International Journal on Advanced Science Engineering Information Technology

Vol.10 (2020) No. 3
ISSN: 2088-5334

Novel of Cogging Torque Reduction Technique for Permanent Magnet Generator by Compounding of Magnet Edge Shaping and Dummy Slotting in Stator Core

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Abstract—This paper dealt with the investigation and implementation of the cogging torque reduction technique in permanent magnet generators with a fractional slot stator/rotor combination of 24 slot/18 pole structure. A novel of cogging torque technique in a permanent magnet generator was developed and proposed in the paper. In the study, the cogging torque reduction technique was based on the compounding of two cogging torque reduction techniques, i.e., the magnet edge shaping with dummy slotting in the stator core of the fractional slot number. By employing the CT reduction technique proposed, effects on the decreasing of tangential flux density in the air gap of the permanent magnet generator, while the normal flux density almost remained constant. The tangential flux density is one important parameter regarding the peak of cogging torque in permanent magnet generator or other electrical machine structure. The normal and tangential flux have been analyzed. The cogging torque of the permanent magnet generator was analyzed and presented in the paper. By compounding both cogging torque reduction techniques, i.e., magnet edge shaping and dummy slotting in stator teeth have been expected to achieve the cogging torque reduction. The electromagnetic performance of the permanent magnet generator was performed using a finite element analysis of FEMM 4.2. It has been proved that by combining of magnet edge shaping and dummy slotting in stator teeth can reduce the cogging torque of permanent magnet generator significantly. It has been found that the cogging torque reduction for the proposed structure around 98.08 % compared with the initial structure.

Keywords—PMG; magnet edge shaping; dummy slotting; cogging torque; finite element.

I. INTRODUCTION

Nowadays, there has been increased interest in applying permanent magnet generators (PMGs) for small wind turbine systems. This is caused by the fact that PMGs are compact, high efficient, reliable, and self-excited. Electric power generation in the wind power system is obtained from the conversion of wind speed converted into mechanical energy with the aid of the rotating blade. In addition, the mechanical energy in terms of rotation of blade is provided to rotate the generator rotor to produce electric energy. Generally, in small wind turbines systems do not use any gearbox or other apparatus to provide the rotating of any generator. In other words, the PMGs used for small wind power usually with direct-rotates rotors from the rotating blade.

The advantages of direct-rotates in wind power system are simple controls, low speed rotation, light weight, and higher efficiency. However, it has been found that the drawback in PMGs applications particularly in low speed condition is the cogging torque (CT) of the PMG. The presence of CT in PMG can decrease the self-starting ability of the PMG. CT out come from the PMG also produces noise, mechanical vibrations and may be other unwanted performance. Based on the discussion, it can be concluded the CT is the most important issues regarding the PMG applications. For that reason, the CT must be concerned and analyzed in the stage of design to get any suitable machine performance. The CT in PMGs is a pulsating torque caused by the interaction of magnet flux in rotor core and stator slot opening. Based on the discussion it can be concluded the CT of PMG could be minimized or it high possibility to reduce by modification machine structure, i.e. magnet structure, or stator core. The CT reduction also can be achieved by combining of magnet edge shaping and dummy slotting in stator. The combining of the two CT reduction technique is considered and conducted in the paper. As the CT in PMG generated by magnets flux in rotor core, in the beginning one can pay attention on the magnet structure optimization. The reason is that the magnets in rotor is the source of the CT. The other choice in reduction optimization stator core can do the CT in PMG. In this study the dummy slotting in stator core has been investigated. Since the last three years, there have been many CT reduction techniques for PMGs developed and proposed in worldwide, they have been cited in the paper. Their reports regarding the CT reduction of PMGs studied have been reported and well documented. Most of the CT torque techniques proposed by past researchers by modification the PMG structure from stator core or magnet rotor side. For example, skew of magnet was conducted to minimize the CT of machines [1]-[4], [19], [30]. Another CT reduction technique, i.e. is by employing the fractional slot number has been investigated by scholars in [12], [18], [29], [35], magnet slotted studied in references [5], [18], [22], [23], [40].

From stator side, the slot opening was optimized [32], stator shoe depth variation [18], magnet-shaping [6], [11], [12], [14], [15], [17], [25]-[27], [41], magnet pole-arc[31], [34], [36]-[39], dummy-slotting, [8], [9], [28], [42]-[45], stepped slot opening [32]. In fact, every CT reduction technique implemented in PMGs structure has its own characteristics and advantages. However, the most effective technique in reducing the CT in PMG is by compounding two or more of CT reduction technique, instead only CT reduction technique. In this study refers to the CT reduction technique by employing of two existing of CT reduction techniques, i.e. magnet edge shaping and dummy slotting technique. It is expected the combining of magnet edge shaping and dummy slotting in stator core of PMG promises to achieve a better CT reduction compared with another techniques.

