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Effect of Combining of Shaping at Magnet Edge and Dummy Slotting at Stator Core on the Cogging Torque Reduction in Permanent Magnet Generator

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Abstract

Effect of combining the shaping at magnet edge and dummy slotting at stator on the cogging torque reduction in permanent magnet generator was studied. The cogging torque is the most issues in permanent magnet generator application, since it effects to reduce the generator performance. A permanent magnet generator with 24 slots and 20 poles structure is presented. For purpose of study, in the beginning the permanent magnet generator with conventional structure has been investigated as the basic reference of initial structure. In order to improve the performance of the permanent magnet generator, the magnet edge was shaped but the stator core is kept remain conventional structure. It can be found that the magnet edge effects to inprove a little bit of the performance of the permanent magnet generator. In the next investigation, the magnet edge slotting and dummy slotting in stator core of the permanent magnet generator was combined. Using the FEMM 4.2, the cogging torque value of the proposed of permanent magnet generator were analysed and compared. It was found that cogging torque reduction of the permanent magnet generator with combining the dummy slotting at stator core and magnet edge shaping can reduce the cogging torque from 0.0028554 N.m (intial base line) to 0.0000165 N.m (proposed model). In other word, the cogging torque can be to around 99.42 % compared with the base line. The magnet flux density at core of the permanent magnet generator proposed can be reduced to 35 %.

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Abstrak

Pengaruh penggabungan pembentukan tepi magnet dan slot dummy pada stator terhadap pengurangan torsi cogging pada generator magnet permanen telah dipelajari. Torsi cogging merupakan masalah yang paling besar pada aplikasi generator magnet permanen, karena berdampak pada penurunan kinerja generator. Generator magnet permanen dengan struktur 24 slot dan 20 kutub disajikan. Untuk keperluan penelitian, pada awalnya telah diteliti generator magnet permanen dengan struktur konvensional sebagai acuan dasar struktur awal. Untuk meningkatkan kinerja generator magnet permanen, tepi magnet dibentuk tetapi inti stator tetap berstruktur konvensional. Dapat ditemukan bahwa efek tepi magnet sedikit meningkatkan kinerja generator magnet permanen. Pada penyelidikan selanjutnya, slot tepi magnet dan slot dummy pada inti stator generator magnet permanen digabungkan. Dengan menggunakan FEMM 4.2, nilai torsi cogging dari generator magnet permanen yang diusulkan dianalisis dan dibandingkan. Ditemukan bahwa pengurangan torsi cogging pada generator magnet permanen dengan menggabungkan slot dummy pada inti stator dan pembentukan tepi magnet dapat mengurangi torsi cogging dari 0,0028554 N.m (garis dasar awal) menjadi 0,0000165 N.m (model yang diusulkan). Dengan kata lain, torsi cogging dapat mencapai sekitar 99,42 % dibandingkan dengan base line. Kerapatan fluks magnet pada inti generator magnet permanen yang diusulkan dapat dikurangi hingga 35%.

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1. INTRODUCTION

In our daily life, permanent magnet machines (PMMs) or permanent magnet generators (PMGs) have been widely used in many applications such as a motor in robotic, pump, electric vehicles and many more. In renewable energy systems such as in wind power system, the PMMs have been applied as generator to harvest electrical energy. Naturally, the wind speed in all over the world never constant, and even sometimes it run very low. As consequence, the power of the wind is not sufficient to drive the blade of the wind power. In the other hand, it has been experienced that the most important issue related to the wind power application is the presence cogging torque (CT). As the flux of rotor is excited by permanent magnet material, it leads the magnet flux density tend to high compared with conventional electrical machine. Both of CT and magnet flux density are important issue, so that they must be minimized in order to adjust generator application. In fact, the CT can reduce the generator performance, since it could cancel the self-starting capability of the machine especially in low-speed condition, or the power of prime mover is low. In addition, if the magnet flux density at machine core is much higher that the material core capability, it might increase the high eddy current losses, then reduce the power output of the permanent magnet generator (PMG).

In this paper, both of issue CT and magnetic flux density on the PMG have been studied. In fact, the CT in PMG is complicated. The CT can be divided into two categories, i.e stage of design, and stage of manufacturing. In the stage of design, the CT phenomena is studied and investigated as the interaction between the flux of magnet material in rotor core and slot opening in stator of PMG. Thus, it can be concluded that the CT in PMG is influenced by the material type and the construction of machine.

It refers, that the CT generated in PMG have been existed when for the first time of any PMG was built. The CT which is investigated based on the material and structure of the PMG is called natural cogging torque [14]. While, in the stage of manufacturing, the CT in PMG also exist which caused by the imperfection of material handling when the PMG was fabricated. This kind of CT is called additional CT.

