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MINIMIZATION OF TORQUE RIPPLE IN 24-SLOT 16-POLE INSET PERMANENT MAGNET GENERATOR BY EDGE-ROUNDED MAGNET POLES AND STATOR TEETH NOTCH TECHNIQUES

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ABSTRACT

Torque pulsations such as torque ripple produce magnetic vibration and noise in permanent magnet machines. Thus, it is important to minimizing the torque ripple in permanent magnet generator design. This study reports a novel strategy in order to minimize the torque ripple in the 24-slot 16-pole radial flux inset permanent magnet (RFIPM) generator by using a geometric modification on magnet poles and stator teeth. We proposed four model of RFIPM generator with stator teeth notch and edge-rounded magnet (ERM) poles. Finite element method magnetic (FEMM) are used for computation of the torque ripple. We found that the modification of stator teeth notch and ERM poles significantly lowered the torque ripple of the RFIPM generator, and the lowest achieved by the combination of stator tooth with one notch and ERM poles with a reduction value of about 80% (torque ripple of 5.78%).

Keywords: *Torque ripple reduction, finite element method magnetic, edge-rounded magnet poles, stator teeth notch, radial flux inset permanent magnet generator*

1. INTRODUCTION

Electrical machines have a huge influence on the reduction of energy consumption. The consumption of electrical energy can be saved by designing the construction of electrical machines with better efficiency. The use of permanent magnets in construction of electrical machines can improve the efficiency and reliability of the machines by eliminating the excitation losses [1][2]. By eliminating gearbox, direct drive permanent magnet machines have many advantages such as higher reliability and efficiency, reduced maintenance, noise and weight [3].

For designing a low speed direct drive generator, torque quality is one of the challenges. Torque distortions such as cogging torque and torque ripple produce magnetic vibration and noise. In direct drive applications they are transmitted directly to the load and drive shaft, which in return, affect the lifetime of the drive train. That's why in designing permanent magnet generators, it is important to minimizing the torque ripple.

The main task of this paper is to investigate the effects of both stator teeth notch and ERM poles on torque ripple reduction of the 24-slot and 16-pole RFIPM generator. We proposed four models of ERM poles with stator teeth notch and used FEMM to simulated the torque of RFIPM generator in this study and calculate the torque ripple to find which one has the lowest value. These research contribution is to found a new model of 24-slot 16-pole RFIPM generator with minimize torque ripple.

2. TORQUE RIPPLE

Torque generation has been fundamentally described by Maxwell's stress tensor illustrated well the fundamental principle of torque generation. This method is expressed as [4]:

$$T = \frac{l}{\mu_0 (R_{si} - R_{ro})} \int_S r B_n B_{tan} \, dS \qquad (1)$$

where l is the stack length of the machine, R_{si} is stator inner radii, R_{ro} is rotor outer radii, B_n and B_{tan} denote the radial and tangential flux densities in the elements of surface S and formed between radii R_{ro} and R_{si}, dS is the surface of one element. The torque of electrical machine has two components, and its expressed as [1]:

$$T(\alpha) = T_0 + T_r(\alpha) \qquad (2)$$

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Where T_0 is a constant or average component and $T_r(\alpha)$ is a periodic component, which is a function of time or angle α. The periodic component causes the torque pulsation called torque ripple. Cogging torque is given by the interaction between the rotor magnetic flux by permanent magnets and reluctance variations due to the slotting of the stator (cogging torque also called "no current torque"). Torque ripple is caused by the non ideal distribution of flux density in the air-gap. It is generated by the interaction of the current fundamental harmonic and the EMF harmonics [5]. Torque ripple can be defined by [1]:

$$t_r = \frac{T_{max} - T_{min}}{T_{av}} \quad (3)$$

where:

$$T_{av} = \frac{1}{T_p}\int_{\alpha}^{\alpha+T_p} T(\alpha)d\alpha = \frac{1}{T_p}\int_{0}^{T_p} T(\alpha)d\alpha \quad (4)$$

and T_p is the period of the torque waveform.

In general, there are two approaches for reducing the torque ripple. The first strategy is to improve the magnetic design of the electric machines by changing the geometric of stator and rotor poles. The other one is to use the electronic control technique which is based on optimizing the control parameters such as supply voltage, turn-on and turn-off angles, and current level [6][7]. Compared to the later technique, the former method is more desirable because it may effectively reduce the torque ripple, meanwhile the electronic control technique requires a precise real-time excitation current according to the real-time computations. In addition, real-time computation is very sensitive with the reliability and accuracy of the sensors used in the control system [8][9].

