tag{1}$$

where, τ_{cog} is the cogging torque, W_m is the magnetic energy of the PMSG and θ_m is the mechanical angle of the rotor [6]. The cogging torque period is defined by the numbers of poles and slots. The cogging torque seen in a PMSG can be modeled by the sum of all produced fundamental torque because of the interaction between each magnet and the edges of slot opening [10]. In a slot pitch rotation, the number of the cogging torque periods, N_{SP}, is an important indicator, in that they provide information about the spatial displacement of the fundamental cogging torque waveforms. If the phases of the fundamental torques are different, the seen cogging torque is zero. N_{SP} in a slot pitch rotation is given by the below equation

$$N_{SP} = \frac{2p}{HCF\{Q, 2p\}}, \tag{2}$$

where, p is the number of pole pairs, HCF is the highest common factor and Q is the number of slots [7].

The spatial period of the cogging torque, T_{SP}, is expressed as below

$$T_{SP} = \frac{2\pi}{LCM\{Q, 2p\}} = \frac{2\pi}{N_{SP} Q}, \tag{3}$$

where, LCM and 2π are the least common factor and the mechanical angle of a rotor rotation (360°), respectively. As described in (3), the T_{SP} is inversely proportional to the N_{SP}. The minimum value of the N_{SP} equals one. This value presents same phase waveforms culminate in maximum cogging torque. Its higher values induce lower cogging torque throughout slot pitches due to the distribution of fundamental torque waveforms [18].

The cogging torque can be explained by Fourier series as below

$$\tau_{cog} = \sum_{k=1}^{\infty} T_k \sin(k N_{SP} \theta), \tag{4}$$

where, T_k is the Fourier coefficient of k^{th} harmonic and θ is the electrical angular position [19].

B. *Pole Shifting*

When each PM is placed on the rotor by an equal angle, the torque composed by stator slots of the PM is the same phase to the others [20]. Therefore, the cogging torque becomes high. If the PMs are properly shifted, the harmonic components of the cogging torque can be eliminated, or can be lowered at a great rate [16]. Then, the cogging torque is significantly reduced by the removing or decreasing of the harmonic components. The placement of the PMs is also called the asymmetrical placement [20].

In order to reduce the cogging torque, the shifting angle value that will be used in the pole shifting can be found by below equation

$$\theta_k = \frac{2\pi (k-1)}{2 p N_{SP} Q}, \tag{5}$$

where, θ_k is the shifting angle value. The definition of the shifting angle aims to reduction of the fundamental harmonics with PM symmetry. In this case, there are still other harmonic components. So as to reduce the cogging torque, not only the fundamental harmonics with PM symmetry but also the introduced harmonics that occurs after the pole shifting should be removed [16].

C. *The Designed Rotors and the PMSG*

The designed and manufactured PMSG parts are given in Fig. 1. The PMSG consists of 1) the stator with 36 slots, 2) the back plate, 3) the front plate and the shaft, 4) the rotor having 12 poles without the pole shifting and 5) the rotor having 12 poles with the pole shifting.

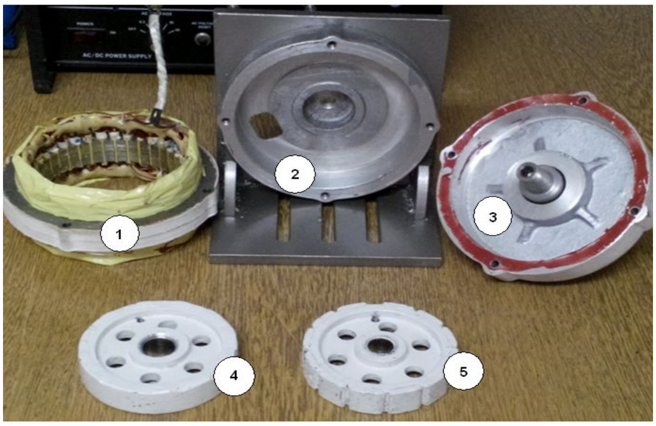

Fig. 1. The designed and manufactured all parts of the PMSG.

In Fig. 1, it should be noted that the first two rotors has an internal rotor without the pole shifting, while the last rotor has an internal rotor with the pole shifting. They have been experimentally examined to compare the cogging torque values without and with the pole shifting.

The stator of the PMSG has 36 slots and the output voltage is 3 phase, 12 V. The integer slot winding has been used in the stator winding. In Fig. 1, part number 4, the constant angle (360/12 = 30°) has been employed in the placement PMs of the rotor without the pole shifting, and each slot pitch is 360/36 = 10°. The cogging torque of the rotor without the pole shifting is high, due to the fact that it has all harmonics of the cogging torque.

In Fig. 1, part number 5, in the placement PMs of the rotor with the pole shifting, the shifting angle value for the pole shifting from (5) has been calculated θ_0 = 0.833°. For other PMs, the other shifting angles have been found from the following equation

$$\theta_k = 0.833(k-1), \tag{6}$$

where, k = 1, 2, 3, …, 12.

D. The Measurement System of PMSG Cogging Torque

The setup of the cogging torque measurement system of the designed and manufactured PMSG is given in Fig. 2.

Fig. 2. The setup of the cogging torque measurement system of the designed and manufactured PMSG.

The cogging torque of the PMSG with two different designed rotors without and with the pole shifting has been measured by the Crane Electronics UTA-451-0020-0P 5 Nm brand/model transmitter. The display instrument of the transmitter has been also employed the Crane Electronics TO-890-01CR-0-EUR brand/model display. The measurements for receiving of the peak and normal values of the cogging torque have been executed in two different modes of the display instrument: 1) the peak to peak mode and 2) the instantaneous mode, respectively. All of the measurements have been repeated both the rotor without and with the pole shifting.