To study, a construction the fractional slot number with 24 slot /18 pole of PMG has been selected and investigated. Another study regarding the CT reduction technique by constructing the magnets of PMG in term of bread loaf system. In bread loaf system, the magnets height in the edge of the magnet are shorter compared with the center of magnet, which was conducted in [2]–[6]. Another advantages of magnet edge shaping in PMG is the fact that not only can reduce the CT peak value of machine, but the technique can minimize the commutation torque ripple as well. However, the torque ripple issue is not studied or discussed detailed in the paper.

The purpose of this work is to develop and propose a novel CT reduction technique based on the combining of the magnetic edge shaping and dummy slotting technique in stator core of PMG. As has been mentioned before, the combining of the two CT reduction techniques could be expected to achieve a higher of CT reduction of the PMG proposed. For computing the CT peak value of PMGs studied, the finite element method (FEMM 4.2) has been used in this study. The contribution of this work is that CT reduction of the PMG proposed can be achieved significantly with optimized of magnet structure combined with dummy slotting. The CT peak value of PMG proposed, i.e. by employing the magnet edge shaping and dummy slotting in stator teeth can be reduced to around 98.08 % compared with initial structure.

II. Material And Method

A. Initial Structure of PMG

The PMG is one of electric machine has been used in renewable energy systems, one of them in wind power turbine. In general, the PMG is with a surface mounted magnet, or inset mounted magnet. In the paper, the PMGs studied refer to the inset PMGs, as shown in Figure 1.

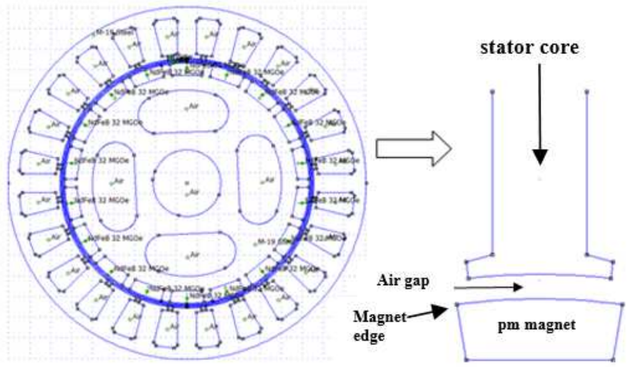


Fig. 1 PMG of Initial Structure (no magnet edge shaping and dummy slotting)

In Figure 1, it can be seen the permanent magnets in rotor is full occupy the air gap of the Initial structure of PMG. As a result, the quantity of total magnet flux density flowing into air gap will high, leads to generate normal and tangential flux force acting on the air gap. Therefore, the rotor of the machine is difficult to be rotated by prime mover. For a purposed to applying in wind power turbine, magnetic flux force in air gap must be minimized. In this study, the tangential magnetic flux density has been minimized by employing the combining of magnet edge shaping and dummy slotting in stator core of PMG proposed. The effectiveness of reducing the magnetic flux force related to reduce the CT of PMG is essential, as conducted in this study.

There are two kinds of magnetic flux force in air gap of machine, the normal magnetic and tangential flux force.

The normal magnetic flux density is one of branch of magnetic flux density as mentioned. It is generated by the permanent magnet in air gap, which tends to flow into perpendicular to the stator teeth. Unlike the normal magnetic flux density, in general the tangential flux density prefers to distribute into the stator slot of the PMG, leads to generate tangential force in air gap. To get any suitable of wind power turbine requirement, both of normal magnetic flux and tangential magnetic flux density, they should be considerably in the stage of design.

In this paper, the PMG structure for wind power turbine application is proposed, which adopted from the inset structure of PMG. In inset structure of PMG, the rotor has any teeth located between magnets, so it the same of magnet rotor of commercial surface PMGs. As in the magnet is mounted magnet with inset rotor structure, the main flux of the PMG is generated by magnets in rotor. The magnet flux from the magnet edge then it is distributed into the air gap of the PMG.

In conventional PMG structure as in Figure 1, the intensity of tangential magnetic flux density is high. As has been stated before, the tangential magnetic flux density flowing into the slot opening of the machine, which leads generate any attraction force and effect to resist the self-staring of the rotor rotation.

B. PMG with Magnet Edge Shaping and dummy Slotting

To minimize the effect of tangential and normal magnet force in air gap of PMG, the magnet edge shaping and dummy slotting in stator core can be combined. The effect of combining the magnet edge shaping and dummy slotting in stator on the tangential force and normal force is investigated and discussed in this study. The PMG structure with the magnet edge shaping and dummy slotting in stator core, as shown in Figure 2.