In this paper, authors have focussed only on the natural CT. Actually, the CT in PMG is hard to decrease into zero value since it is influenced many factors related to the PMG structures, except for the PMG with slotless. On other hand, in renewable energy application such as in wind power system, usually requires a very low cogging torque peak value. In order to increase the ability of the wind power system to start up, a CT value of 2 % or less of the rated torque of the PMG is required. It means that, the CT reduction for wind power system must have at least 98 % of the rated torque of the PMG. Also, in special application such as CNC, robotic system and many more, the CT of PMG must be as low as possible. According to the past researcher [**1**], a good design of permanent magnet machine, if the CT content of the machine lies between 1-2% (two percent) of the rated torque or the CT reduction of the PMG 98 % of the rated torque. However, until nowadays, to realise a very low CT value in practical is still difficult task in PMG design. The fact that the CT in electrical machine can only be minimized but it cannot be totally removed from the machine, even in manufacturing have used a modern machine tools. In the design stage, the CT of any PMG is naturally caused by the interaction of stator slot or slot opening width and the magnet edge of the machine. While in the stage of design, the CT also might be influenced by the imperfection in manufacturing (manufacturing stage). The purpose of this work is to develop and introduce a new technique to reduce the CT of PMG by employing the combination of magnet edge shaping and dummy slot in stator core. The novelty of this paper is that the fact that can combine the existing CT reduction and improve the CT reduction in PMG. In this paper, the CT analysis is limited and focussed in the design stage instead of manufacture stage. For purpose of analysis the PMG structure, some assumptions have been used in this study:

1. The magnetic flux orientation was assumed to be radial.
2. End effect of the PMG is neglected.
3. The magnet poles have the same characteristics.
4. Saturation in both stator and rotor core of the machine is neglected.
5. No current in stator winding or open circuit.
6. The width and length of the stator teeth is not optimized.
7. The magnet structure of the magnet has been optimized using response surface method (*RSM*).

As has been mentioned in the beginning of this paper, a fractional slot number of 24 slots / 20 poles of PMG generic model have been adopted and studied. This type of structures was popular based on reference [1]. The permanent magnet structure used for the PMG proposed have been adopted to be bread loaf type. According [13], many commercially available machine drives, the typically cogging torque from 5 to 15% from the rated torque of the machine. And, due to the imperfection of manufacturing in mass production, the CT of machine may be increase more than 25 % even it has been introduced a properly design permanent magnets. Many CT techniques have been proposed by researchers in worldwide since the last two decades. The results of the research on CT reduction methods for PMG have been reported and well documented as well. Some of the CT reduction techniques have been proposed such as dummy slot in stator teeth [2]-[4], slotting in magnet edge [5]-[8], shaping in magnet edge [9]-[12]. However, the most effective way to minimise the CT in PMG is by combining the magnet edge shaping and dummy slot at stator core of machine.

The advantage of this technique is the fact that the distance between the points at magnet edge to the slot opening could be adjusted to a proper value. This technique aims to improve the proper contact between magnet edge and slot opening in stator core. Moreover, as the result the CT frequency of the PMG become increase much higher which leads decreasing the peak of CT of machine. In our work, a generic model of PMG with 24 slots / 20 poles structure have been selected and studied [1]. In the beginning, the initial or base line model magnet structure of the PMG was analysed. As can has been predicted the CT of PMG must be high. The CT of machine is high since the magnet or/and stator structure of the PMG is not optimized. To minimize the CT of PMG or any permanent magnet machine, the magnet structure or stator teeth or both of magnet structure and stator teeth must be optimized. The purpose of optimization is to mimize the interaction between magnet edge dan slot opening at stator core.

Using the magnet edge shaping with combined stator slotting, it reduces the CT of the PMG as low as possible and. It has been expected the such kind of technique could be realized in real structure of PMG. The CT of the PMG have been analysed with considering the possibilities to the real machine structure such as the bolts in the rotor and stator core. Some axial channels in rotor core of the PMG model also have been introduced. Effect of combination the magnet edge shaping with dummy slot in stator core on the CT reduction in the PMG was presented in this paper.

2. LITERATURE REVIEW

2.1 Initial Structure of PMG

The PMG structure proposed in this paper refers to the CT reduction in the stage of design. In this paper, the CT of the PMG of fractional slot number with 24 slot / 20 pole structure was selected. The CT reduction technique which developed in this paper was by combining two of existing techniques, i.e. shaping in magnet edge and dummy slotting in stator core. Combining the magnet edge shaping with dummy slotting in stator core is one of new technique in achieving the CT reduction in fractional slot number type of PMM. The effectiveness of proposed structure was validated using finite element analysis based on FEMM 4.2. In general, the CT reduction can be summarized in Figure 1. In the stage of design, it shows that the CT reduction in PMG can achieved by optimized of the structure of rotor, stator or combined of both of stator and rotor structure. The initial structure of the PMG study in this paper as shown in Figure 1.

