Analysis of Anti-Notch Method to the Reduction of the Cogging Torque in Permanent Magnet Synchronous Generator

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Abstract: Cogging torque is one of the electromagnetic torque that occurs in the electrical machine, especially an electric machine that uses permanent magnets in the rotor. Cogging torque needs to be minimized so as not to hinder the rotation of the generator and do not lead to premature wear on the engine due to friction. The purpose of this study was to analyze the cogging torque reduction that occurred in permanent magnet synchronous generator 8 pole 12 slot using anti notch. This research was conducted by FEMM 4.2 software, the proposed design is an anti notch triangle and a combination of anti notch. The results obtained are for triangular cogging torque reduction of 76% for and 81% positive peak to negative peak. while the cogging torque reduction to a combination, a decrease of 51% occurred at the peak of the positive and 54% at the peak of negative.

Keywords: Cogging torque, Reduction, Anti-notch, Triangular, Finite Element Method

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1. INTRODUCTION

Electrical machines most widely used to support human activities in industry, education, and other uses. It is divided into electric generator and electric motor. Base on it is rotation, it is devided into synchronous and asynchronous. This is called the synchronous machine when the rotating field of the rotor and stator is the same when the rotor rotates at the same speed [1]. Permanent magnet synchronous generator (PMSG) is one of the electric machines that has a synchronous rotation, and and the rotor using a permanent magnet to generate a magnetic field that will excite generator.

PMSG widely used for power generation of renewable energy, particularly wind turbines. The advantage of using a permanent magnet, the magnetic field required to excite the generator can be produced by a permanent magnet. Besides that, one of the disadvantages using PM is the emergence of cogging torque, because of the interaction of magnetic fields with the slots in the stator when the rotor rotates. It causes the rotation of the generator becomes slow/heavy, causing noise and friction can shorten the life of the generator. Reduced the cogging torque becomes important, and it has been done by previous researchers with a variety of methods.

The author of [2], using finite element analysis to analyze the cogging torque reduction, by applying the method notch on the stator teeth and the structure of the air gap becomes asymmetrical for brushless direct current motors (BLDC). the application of these methods, the reduction of cogging torque is obtained in 12% of its original models. Different conducted by L. Hao, et. al [3], notch added to the surface of the rotor. The machine used is a combination of flux-switching PM (FSPM) and axial field PM machine, the machine is called the Axial-switching field flux permanent magnet machine (AFFSPMM). Reduction of cogging torque is obtained in 43% of their origin.

In his paper, Li [4] was able to reduce the cogging torque by 95.8% on a modular PM machine by adding a dummy slot and forming the rotor core into core E and C cores thus obtained cogging torque reduction amounted to 95.8%. lately, a lot of researchers who studied the effect of manufacturing generator to the value of the cogging torque [5-7]. Stiaan [5] compare the analysis of the effect of imperfections in the manufacturing process of the cogging torque values using two methods, namely the analytical method of differential equations (PDE) and the finite element analysis (FEA). The results obtained are imperfections of the manufacturing process will affect the value of the cogging torque is desired. Creating a complex design generator will cause large errors in the manufacturing process so that the cogging torque reduction to be achieved is not optimal.

From the above background, the aim of this study is to analyze the reduction of cogging torque by using an anti - notch. This method is the opposite of the method of the notch by adding small teeth with a triangular shape that is placed on the surface of the stator tooth. Simulations carried out by FEMM 4.2 software is open source, the analysis focused on the distribution of flux, energy, and air gap which resulted in reduced cogging torque values.

2. COGGING TORQUE BASIC THEORY

To obtain the value of the cogging torque, can be done by analyzing the energy stored in the air gap using the following equation [8]:

$$W_c = \int \frac{B_\theta^2}{2\mu_0} d(v_r) \quad (J) \tag{1}$$

where W_c is the energy stored in the air gap is between permanent magnets and stator teeth with the unit Joule (J), B_θ is flux density at rotor position angle with the unit Tesla (T), μ_o is permeability. With a value of stored energy, then the value of the cogging torque can be obtained by the following equation [9] :

$$T_{ec} = \frac{dW_c}{d\theta} \tag{2}$$

Where T_{ec} is cogging torque values with the unit Newton meter (Nm), and θ rotation angle rotor with units of radians (rad).

while Qingling et al [8] get cogging torque values to determine the changing of reluctance in the air gap, which vary with rotor position. it can be seen from the following equation:

$$T_{cog} = -\frac{1}{2}\varphi_\delta^2 \frac{dR_\delta}{d\theta} \tag{3}$$

where R_δ is the value of reluctance in the air gap, φ_δ is the value of flux in the air gap.