3. LITERATURE REVIEW

Several researches on torque ripple reduction by modifications of the geometric design has been done, such in [10], where the authors using magnet pole shaping technique for torque ripple reduction on an 18 slot and 12 pole surface mounted PM Brushless DC (PM BLDC) motor. The performance parameters were computed and analysis by 2D FEA. The results shows that the torque ripple reduced from 35.26% (the basic one) to 16.89% (30 mm offset model). Modification on permanent magnet also used in [11] to reduce cogging torque and torque ripple for an outer rotor radial flux surface mounted permanent magnet generator.

The effectiveness of skewing rotor method with/without magnet shaping on the torque ripple for surface mounted PM machine are investigated in [12]. Skewing rotor also used in [9] for torque ripple and cogging torque reduction on 9-slot/6-pole surface mounted PM synchronous motor. However, the results show that skewing may cause the torque ripple increase if the magnet shape is not designed carefully.

The reduction of the torque ripple for outer rotor surface mounted PM synchronous machines and inner rotor interior PM synchronous machine with fractional-slot non-overlapping windings by teeth widths adjustment and permanent magnet skewing is presented in [13]. The optimization technique was carried out by FEA. Shaping the stator teeth for reducing the torque ripple also use in [14]. The authors compared three models of surface mounted PM motor with different stator teeth shape. And then modified the stator teeth shape by setting the design parameter x based on model 2 and 3. The analysis results show that the minimum value of cogging torque and torque ripple is not at the same point of design.

In [15], the authors investigated cogging torque minimization and torque ripple reduction in surface mounted PM synchronous machine using different magnet widths (one magnet has different width from the other). The torque ripple reduced from 30.57% to be 2.49% with these method. However the asymmetric of magnets distribution in rotor created unbalance magnetic pull on it. An analytical approach for optimizing inner rotor surface mounted PM synchronous generator with concentrated windings design for wind power applications is presented in [16]. The authors using both the PM shape design and skewing stator to reducing the torque ripple and cogging torque.

We are using both stator teeth notch and ERM poles modifications to reducing the torque ripple of 24-slot and 16-pole RFIPM generator. We proposed four combinations of stator teeth notch and ERM poles and investigated which one produced the lower torque ripple.

4. PERMANENT MAGNET GENERATOR

The use of permanent magnets in the synchronous machine makes the machine into a lighter, smaller and more efficient than the electrically-excited synchronous machine, and making it more suitable for gearless applications. Radial flux permanent magnet generator chosen for this study because, according to [17], radial flux

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synchronous machine has an outer diameter smaller and cheaper than the axial flux type machine, so it is more suitable for applications that require low speed.

RFIPM in this study has the inner rotor which has advantages in terms of assembly, because the stator winding will simplify installation, in addition to the number of slots can also be more than the outer rotor-type with the same outer diameter [17]. Figure 1 shows the basic model of RFIPM generator and the main dimensions of the RFIPM generator is shown in table 1. We already found the torque of RFIPM generator from the earlier studies (Figure 2) and the torque ripple calculated with equation (3) is 29.87%.

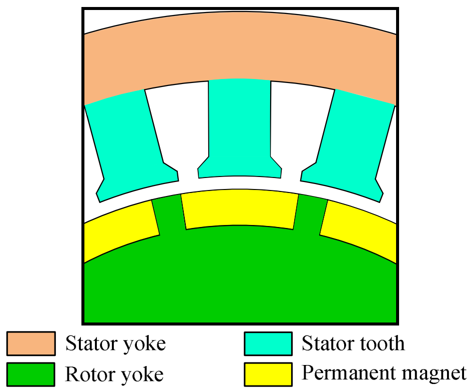

Figure 1 : The Cross Section of Basic Model of RFIPM Generator.

Table 1 : Main Dimensions of RFIPM Generator.

Parameters	Symbols	Value	Unit
Number of slots	Q_s	24	-
Number of poles	p	16	-
Stator outer radii	R_{so}	204	mm
Stator inner radii	R_{si}	142	mm
Rotor outer radiii	R_{ro}	140	mm
Rotor inner radii	R_{ri}	130	mm
Magnet thickness	l_{pm}	5	mm
Air gap length	g	1	mm
Pole arc/pitch ratio	α	0,80	-

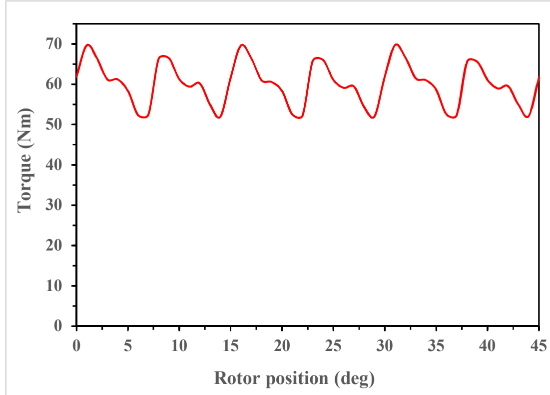

Figure 2 : The Torque of 24-Slot 16-Pole RFIPM Generator for Basic Model.