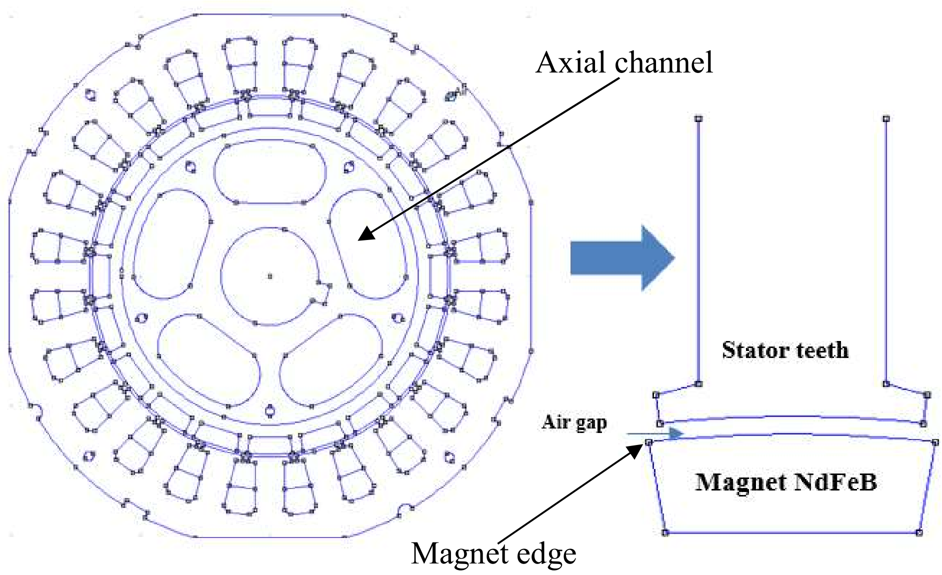

Figure 1. Initial Structure of PMG of 24 slots / 20 poles

2.2. Cogging Torque Reduction Classification

As have been mentioned in the beginning of this paper, many CT reduction techniques have been developed and proposed in worldwide. The CT reduction technique can be summarized in Figure 2. It can be obsereved that, the CT technique can be achieved by using one of CT techniques, thus the CT reduction can achieve by combining more the existing CT technique. Of course, every CT technique has adavantages and disadavantage. So that, it cannot be judged that one technique is superior or better than other CT technique. In our proposed structure, a combination of dummy slotting at stator core and shaping in magnet edge was studied and presented.

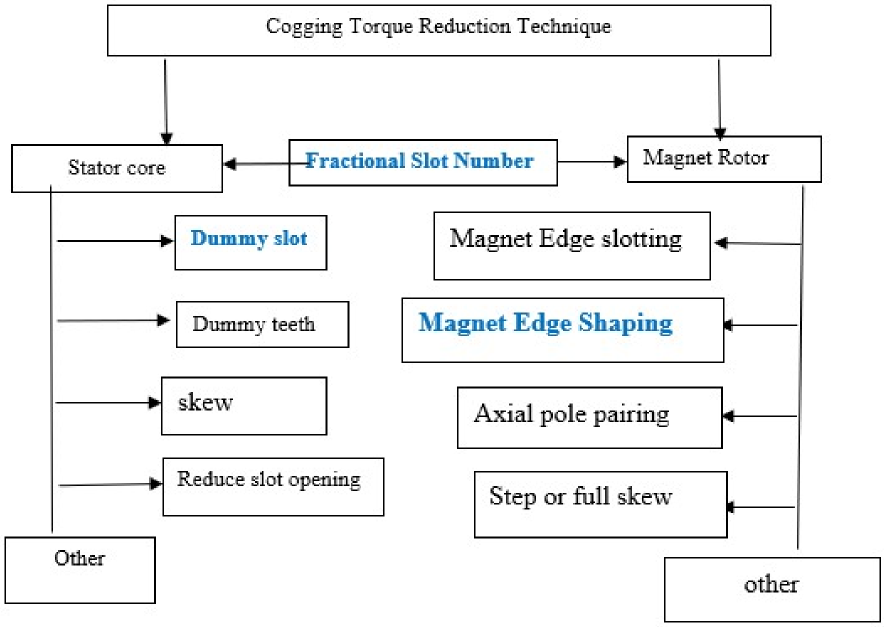

Figure 2 Cogging Torque Reduction Technique Classification [13]

3. PROPOSED STRUCTURED

As can be observed from Figure 2 the CT can be reduced by modification the stator or magnet rotor structure. In this paper, a combination of dummy slotting in stator core and shaping in magnet edge of rotor has been offered and developed as one of new solution to achieve the CT reduction in PMG. The characteristics of this technique may be lied that by shaping the magnet edge, the source of CT in the magnet of the PMM can be cut directly. With pairing of dummy slotting at stator teeth, the CT reduction achievement is much higher compared with using the only one of CT reduction technique. The slot opening at the stator core of PMGs studied were set to be 2 mm, which may be the most common in conventional stator structure. With the value of slot opening width of 2 mm, it might be quite large and easy to insert the conductor into the slot of the PMGs when they are being manufactured. It is also easy for rewinding the machine. The other advantages of using a larger slot opening width, is the fact that by increasing the slot opening, the magnetic loading effect of the machine can be minimized. The PMG structure investigated in this paper was presented in Figure 3.

