The Implement of Permanent Magnet Material Variations on the Reduction of Cogging Torque in PMSG

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Abstract. Permanent magnet synchronous generator is a type of electric machine that is extensively adopted for wind turbines. However, the operation of permanent magnets in the rotor sets up a unique issue, particularly an enormous cogging torque value. Cogging torque is a torque that occurs because the interaction that takes place between the flux provided by a permanent magnet and the slot on the stator. This torque affects the rotor’s initial movement in the generator where the rotation of the rotor will be heavy and not smooth. Therefore, this torque is crucial to be decreased so that indeed in small wind speed inputs, the rotor can rotate. In this research, variations in the handling of permanent magnets will be analysed, especially Alnico, NdFeB, Ceramics and SmCo employing the anti-notch method. From the results achieved, each type of permanent magnet influences the value of tangential flux density which further influences the value of cogging torque reduction. By applying the new anti-notch method, the cogging torque value is significantly reduced compared to the reference generator design.

1. Introduction
Permanent magnet synchronous generator (PMSG) is a type of generator that is generally utilized for electricity generation that uses wind as the driving fuel. The adoption of permanent magnets in the rotor emerges in unique problems that must be fixed, particularly the emergence of cogging torque. Cogging torque is the torque that emerges outstanding to the interaction between the magnetic flux from the permanent magnet in the rotor to the slot in the stator. This torque will involve the initial cycle of the generator, the higher the cogging torque value the rotor cycle will be harder. This means, to turn the rotor, a higher wind speed is demanded. Whereas it is noticed that the wind speeds that strike most often in places in the earth are light to medium wind speeds of between 3-4 m / s. This has pointed to the attention of research to reduce the cogging torque value on electric machines.

Many researchers have conducted research on how to diminish the cogging torque value on an electric machine. The method used is essentially broken up into two grand methods, particularly: first by modifying the stator geometry [1,2] and second by modifying the rotor geometry [3], comprising the permanent magnet. Stator geometry modification is accomplished by notch teeth pair [4,5], segmentation [6,7,8]. While the modification of permanent rotor and magnet is accomplished by magnet shifting [9,10], pole pairing [11,12,13] notching teeth [14,15,16,17,18] and segmentation on magnetic poles [6,7,8].

In this research, was conducted to reduce the cogging torque with the anti-notch method. This method is a new method which is the opposite of notching by adding a small, half-cylinder shaped tooth on the
surface of the stator teeth. Changes in permanent magnet material (PM) were further carried out to obtain materials that most impressed the reduction in the minimum cogging torque value. The hypothesis is that replacing PM material will involve the decline in cogging torque values. The PM materials employed are those comprised of rare earth magnet materials. The guidelines to be investigated are cogging torque, density flux and field intensity generated by the PM materials.

2. Cogging Torque Reduction
The adoption of a permanent magnet on the generator brings its own issues for the generator, especially the emergence of cogging torque at the start point of the rotor movement. Cogging torque is the torque that emerges at the start point of the rotor movement which comes from in the rotation of the rotor becoming heavy and noisy. This torque is caused by an interaction between the slots on the stator and the magnetic flux generated by a permanent magnet placed in the rotor [19]. If the cogging torque is represented, it will be a persisting wave. The frequency of cogging torque repeats depends on the number of slots and poles that are occupied by the electric machine. The frequency of cogging torque repetition is modeled as Fourier series, which can be understood from the succeeding equation:

\[ T_{co} = \sum_{n=1}^{\infty} T_n \sin(nN_{co} \theta + \varphi_n) \]

where:
- \( T_{co} \) represent the cogging torque in Nm, the value of \( n = 1 \) describes the early torque that occurs \( T_1 \), that is as the peak of the principal torque cogging while \( \theta \) as the mechanical rotor position. The basic equations of cogging torque are obtained from the initial derivative of coenergy to differences in the mechanical angle of the rotor, as determined in the accompanying equation:

\[ T_{ec} = \frac{dW_c}{d\theta} \]

and the coenergy is retrieved from computations applying the ensuing equation:

\[ W_c = \int \frac{B_n^2}{2\mu_0} \, d(v_r) \]

where:
- \( T_{ec} \) is electromagnetic torque, which is another mention for cogging torque in Nm, while \( W_c \) is the energy in joules and \( v_r \), is the area total depended on to encounter cogging torque. To observe the effect of distance, normal and tangential directions of density flux, and variations in permeability of magnetic materials to a reduction in the value of cogging torque, \( T_{ec} \) can be considered applying the supporting equation:

\[ T_{ec} = \frac{L}{\lambda_s \mu_0} \int r B_n B_r ds \]

where:
- \( L \) is the length of the rotor (m), \( l_g \) is the length of the air gap (m), \( r \) is the dummy radius (m), \( B_n \) is the normal density flux (T), \( B_t \) is the tangential flux density (T), \( S_g \) is the area the air gap surface area, and \( L S_g \) is the volume of the air gap (m³).