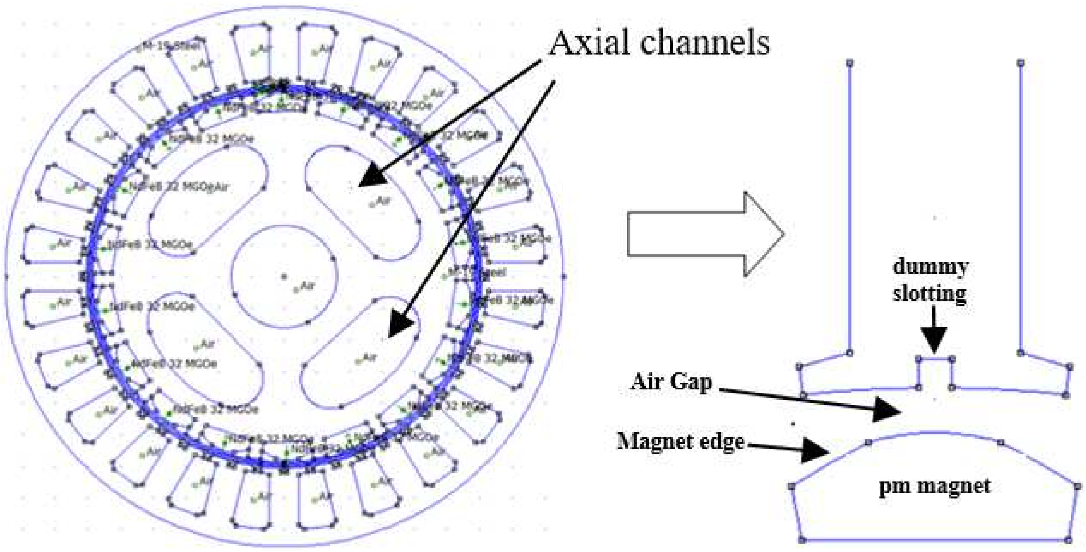


Fig. 2 PMG of proposed structure

In Figure 2, represents the PMG of proposed structure for wind turbine application. The structure of PMG proposed is based on conventional or initial structure of PMG. For the wind turbine application purpose, the magnets and stator core have been optimized. In the paper, two techniques regarding to fulfill the wind turbine application have been employed. As can be observed in Figure 2, the magnet edge is slotted with paired with a dummy slotting in stator teeth. In the PMG proposed structure, some axial channels located in rotor core of machine have been introduced. However, the effect of axial channel on the CT of machine is not studied detailed in the paper.

C. Cogging Torque Theory

CT in PMG is generated by the interaction of magnetic flux force in rotor and stator slot opening in stator core. Usually, the conventional PMG structure has a higher CT compared with the non conventional as in Figure 2. The CT is a negative torque created when the magnets in rotor core attempt to align themselves with a maximum amount of ferromagnetic material of the PMG. The CT in PMG is often very small relative to the beneficial mutual torque produced by an electric machine. However, it is one of the most important issue in PMG application since it causes air gap reluctance differential to the mechanical rotor position. The air gap reluctance R_g will vary as the rotor of PMG is rotating. As each magnet in the rotor of the PMG rotates past the stator teeth, the R_g of PMG experienced by the magnet under the slot openings of stator changes. It is caused of the longer flux path length into the stator slots terminating on the stator core shoes of the machine. Therefore, every slot opening in stator core creates a varying reluctance for the magnet flux, thereby creating CT. If the stator teeth in PMG or any electrical machines do not have any stator shoes, the R_g will increase and the CT would be much greater. Thus, the primary purpose for shoes is to minimize the CT in the PMG. However, the stator shoe design in stator core of any PMG represents a fundamental tradeoff. The narrower the stator slot opening width (SOW), the smaller the CT peak value becomes in the PMG. In the limiting case, only the PMG with slot less openings structure, can have a zero CT. On the other hand, the stator slot opening must be wide enough to insert coils into the stator slotting. The size of stator slot opening width should be met with the cost of inserting coils. As a rule of thumb, the stator slot opening must be at least two to three times the covered diameter of the wire placed in the stator slots. It must be noted, any side effect of making the stator slot opening too narrow, can increase the stator slot leakage inductance component of the winding.

D. Cogging Torque Reduction Technique

As mentioned in previous part of this paper, it has been understood that the CT in PMG is caused the interaction of magnetic force generated by magnet structure in rotor core and stator core or slot opening. Thus, it can be concluded that modification of the stator core or magnet rotor structure can minimize CT in PMGs. In addition, the achievement of CT reduction of PMG can promised by combining the modification in magnet rotor structure and stator core. Another parameter effect to CT peak of PMG, is material used for construction of the PMG. Thus, the main concern in this paper is by combining the magnet edge shaping and dummy slotting in stator core of PMG proposed with considering of material for stator and rotor core. For purposed of study, the M-19 Steel has been used for both of stator and rotor core, while for magnet rotor, the NdFeB has been selected.

A modification of both magnet structure and stator core to minimize the CT peak value in PMG proposed and PMG of Initial Structure was presented in the paper.

The CT peak value reduction technique classification can be summarized, as shown in Figure 3.