5. MAGNET POLE AND STATOR TEETH SHAPING

From the previous studies, we found that edge-rounded magnet shape with parameter x = 2 mm (ERM 2) produced torque ripple 7.76%, reduced 74.02% from basic model (29.87%). Than in this study we designed four different models of stator teeth notch with ERM 2. Figure 3 shows the cross-section view of respective developed models of RFIPM generator.

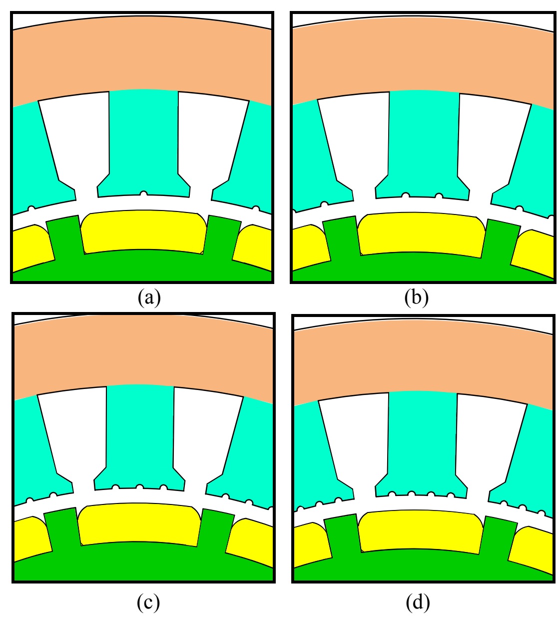

Figure 3 : Cross Section View of Proposed Design of Edge-Rounded Magnet Poles and Stator Teeth Notch: (a) Model 1; (b) Model 2; (c) Model 3, (d) Model 4.

As the geometric modification of stator teeth does not change their height and width, the cross-section area of air-gap for proposed models are

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slightly bigger than that of the basic model and ERM 2 due to removal of stator teeth material. The cutting residue in magnet pole Δm (mm^2) and stator tooth Δt (mm^2) is identified by red color in Figure 4.

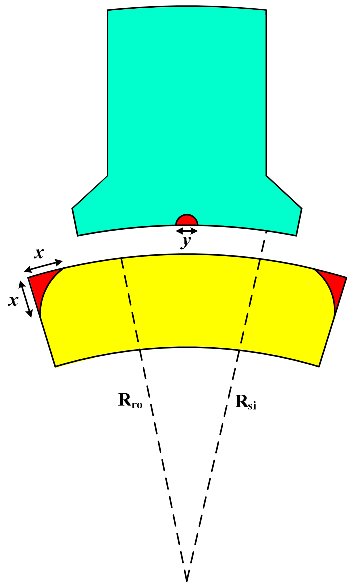

Figure 4 : Cross Section Area of Magnet and Stator Tooth Cut.

The cross-section area of magnet cut Δm (mm^2) and stator tooth cut Δt (mm^2) for p poles and Q_s slot are obtained using the following equation:

$$\Delta m = xpR_{ro} - p\left(R_{ro}(R_{ro} - x)\sin\left(\frac{x}{R_{ro}}\right)\right) - \frac{2\pi - 3\sqrt{3}}{6}\left[\left(R_{ro} - (R_{ro} - x)\cos\left(\frac{x}{R_{ro}}\right)\right)^2 + \left((R_{ro} - x)\sin\left(\frac{x}{R_{ro}}\right)\right)^2\right] \quad (5)$$

$$\Delta t = nQ_s\left[0.5\pi\left(R_{si}\sin\left(\frac{y}{2R_{si}}\right)\right)^2 - 0.5R_{si} + R_{si}^2\sin\left(\frac{y}{2R_{si}}\right)\cos\left(\frac{y}{2R_{si}}\right)\right] \quad (6)$$

where R_{si} is the stator inner radii and R_{ro} is the rotor outer radii of RFIPM generator (mm), x is the length of magnet cut (mm) and y is the length of stator notch cut (mm) and n is the notch for 1 stator tooth (in this case n = 1, 2, 3 and 4). Using equation 5 and 6, we can find the air-gap cross-section area (A_{gap}) for proposed models by the following equation:

$$A_{gap} = \pi(R_{si}^2 - R_{ro}^2) + \Delta m + \Delta t \quad (7)$$

From that, we can calculate the volume of magnet poles and air-gap as well, as shown in table 2.