By using analysis of Maxwell Stress Tensor, will obtain the cogging torque value is more precise. Tensor flux density affects the value of the cogging torque is generated, as well as the length of the rotor and wide air gap. To determine the cogging torque value, can be using this following equation:

$$T_{ec} = \frac{L}{\ell_g \mu_0} \int_{s_g} r B_n B_t dS \tag{4}$$

where B_n is the normal flux density in the air gap, B_t is the tangensial flux density with the unit Tesla (T), L is the length of the rotor in meter or milimeter, ℓ_g is length of the air gap in meter or milimeter, S_g is the surface area of air gap.

3. PROPOSED MODEL

In this research, the model used for the simulation is a reference model and models developed. For the reference model, the specified parameters listed in Table 1, below:

Table 1: Proposed model for permanent magnet synchronous generator

Parameter	Dimension
Number of Phase	3
Number of Slot/Pole	12/8
Outer Stator radius	95 mm
Inner stator radius	50 mm
Air gap	2 mm
Magnet thickness	6 mm
Stator, rotor material	M19 Steel
Permanent Magnet material	NedFB 50 MgOe
Shaft material	1018 Steel

The algorithm simulation models :

- create a model of PMSG reference design based on the parameters specified in the table. The resulting design is as follows:

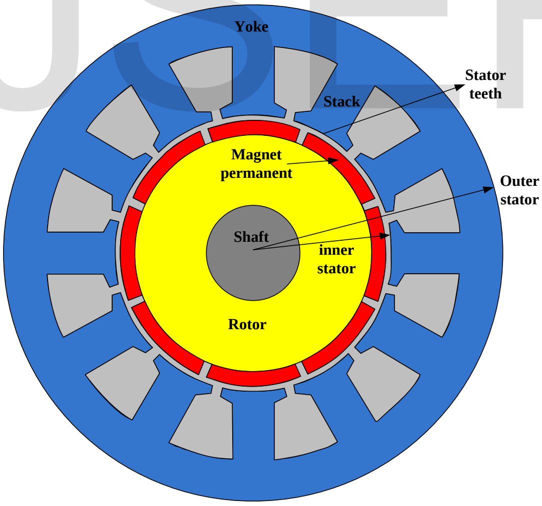

Figure 1 : Reference Model of PMSG

- Reference model simulated using finite element magnetic method software version 4.2 (FEMM 4.2). It is open source, based on the magnetic analysis.
- The rotor is rotated counter-clockwise with each 1-mechanical degree displacement that will produce the flux density, cogging torque values, and the average flux.
- modification of the model is called the triangular models. in this paper will be made two modifications models, namely triangular anti-notch and a combination of anti-notch with 2 notches.

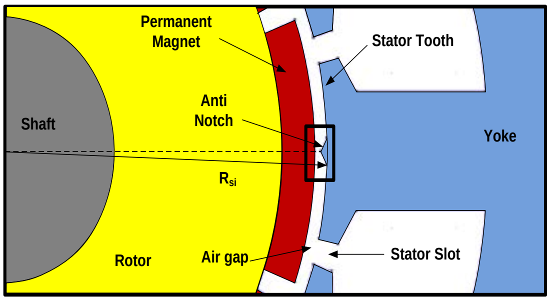

Figure 2 : Proposed Model of PMSG with triangular anti-notch

- Then the reference model was modified in the stator teeth surfaces by adding a triangular tooth with an angle of 90 degrees (figure 2).

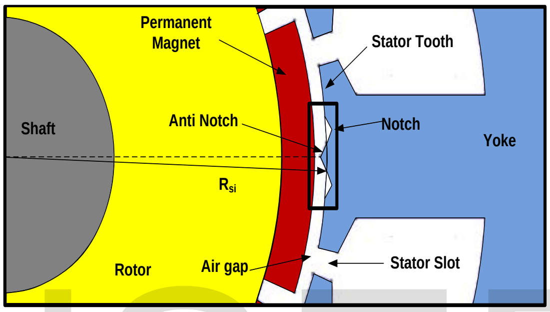

Figure 3 : Proposed Model of PMSG with combination triangular notch and anti-notch

- Another model is combine model, in this model consist of one anti-notch and two notch placed on the surface of stator teeth. Both of them are triangular with an angle of 90 degrees and the same width of 4 degrees (figure 3).

4. RESULT AND DISCUSSION

Here are the analysis of the wave of the cogging torque, flux density distribution and the effect of changes in the air gap to the value of the cogging torque, which is obtained from the reference model simulations and models proposed using FEMM 4.2 software.