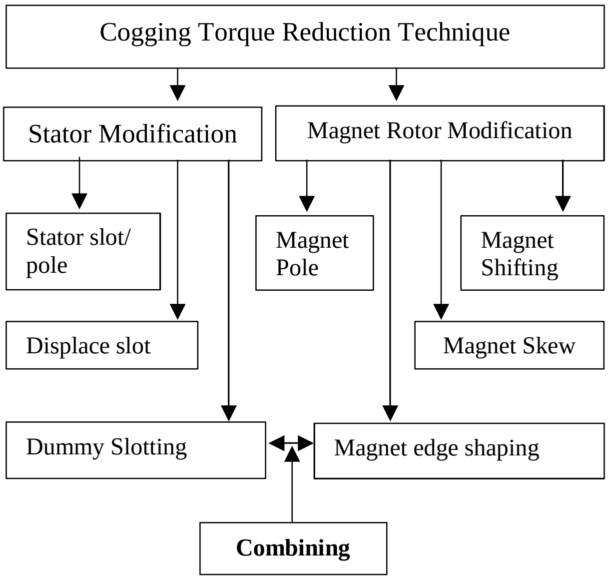


Fig. 3 Cogging Torque Reduction Technique for PMGs [41]

For achieving the CT peak value reduction of the PMG, the combining of two cogging torque reduction techniques, i.e. the dummy slotting in stator core and magnet edge shaping has been developed and proposed. The combing of magnet edge shaping and dummy slotting can be observed, as shown in Figure 2 (blue color). For study, authors have started to modify the magnet structure of PMG proposed. In the next step performing modification of stator core parameters with dummy slotting, as presented in Table I and Table II, respectively.

TABLE I
STATOR PARAMETERS OF PMG STUDIED

No	Parameter Names (degree)	Symbol	unit
1	Base of the magnet angle (^{0})	α_0	0^0
2	Side of Magnetic Angle (^{0})	α_1	3.5^0
3	Centre of Magnetic Angke (^{0})	α_2	35^0
4	Bottom of Stator Angle (^{0})	α_3	6^0
5	Side of Stator Slot Angle (^{0})	α_4	45^0

TABLE II
ROTOR PARAMETERS OF PMG SIMULATED

No	Parameter Name (mm)	Symbol	Unit
1	Max. height of magnet (mm)	U-V	5.50
2	Min.Height of Magnet (mm)	A-B/C-D	3.00
3	Shoe Height of Stator (mm)	SHS	2.10
4	Slot Opening Width (mm)	SOW	1.80
5	Width of Stator Shoe (mm)	WSS	16.26
6	Height of Stator Teeth (mm)	HST	16.04
7	Air gap length (mm)	AGL	2.00
8	Slot Height (mm)	SH	17.75

E. Cogging Torque Computation

The paper refers to CT reduction technique of PMG by employing the combination of magnet edge shaping and dummy slotting in stator core. As it has been known that both of magnet edge shaping and dummy slotting techniques are the CT reduction techniques. They are any good one of CT reduction technique and has been implemented in permanent magnet machines performance, as has been reported in the beginning of this paper. The CT reduction technique proposed in this study can be shown in Figure 2. The analytical method used in this study was based on the previous research [12],[18],[41]. It has been understood the analytical calculation in PMG presents complex geometry, which is very difficult task to analyze using conventional computation technique.

The mathematical equations consist of explicit links between all parameters and considered physical phenomena in the PMG structure. In all circumstances, the analytical method is the favorite one for the PMG design optimization of PMG structure in inhomogeneous regions. Since it is inhomogeneous, leads to have any high number of boundary condition. The slot opening width (SOW) of machine effect should be considered to compute the magnetic field flux distribution in the air gap of machine studied accurately. For analysis, and to obtain the magnetic field solution of the machine studied, the structure of the PMG can be divided into several regions (SR), as shown in the Figure 4.

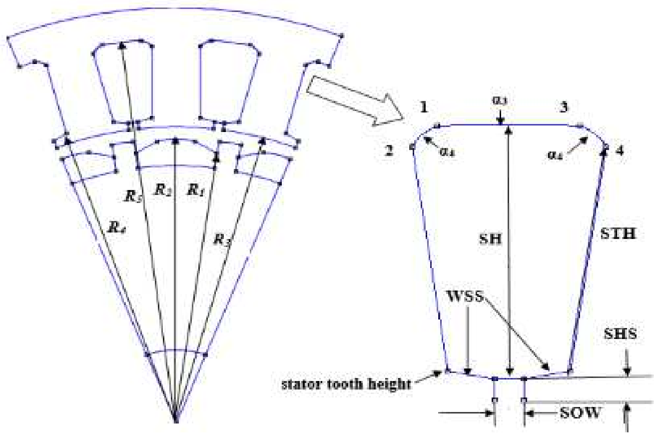


Fig. 4 PMG proposed with detailed stator slot opening [41].

In Figure 4, the R_1 represents the distance of the minimum height of magnet to the rotor center, R_2 is distance of maximum height of magnet to the rotor center, R_3 is distance between rotor center and stator shoe surface, R_4 is distance between rotor center to the stator tooth height and R_5 is the distance between rotor center and bottom of the stator slot opening.