Table 2 : Calculated Volume of Magnet Poles and Air-Gap in 24-Slot 16-Pole RFIPM Generator.

	Magnet volume (mm^3)	Air-gap volume (mm^3)
Basic model	128,930.96	33,665.3
ERM 2	125,781.67	36,814.6
Model 1	125,781.67	37,528.73
Model 2	125,781.67	38,242.86
Model 3	125,781.67	38,956.99
Model 4	125,781.67	39,671.12

6. RESULTS AND DISCUSSION

In this paper, we simulate RFIPM generator with four types of stator teeth notch with edge-rounded magnet (model 1, model 2, model 3 and model 4) using FEMM 4.2. During the simulation, the rotor position is gradually turned for every 1º starting from 0º to 45º. The torque obtained by simulation is plotted in Figure 5. Figure 6 shows the values of torque ripple RFIPM generator calculated using equation 3. We found that the combination of stator tooth notch with ERM 2 models exhibited a lower torque ripple than the basic model and ERM 2 (without stator teeth notch). The lowest torque ripple was achieved by model 1 (5.78%), followed by model 3 (5.86%), model 4 (6.68%) and model 2 (7.17%).

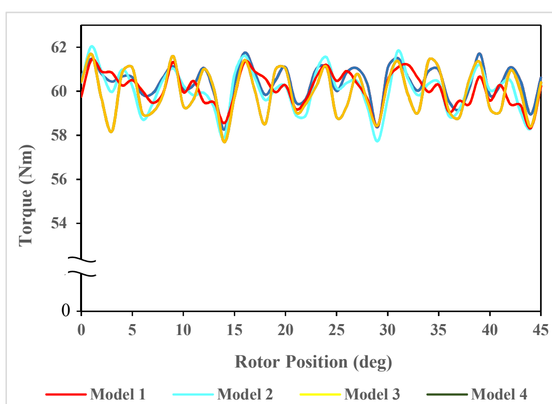

Figure 5 : The Torque of 24-Slot 16-Pole RFIPM Generator for Proposed Models.

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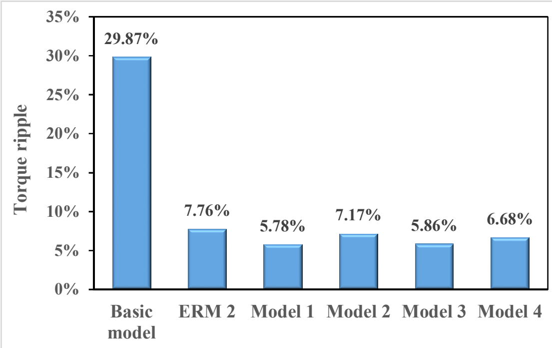

Figure 6 : Comparison of Torque Ripple of Basic Model, ERM 2 and Proposed Models of RFIPM Generator.

In respect to the basic model, the torque ripple reduction of model 1 achieved 80.63%; model 3 of 80.38%; model 4 of 77.66% and model 2 of 75.99% (Figure 7). From table 2 we could see that the proposed models have the same volume of permanent magnet with ERM 2 and reduce 2.44% from the basic one, so its make them have cheaper permanent magnet. And with the notch we made on stator teeth, we could reduced the material about 11.48% (model 1) to 17.84% (model 4) from the basic model. We also correlated the increment of air-gap volume. Although, the increasing values of those parameter tended to decrease the torque ripple, however we found that there should be optimized values between the parameters.

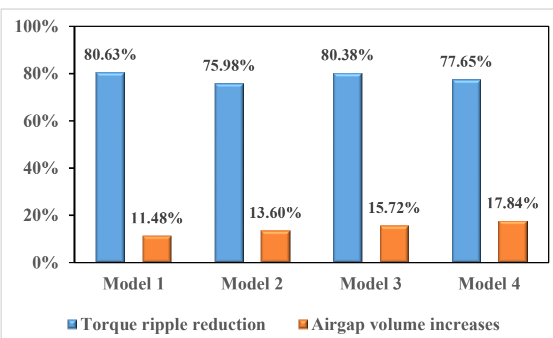

Figure 7 : Comparison of Torque Ripple and The Increases of Air-Gap Volume of RFIPM Generator.