4.1 Cogging Torque

The cogging torque wave is always repeated starting from the rotor position 0 degrees up to 360 degrees. For this research, the wave of the cogging torque in 1 slot pitch of 30 degrees is load two waves of the cogging torque. So that, one period of the cogging torque is 15 degrees mechanical rotor position. From the simulation results, the value of the cogging torque of each model can be seen in the following figure:

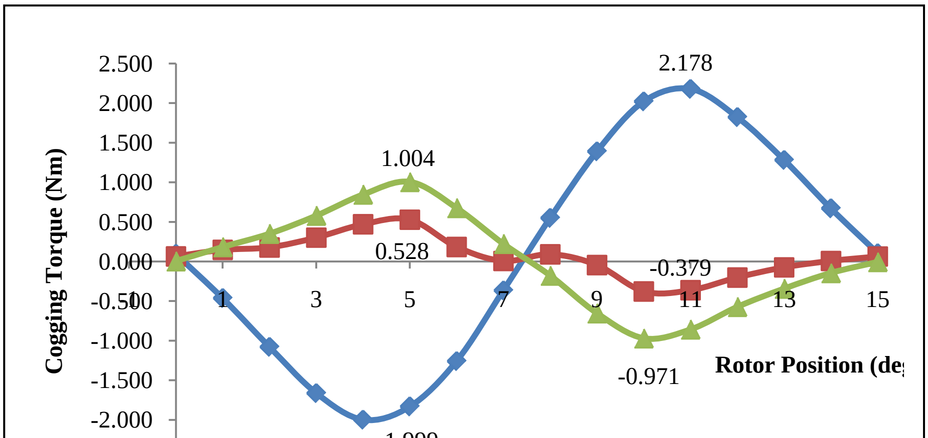

Figure 4 : Comparation Cogging Torque Wave of Reference Model and Triangular anti-notch Model of PMSG

Figure 4 describes the first period of the cogging torque to the reference model, triangular models and combination model. The blue line is the cogging torque values for the reference model, red line for the model triangular and green lines on the model combinations. The lowest cogging torque peak occurs in a triangular model of the peak value of 0.528 T positive and negative peak at -0379 T. In cogging torque reduction can be seen in the following table:

Table 2: Percentage of Cogging Torque Reduction.

Peak	Triangular Model	Combine Model
Negative	81 %	51 %
Positive	76 %	54 %

The highest cogging torque reduction is triangular models. In this model, there is the anti-notch triangle whose volume reduces the volume of the air gap. While the combination model, the resultant of volume 1 anti-notch and 2 notches result in increased the air gap volume.

4.2 Flux Density Distribution

One of the simulation result is flux density distribution. It represent the flux density in whole area of generator models. The different flux density distribution can be seen in the figure below :

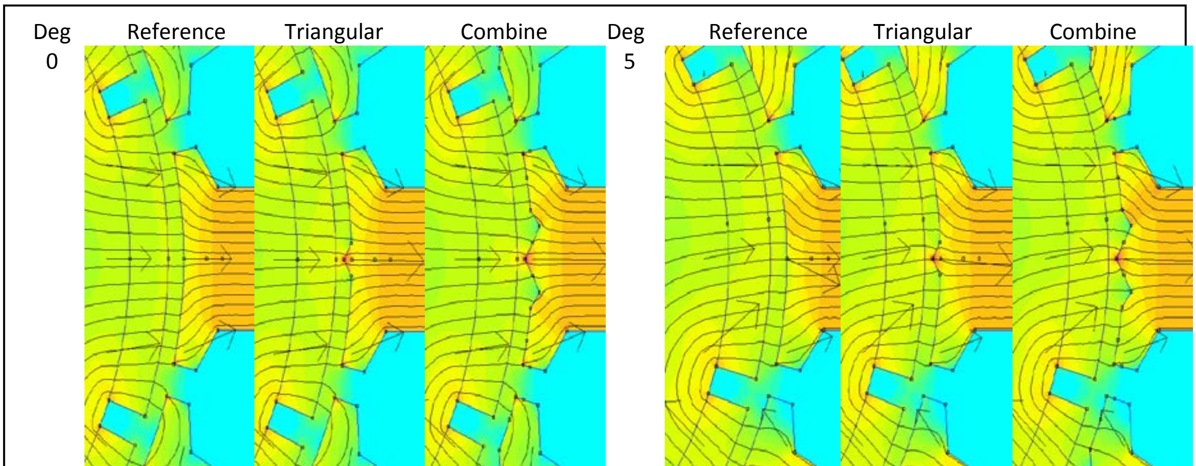

Figure 5 shows the distribution of flux density in all three models. The different colors indicate the differences in flux density. The orange color indicates the highest value of B, the value is 1.9 Tesla while the green color instead with the value is 0.08 Tesla. The image representing the starting position at 0 degrees, 5 degrees for the positive peak of cogging torque, the position of the negative peak at 10 degrees and 15 degrees position back to the starting position.