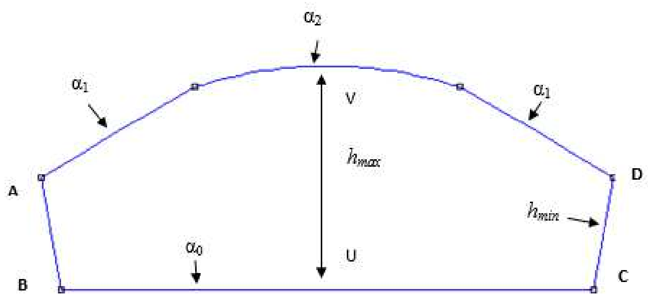


Fig. 5 Detailed of magnet structure

Figure 5 represents the detailed of magnet edge shaping proposed in this paper. All the size regarding the magnet edge shaping to reduce the CT peak value of the PMG proposed have been considered, as shown in Table 1. While the parameters in Table 2, related to the dummy slotting in stator core or stator teeth. From Figure 4, it can be observed that employing the magnet edge shaping technique effects to increase the distance between magnet edge and the stator core of machine. In this paper, t1he magnets edge was shaped with the minimum height of the magnet edge (A-B or C-D) of 3 mm. As the magnets edge have been shaped, it then forms any new pole arc or angle in both side of magnet edge structure.

For optimizing the CT reduction of the machine have determined with 3.5^0. To keep the distance between magnet center and stator slot opening, the angle or pole arc of the magnet center has been computed and optimized as much as 35^0. The maximum height in magnet center after have providing magnet edge shaping is 5.5 mm. As a result, the magnet structure proposed cross-section (2D) or volume (for 3D) become smaller compared with the magnet of Initial Structure.

This also leads to minimize magnetic flux distribution flowing in air gap of the PMG. In turn, the air gap cross section of the PMG has become increased, which leads to reduce the air gap reluctance (R_g). As a result, the tangential flux in the magnet edge also become decrease, leads the tangential force acting on the air gap of machine also decreased. It can be identified that tangential force in air gap can affect to increasing the CT of PMG. The relation between tangential force to the CT of PMG will be discussed later in the paper. Another effect of magnet edge shaping can provide a new edge point of magnet. After magnet edge shaping, the have been 4 edge points in each magnet, leads promise to increase the CT frequency which in turn reducing the peak of the CT. In the paper, the saturation issue regarding the effect of magnetic flux density in stator and rotor core is not study detailed, but it just shows any general case. Since the magnetic flux distribution is analyzed with 2-D of finite element, the study related to the magnetic flux density in the PMGs is carried out in polar coordinate. Based on this procedure, the magnetic vector potential *A* of every PMG structure has only in the axial direction component. It refers, that the end effect losses in PMGs studied is not considered. The stator and rotor permeability of all PMGs studied and is assumed to be infinite.

In addition, demagnetization characteristic of the magnet structure has been assumed to be linear. Also, the polarization vectors of the magnets perfectly radial direction, the relative permeability equal to the unity and at last the sides of the slots have a purely radial direction as well. In both of Figure 3 and Figure 4, the PMGs structure is analyzed based on the sub-domain (SD) technique. In SD technique, all the parameters related stator shoe, stator slot opening width and many more related to the machine core can be considered, instead simplifying [42].

In the first region of PMG, contains the permanent magnets and is delimited by radius $R_1 \leq r\ R_2$. The distance between magnet surface and stator slot opening (air-gap) of the PMG is lied between $R_2 \leq R_3$ as in the second region. While the third region is located between $R_3 \leq r \leq R_5$ include all the stator slots. With the same way, one can observe in another region. However, the investigation of magnetic field studied in this is focused in air-gap of the PMG, i.e. in $R_2 \leq R_3$ region. The SD technique consists of solving the Maxwell Equation directly in different SD such as in air gap, stator slots and magnets by using variable separation technique (VST). The magnetic flux field can be obtained in every region by using the interface and boundary conditions.

In the paper, the CT of PMGs studied was analyzed with the no-load condition, which refer no electric current in stator coil. Based on this assumption, the calculation of the magnetic flux field distribution in other regions of the PMG such as in the stator slots and air-gap be are conducted by applying the Laplace Equation solution. The differential equation in each region as given in Equation (1) and (2) [41].

$$\nabla^2 \mathrm{A} = -\mu_0 (\nabla \mathrm{x} \mathrm{M}) \quad (1)$$

In the first region of the PMG

$$\nabla^2 A = 0 \quad (2)$$

In the other regions (2nd, 3rd, and 4th region). μ_0 is permeability in free space. **M** is the magnetization of permanent magnet which may be consists two parts or only, it is depended on magnetic magnetization. In the paper, the axial flux magnetization is zero, since magnetization of the magnets is radial. In polar coordinates it can be expressed as:

$$\frac{\partial^2 A^1}{\partial r^2} + \frac{1}{r}\frac{\partial A^1}{\partial r} + \frac{1}{r^2}\frac{\partial^2 A^1(r,\theta)}{\partial \theta^2} = -\frac{\mu_0}{r}\left[M_\theta(\theta) - \frac{\partial M_r(\theta)}{\partial \theta} \right] \quad (3)$$

$$\frac{\partial^2 A^{2,3,4}(r,\theta)}{\partial r^2} + \frac{1}{r}\frac{\partial A^{2,3,4}(r,\theta)}{\partial r} + \frac{1}{r^2}\frac{\partial^2 A^{2,3,4}(r,\theta)}{\partial \theta^2} = 0 \quad (4)$$

Both of magnetic flux density (*B*) and magnetic field vectors (*H*) in these regions are coupled the Equations (5) and (6).