From Figure 8, we can see that the trendline of the changed of torque ripple from model without notch (ERM 2) to model with 4 notch (model 4) follow the polynomial function as described below:

$$y = 0.0045x^4 - 0.0374x^3 + 0.0971x^2 - 0.0841x + 0.0776 \quad (8)$$

From the function of trendline we can predict the torque ripple for more notch on stator tooth, but the prediction concluded that the torque ripple may be up not down, bigger than the proposed models that we simulated. Its because the more notch on stator teeth make the edge of the tooth thinner and may cause saturation of magnetic flux density on it.

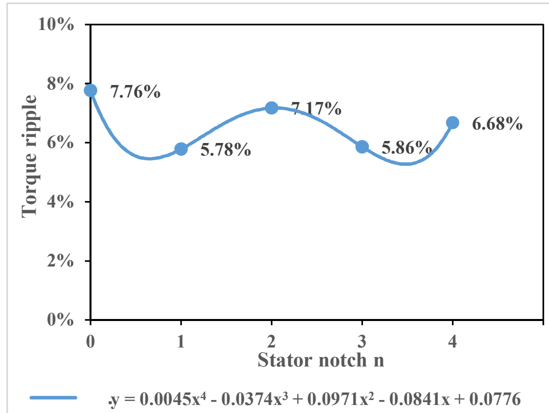

Figure 8 : Trendline of Torque Ripple of Proposed Models of RFIPM Generator.

Since model 1 has the lowest torque ripple, we should see the comparison between basic model and model 1 for magnetic flux density B_n and B_{tan} at the surface of permanent magnet. From Figure 9 and 10, we found that magnetic flux density B_n and B_{tan} on model 1 has the same patern of wave with basic model, but the magnitude may be a little bit decreased. These phenomenon may couse the output of RFIPM generator also decreased.

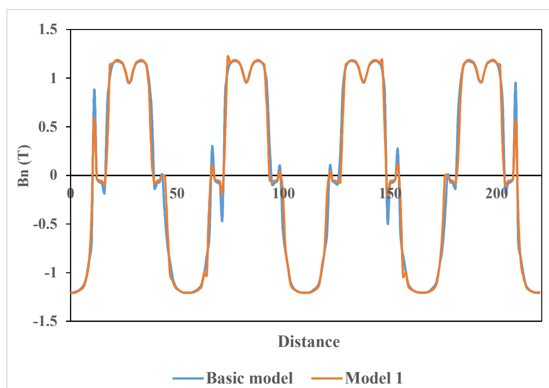

Figure 9 : The Radial Magnetic Flux Density B_n Distribution at The Surface of Permanent Magnet.

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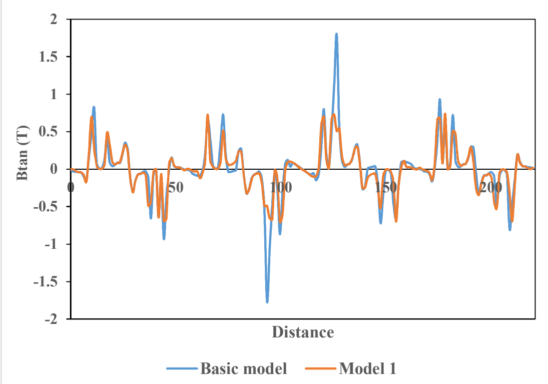

Figure 10 : The Tangential Magnetic Flux Density B_{tan} Distribution at The Surface of Permanent Magnet.

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8. CONCLUSION

This study investigated the effects of combination between stator teeth and magnet poles shaping on torque ripple reduction of the 24-slot and 16-pole RFIPM generator. Using FEMM 4.2, we simulated the torque of four different combination of stator tooth notch and edge-rounded magnet poles techniques. We found that the model 1 (the combination of one notch of stator tooth and edge-rounded magnet 2 mm) showed the lowest torque ripple (5.78%), reduced 80.63% from the basic model and 25.52% from ERM 2 model. These shaping techniques does not disturb the magnet flux wave at the surface of permanent magnets, but since the magnitude of B_n and B_{tan} a little bit decrease, it may reduced the output of RFIPM generator.

For the future works, we need to found the output and efficiency of the 24-slot and 16-p0le RFIPM generator from the model 1 (that has the lowest torque ripple) and compare the results with the basic model.

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