In each position, there are differences in all three models. The diffrence color on the stack shows the difference value of B on the stack. There were changes in direction of B_n and B_t when the rotor position changes. When the rotor in position 0 degrees, permanent magnets and stator teeth face lead B to the highest value. In position of 0 degrees, the color distribution of flux and flux density values equal for all three models.

The highest value of B is the stator stack. When the rotor position shifted to a position of 5 degrees, the flux density in the stack is reduced, Bt flux direction change. Shifting permanent magnets result in changes in the value B in the stator teeth. The further shift of permanent magnets in the rotor, visible color distribution on the stack and faded, it indicates the value of B on the stack decreases.

To see the changes in the average value of B that occur in the reference model, triangular and combinations can be seen in Figures 6, 7, and 8.

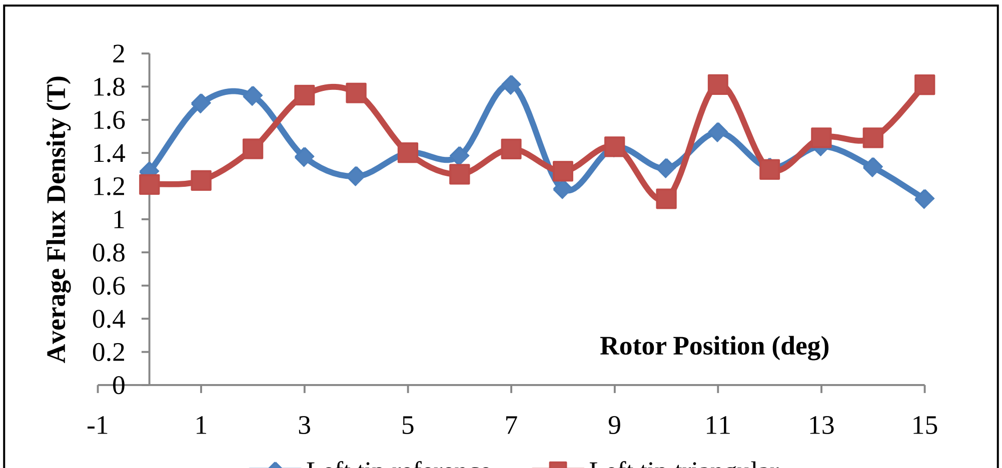

Figure 6 : The average value of flux density (B) on the left of stator teeth

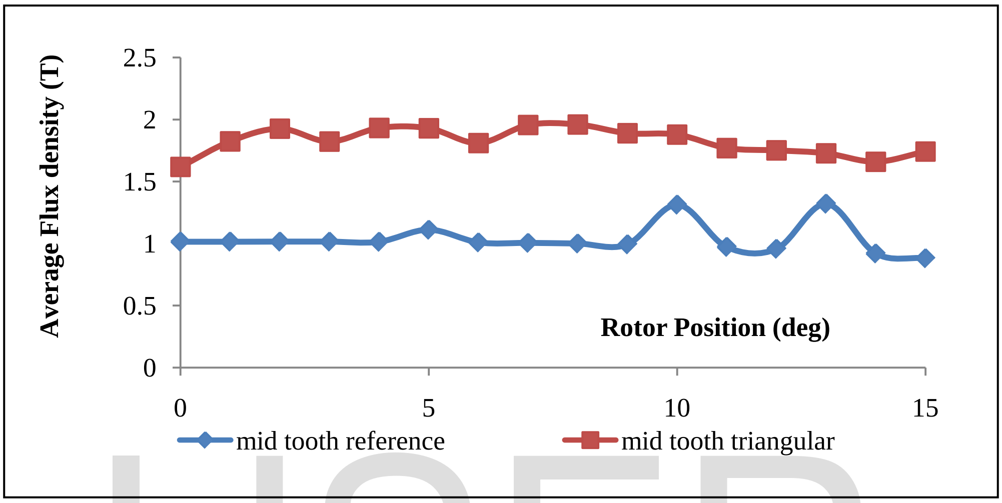

Figure 7 : The average value of flux density (B) on the middle of stator teeth

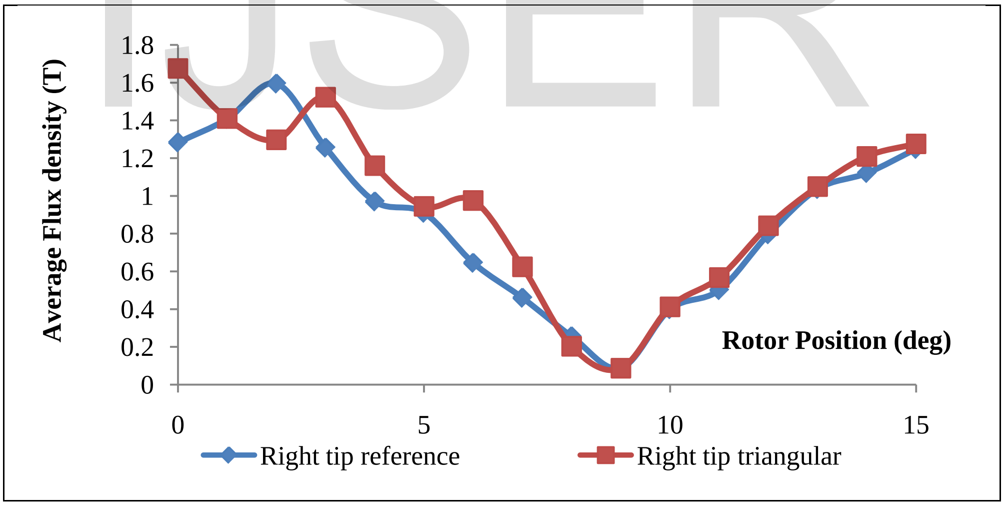

Figure 8 : The average value of flux density (B) on the right tip of stator teeth

Figure 6.7 and 8, shows the changes of B avarage value on the triangular model. In Figure 6, the average value of B at the left tip of the stator tooth has not changed much, the highest value is 1.8 Tesla and the lowest is 1.1 Tesla. At the