For region 1:

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}) \quad (5)$$

For region 2, 3, 4:

$$\boldsymbol{B} = \boldsymbol{\mu_0 \mu_r H} \quad (6)$$

The radial and tangential flux density of the PMG or permanent magnet machine can be deduced from the magnetic vector potential *A* as in Equation (7) and Equation (8), respectively.

Normal or radial flux density as :

$$\mathrm{B_r}(\mathrm{r}, \theta) = \frac{1}{\mathrm{r}}\frac{\partial \mathrm{A}\,(\mathrm{r},\theta)}{\partial \theta} \quad (7)$$

and for tangential flux density, as in Equation (8)

$$\mathrm{B}_\theta\,(\mathrm{r}, \theta) = -\frac{\partial \mathrm{A}\,(\mathrm{r},\theta)}{\partial \theta} \quad (8)$$

The CT peak value of the PMGs studied and PMG proposed was computed based on the Maxwell Stress Tensor (MST). The CT is deduced from radial and tangential flux density in air gap of the PMG. In air gap region of PMG, the CT peak value can be expressed as in Equation 9 [2],[30],[46]:

$$T_c = \frac{L_{eff}R^2}{\mu_0}\int_0^{2\pi} B_r^{(3)}(r,\theta)B_\theta^{(3)}(r,\theta).d\theta \qquad (9)$$

where L_{eff} is the effective length of the PMGs studied, while R is the position in air gap where the CT values calculated. B_r is the normal or radial flux density, and B_θ tangential flux density. As can be observed in Eq. (9), the CT value of the PMG is influenced by the normal flux and the tangential flux density. However, it might be concluded that the tangential flux density influence of tangential flux density is leading on the CT value compared with the normal flux density. The reason is that tangential flux density generates any attraction force acting between magnet surface and slot opening, leads reducing the ability of the rotor to achieve the self-starting.

In wind power application, if the tangential flux density of PMG to generate electrical energy is high, the rotor of machine will hard to be rotated, except with the strong of wind speed. In addition, the tangential flux density effect to increase the CT of PMG. In this paper, both of normal and the tangential flux density of the PMGs structures analyzed are presented. In computing the CT of the PMGs studied, dummy radius (R) was located in the middle of air gap of the PMGs studied. The value of R as much as 11.8849 cm. In order to achieve the accuracy of CT measurement, 5 dummy lines have been employed in the air gap in the PMGs studied. The magnetic flux distribution, normal and tangential flux density were presented in this paper, as shown in Figure 6, Figure 7, and Figure 8, respectively. From Figure 8, it can be seen the tangential flux density of the PMG proposed structure can be reduced significantly, compared with Initial Structure (see Figure 6). The decreasing of the tangential flux density is expected to reduce the CT of the PMG proposed. The validation the effect of tangential flux density on the CT peak value is conducted using FEMM 4.2. The CT value for all PMGs structure studied were compared and presented in this paper.

III. RESULT AND DISCUSSION

3.1 Magnetic Flux Distribution and Magnetic Flux Density.

For computing the magnetic flux distribution and magnetic flux density in air gap, the finite element methods based on the FEMM has been implemented [12], [18], [41], [46]. The simulation procedure using FEMM 4.2 was shown in Figure 5. To mitigate the simulation of the PMGs performance studied, the LUA 4.0 scripting have been coupled with the FEMM has been implemented in our work. The magnetic flux distribution of all core of PMGs studied as shown in Figure 7A, 8A, and 9A, respectively.