3. Research Method
In this research, permanent magnet synchronous generators inner rotor was utilized as reference research objects with 3 Phase, 12 slots and 8 poles. Another dimensions are :
- Diameter of outer stator : 190 mm
• Diameter of inner stator: 100 mm
• The thickness of permanent magnet: 6 mm
• The width of the airgap: 2 mm
• Material of the stator: M19 steel
• Material of the rotor: M19 steel
• Material of the stator: NedFB 50 MgOe
• Material of the shaft: 1018 steel
• The width of slot: 4 degrees

The method proposed to diminish cogging torque in this research is the anti-notch method. That is the setting aside method of the notch, particularly by adding small teeth to the stator surface with a half-cylinder width of 4 degrees and a 90-degree mechanical angle. The later refining is the computation of the value of torque cogging in the reference model and the modified model of the stator tooth with the anti-notch method. Computations are carried out with the support of Finite Element Magnetic Method software version 4.2.

In the pre-processing stage, a generator is designed and split into the small mesh. At the processing stage, the initial value of torque cogging is determined on the reference model, the modification model with anti-notch and modification model if the permanent magnet material is changed. At the post-processing stage, the computation results are analyzed and correlated to the results of the cogging torque reduction that takes place in each condition. Thus, the changes in tangential density flux values are investigated owing to variations in the permanent magnet material. The specifications of the permanent magnet material applied in this research are as follows:

Table 1. Permeability of various magnet permanent materials

| Material's name     | Permeability ($\mu_x$) | Permeability ($\mu_y$) |
|---------------------|------------------------|------------------------|
| NdFeB 52 MgOe       | 1.05                   | 1.05                   |
| Alnico 8            | 6.678                  | 6.678                  |
| Ceramic 8           | 1.43846                | 1.43846                |
| SmCo 27 MgOe        | 1.103                  | 1.103                  |

4. Result and Discussion

All models are simulated using FEMM version 4.2 software. The first condition is the first model that is simulated to obtain the peak value of cogging torque as a reference percentage of peak cogging torque reduction for other models. Later the reference model is modified by adding a small half-cylinder tooth in the middle position of the stator surface. After that, the design of this modification was replaced by permanent magnet material on the rotor with the material in Table I. From the simulation proceeds of all models, it can be analyzed the effect of differences in the permanent magnetic material on the rotor on reducing cogging torque. The entire results can be looked at in figure 1 below. In this research, waves taken for 1 period represent rotor rotation.
Figure 1. Comparison of cogging torque value

From the ends of simulation predictions using FEMM 4.2, the value of torque cogging is obtained on each model and with variations in the permanent magnetic material. In Figure 1 it can be observed that in the reference model the peak value of cogging torque is 2.162 Nm, and it is diminished to 0.146 in the anti-notch modification model with the PM material being NdFeB 52 MgOe, or scaled down by 93%. In Alnico 8 material, the peak of cogging torque becomes 0.062 Nm or decreases by 97.1%. The biggest reduction the peak of cogging torque takes place when applying ceramic material 8, which is corresponding to 97.9% or with a peak value of cogging torque of 0.045 Nm. And when applied SmCo 27 MgOe material, the peak of cogging torque that appears is 0.339 Nm or a reduction of 84.3%.

To determine the changes that take place in modified designs and material differences, formerly based on equation 4 can be identified in differences in the value of tangential density. To observe the differences can be viewed in Figure 2 below.
Figure 2. Comparison of tangential density flux (Bt) with different permanent magnet (a) reference model NdFeB (b) AN model NdFeB (c) AN model Alnico (d) AN model ceramic (e) AN model SmCo

In figure 2 above, the tangential flux density (Bt) figure is taken as many as 180 points in the rotor semicircular position. There are 5 graphs of tangential flux density (Bt), particularly: figure (a) is the Bt value for the reference model, (b) is the Bt value for the NdFeB anti notch modification model, (c) Bt Alnico anti notch model, (d) Bt Ceramic anti notch models and (e) are Bt SmCo anti-notch models. The divergence from the five charts is recognized at the peak value in the Bt wave and the wave period that takes place. The small red circle indicates the peak value of tangential flux density that takes place in each model. While the large red circle indicates the expansion in the wave period that arises. The enhancement of the number of periods or diminishing of the valley wave area, this is caused by the extension of anti-notch on the stator tooth surface. So that the interaction of tangential density flux with hollow zones owing to the slot is diminished. The maximum tangential density flux takes place in ceramic and alnico materials which are around 0.05 T.

5. Conclusion
From the ends of the calculation of the five designs above, it is accomplished that to diminish the peak value of cogging torque, it is necessary to consider the election of material for permanent magnets. Material with high permeability will be effective to produce great magnetic fluxes and this is in conformity with equation 4. The proposed anti-notch method has been proven to significantly diminish the peak of cogging torque.

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