middle of the stator tooth of the triangular model, the highest value of B average is 1.9 Tesla and the lowest is 1.6 Tesla. As well as figure 8, the value of B average between the reference and triagular model almost the same. The highest value is 1.6 Tesla and the lowest is 0.08 Tesla.

4.3 Air Gap Effect

On the model of triangular, wide area air gap is reduced. This is due to there are additional triangular teeth in stator tooth surfaces that reduce the wide area of the air gap. To obtain the area of the triangular anti-notch, can be derived from the slices of triangular anti-notch as follows :

The slice of anti notch is in the region I and II.

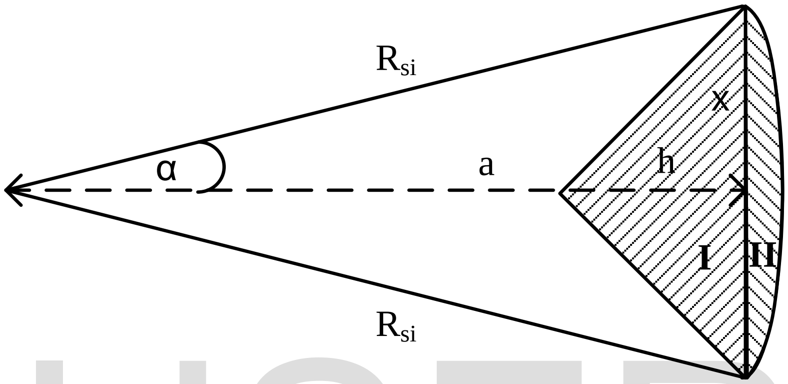

Figure 9 : The slice of triangular anti-notch

To find the extended of triangular anti notch can be calculate with the formula 6 below :

$$L_{AN} = h.R_{si}\sin\alpha + R_{si}^2(\alpha - \sin\alpha.\cos\alpha) \qquad (5)$$

The multiplier for total anti-notch is the total number of anti-notch placed on each stator tooth surface.

5. CONCLUSION

in this study, the simulation process is done on PMSG 12 slot 8 pole using FEMM 4.2 software for cogging torque reduction, the proposed design is a model anti-triangular notch and combine. Analysis of the results obtained, cogging torque reduction is highest in the triangular model of the peak of 81% to 76% for the negative and positive peak. Stator tooth geometry changes can reduce cogging torque but not much change in the value of B stator teeth, except the area of the air gap is reduced.

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