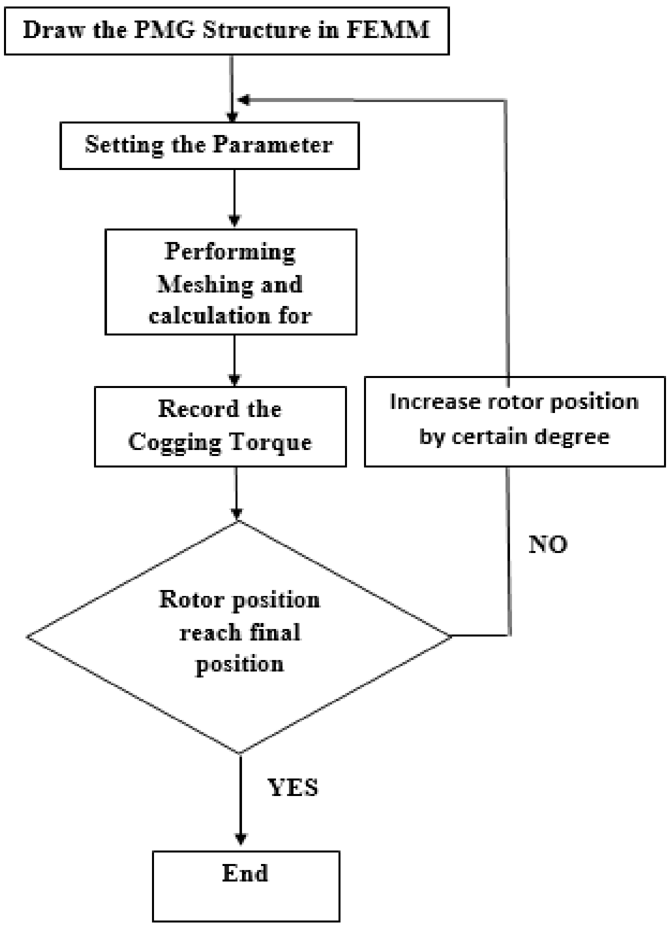
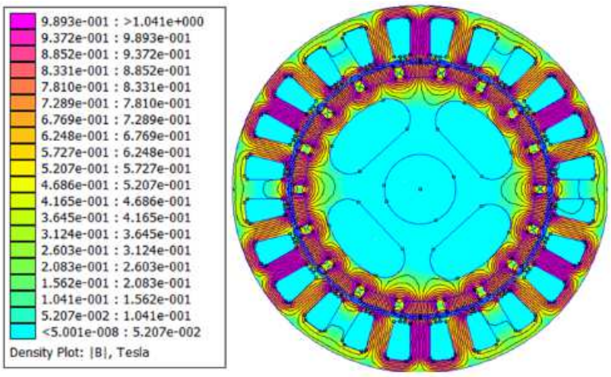
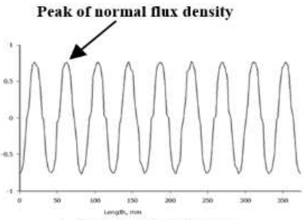


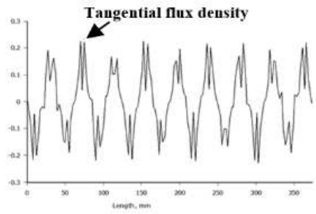
Fig. 6 Computing Steps for CT analysis using FEMM [12],[18]



a. Magnetic Flux Distribution core of Initial Structure



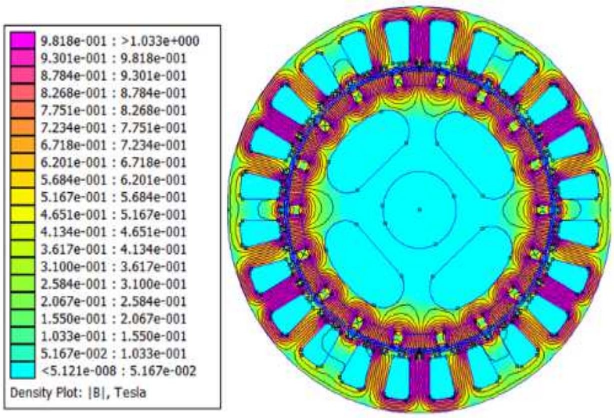
b. Normal Flux Density



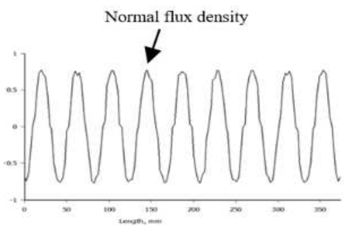
c. Tangential Flux Density

Fig. 7. Norman and Tangential Flux Density of Initial Structure (without dummy slotting and magnet shaping)

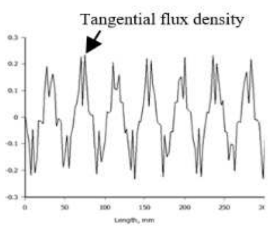
From Figure 6, it can be observed the magnetic flux distribution in the whole of the machine. The magnetic flux density in the core of the Initial structure is around 0.9893 Tesla. The value of normal magnetic flux density and tangential flux density is around 0.65 Tesla and 0.22 Tesla.



a. Magnetic Flux Distribution in Magnet Edge Shaping of PMG without dummy slotting



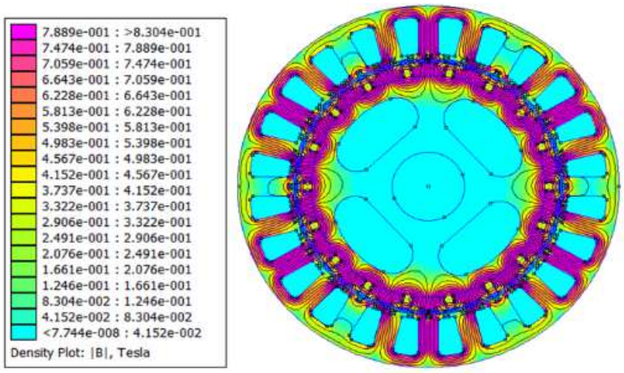
b. Normal Flux Density



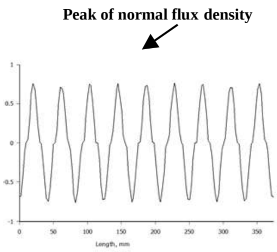
c. Tangential Flux Density

Fig. 8. Normal and Tangential Flux Density of Magnet Edge Shaping of PMG (without dummy slotting)