E. Setup of MWT with PMSG

The setup used for carrying out the performance tests of the PMSG without and with the pole shifting on a MWT is shown in Fig. 3.

Fig. 3. Trucker testing for MWT having PMSG without and with the pole shifting.

Thanks to this setup, the cut-in speeds of the MWT having the PMSG without and with the pole shifting have been measured through this setup by a truck test. A MWT tower of 3.5 *m* has been setup on the test trucker.

For the measurement of wind speeds on trucker, two different vane-type anemometers fulfilled the calibrations in the wind tunnel have been employed. One of them is Prova AVM–03 brand/model anemometer with ± 3 % accuracy at 0.3 m/s–45 m/s wind speed and the other is Kestrel 3000 brand/model anemometer with ± 3 % accuracy at 0.6 m/s–40 m/s wind speed.

III. RESULTS AND DISCUSSION

The cogging torque values of the PMSG without and with the pole shifting have been obtained from the setup of the torque measurement system in Fig. 2. While the cogging torque values are being taken, no load has been connected across the PMSG. As a function of the angle rotation of the rotor without the pole shifting, the cogging torque values of the PMSG are given in Fig. 4.

According to Fig. 4, when the PMs are placed at the equal angle on rotor surface without the pole shifting, the maximum peak to peak value of the cogging torque has been measured about 0.6 Nm. It can be seen that while the cogging torque at 7.5° has been 0.3 Nm, the cogging torque at 12.5° has been 0.25 Nm. In here, there are some small fluctuations in the cogging torque values due to the different angle placement faults of the PMs. There is not any specific place for the PMs on the rotor surface. As a result of this, some shifting has been occurred during the placement of the PMs.

As a function of the angle rotation of the rotor with the pole shifting, the cogging torque values of the PMSG are also given in Fig. 4. It can be seen from Fig. 4 that the maximum peak to peak value of the cogging torque is about 0.2 Nm when the PMs are placed with the pole shifting technique on the rotor surface. Moreover, the maximum cogging torque value at 22.5° has been obtained as about 0.1 Nm. The same value has repeated at 27.5°. In addition, the fluctuations which arose from the faults of the different small angle placement of the PMs have been seen between some cogging torque values.

As a function of the angle rotation of the rotor without and with the pole shifting, the cogging torque values of the PMSG are comparatively given in Fig. 4. It can be understood from Fig. 4 that a significant difference is occurred between the cogging torque values of the PMSG without and with the pole shifting. When the peak to peak cogging torque values without and with the pole shifting is compared, the cogging torque of the rotor with the pole shifting has been reduced about 67 % than the cogging torque of the rotor without the pole shifting.

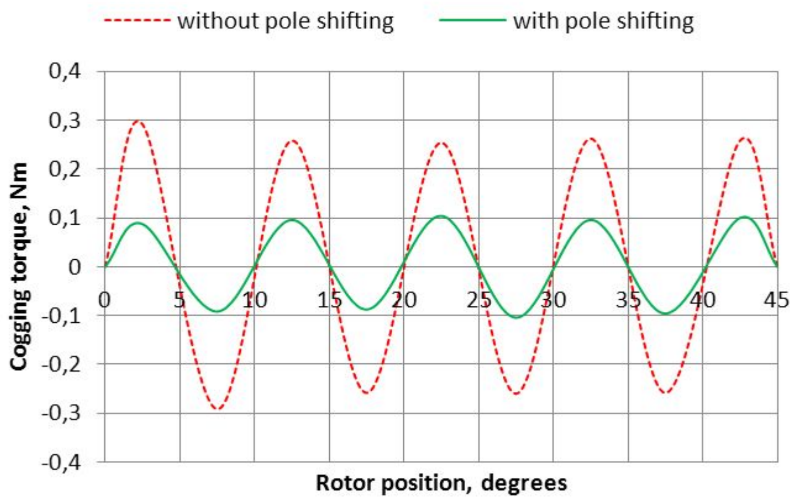

Fig. 4. The cogging torque values of the PMSG as a function of the angle rotation of the rotor without and with the pole shifting.

The reducing of the cogging torque on the PMSG will make a great advantage for electricity generation of the MWT. As the cogging torque decreases, the cut-in speed of the MWT will also decrease. In Fig. 3, for cut-in speeds, the performance analyses of the PMSG without and with the pole shifting have been carried out on a MWT by a truck test. According to the test results, while the cut-in speed of the MWT having PMSG without the pole shifting has been obtained about 4.5 m/s, the cut-in speed of the MWT having PMSG with the pole shifting has been obtained as about 2.7 m/s. Because of reduction of the cogging torque on the PMSG, when attention is paid to these cut-in values, a significant difference between the two cut-in values has been occurred.

IV. CONCLUSIONS

It is demanded that PMSGs have low cogging torque values in industries in which they are used. The PMSGs with low cogging torque provides benefits to their users.

In parallel with this purpose, in this study, a pole shifting technique not bringing additional cost to the manufacturers has been successfully applied to reduce the cogging torque. Two internal PMSG rotors having without and with the pole shifting have been manufactured for comparison. The practical cogging torque values of the PMSG with both rotors have been compared with each other. As a result of these comparisons, the cogging torque of internal PMSG rotor with the pole shifting has been less about 67 % than the cogging torque of internal PMSG rotor without the pole shifting. The PMSGs having internal rotor without and with the pole shifting has been evaluated a performance test on a MWT. Consequently, the cut-in speeds of the MWT without and with the pole shifting has occurred at 4.5 m/s and 2.7 m/s, respectively. Depending on the values with the pole shifting, a MWT having low cut-in and power has been fabricated.

The MWT will provide both high annual energy yield per swept area (kWh/m^2) and low generated electricity cost (€/kWh) at low wind speeds.

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