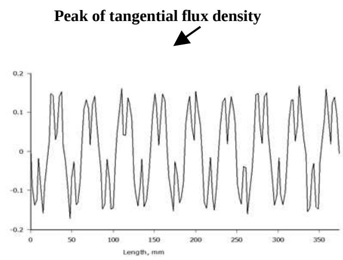
The effect of dummy slotting in stator core on the CT peak value is analyzed and presented. The magnetic flux density in the machine core of dummy slotting structure can be reduce to around 0.9818 Tesla. However, the normal and tangential magnet flux density is still remained constant.



a. Magnetic Flux Distribution of PMG proposed Structure



b. Normal Flux Density



c. Tengential Flux Density

Fig. 9 Normal and Tangential Flux Density of Magnet Edge Shaping (with dummy slotting in stator core)

In Figure 9, one can observe the tangential flux density of the proposed structure. The magnetic flux density in core of PMG proposed is reduced to around 0.7888 Tesla. The peak of tangential flux density drops significantly as much as 0.15 Tesla compared with the initial structure, while normal magnetic flux density is constant. The reduction of tangential magnetic flux density is significant on reducing the CT peak value of PMG. As can be observed in Eq.9, the peak of tangential flux density of the combining magnet edge shaping and dummy slot in stator structure decreases significantly, compared with the initial structure. This caused the effect of the reduction of tangential flux density in the magnet, which influences to decline the CT. All the PMGs studied in the paper regarding the reduction of CT peak value are compared and presented in this paper, shown in Figure 9.

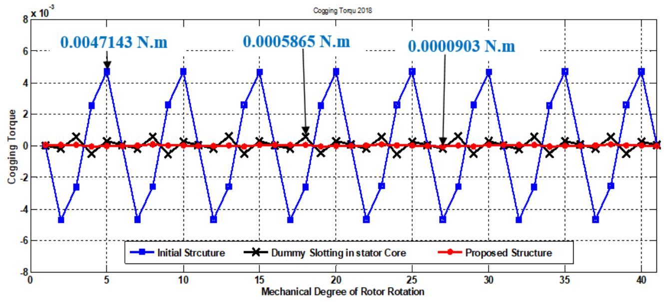


Fig. 10 Comparison of CT Reduction of all PMGs Studied

From Figure 10, it can be seen the CT peak value of PMGs studied changes as rotor rotates. For any PMG with conventional of stator and magnet structure, the effect the slot opening in stator can achieve the CT, and it is much greater, compared with the optimized stator core or magnet structure. It can be observed from the black line in Fig.9 (black line), as the magnet edge shapes the CT peak value becomes decline.

This is caused the magnet edge shaping influenced to minimize air gap magnetic flux circulating in the air gap area. As the magnet edge shaped, the magnetic flux in the magnet edge is less to reach the slot opening in the stator core. Also, the magnet edge shapes the effect to increase the space between the magnet surface and the stator slot. In turn, the magnet edge is reducing the air gap reluctance of the machine. The CT peak values of PMGs studies indicate the condition when the magnets pass in the stator slot opening.

IV. Conclusion

The novel of CT reduction technique by employing the combination of magnet edge shaping and dummy slotting in stator core has been presented in the paper. The CT peak value of PMGs studied was computed using FEMM. In the analysis, the CT peak value of the initial structure of PMG has was computed first. In the Initial structure of PMG, both of magnet structure and stator core of the machine is a conventional one, which has not any slotting or modification.

Using the FEMM, the CT peak value of the Initial structure is computed, and it found around 0.0047143 N-m. After employing the dummy slotting in stator core with conventional stator structure as in Initial Structure, the CT peak of the PMG can be reduced to 0.0005865 N-m, compared with the initial structure. In addition, the CT of PMG proposed structure is achieved by employing the combining of magnet edge shaping and dummy slotting in the stator core. The CT peak value of the PMG proposed can be reduced sharply, from 0.0047143 N-m (Initial Structure) to around 0.0000903 N-m. The percentage of CT reduction PMGs studied is presented. As the basis of comparison, the CT peak value of PMGS studied is compared with the Initial Structure of PMG. The CT reduction percentage of the PMGs with magnet edge shaping combining with conventional stator core is calculated as = [100%-(0.0005865/0.0047143)] = 100%-12.44% = 87.56%. In the same way, the percentage of CT of the PMG proposed with magnet edge shaping and dummy slotting in stator core is calculated as: [100%-(0.0000903/0.0047143)] = 100%-1.92% = 98.08%. It can be concluded that combining the magnet edge shaping and dummy slotting in the stator core can reduce the CT of the PMG proposed significantly.

Future Work

For future research, authors are going to prepare with another number of dummy slotting in the stator core. The other slot/pole combination, such as 24 slot / 20 pole of PMG.

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