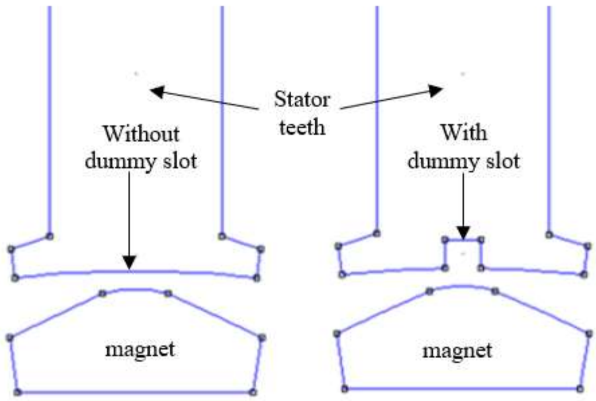

Figure 3 Cogging Torque Reduction Technique

From Figure 3, one can observe and compare that proposed structure of PMG with magnet edge shaping combined and dummy slotting at stator core. The presence of magnet edge shaping increases the air gap area of the machine. In Figure 3, the magnet edge shaping was paired with dummy slot in stator core. The detailed structure of the proposes PMG can be seen in Figure 4.

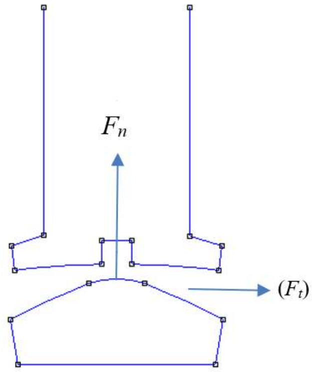

Figure 4. Force in Magnetic

In Figure 4, one can observe that normal magnet force (F_n) is perpendicular to the magnet surface and flowing into stator teeth directly, while the tangential magnet force (F_t) parallel with stator teeth or stator core. In other word, the tangential magnet force tends to distribute into slot opening at stator core. The wider of slot opening width, the higher the tangential magnet force flow into the stator slot. As a consequence, it influences the CT of machine to be increased. The relation between tangential magnet force and CT as shown in the following of this paper.

In this paper, as in the initial structure and as well as the other structures of PMG studied, material used for the PMG proposed is M-19 steel**,** for both of stator and rotor core. The advantage of using this material for PMGs core is the fact this kind of very material are common be used and very popular in PMG design and manufacturing nowadays. Another advantage is the material might support the high magnet flux density in both stator and rotor core of the PMG. The material M-19, can be operated to support the magnet flux density until about 1.5 Tesla. However, if the magnet flux density more than 1.5 Tesla, the PMG core losses could be increased. To produce magnet flux in the PMGs, the permanent magnet material of Nd-Fe-B has been used in our work.

4. ANALYSYS OF MAGNET AND STATOR STRUCTURE

By shaping the magnet edge, the CT of the PMG is reduced. In fact, the residual magnet flux could be declined by using this technique [5]-[8]. However, in order to achieve the CT reduction of the PMG, the combination of shaping in magnet edge and dummy slot in stator teeth have been developed and introduced in this study. As can be seen in the Figure 3b, the dummy slot in stator and the magnet edge shaping has been combined. The combination the two CT reduction technique promises to achieve reduction the CT of the PMG more effectively, compared with initial (see Figure 1). In the study, the pole arc of the shaping magnet has been optimized using design of experiment (*DOE*). However, the procedure of DOE was not studied detail in this paper, and only the selected structure presented. The machine structures of PMGS studied then analysed using finite element method magnetics (FEMM). In this paper, author have used the FEMM version 4.2.

In this paper, the flux of magnets used in the core of PMGs studied are assumed to be unity, and there is no current in the stator slot. The magnetic flux density in air gap of the PMG was generated by the permanent magnet NdFeB located in rotor core. The magnet flux flows into the air gap of the machine radially. Based on this assumption, the CT of the PMGs was calculated shown in Equation (1),[2],[7],[8].

$$T_c = -\frac{1}{2}\emptyset_g^2\frac{dR_g}{d\theta} \qquad (1)$$

Where $\emptyset_g$ is the magnet flux in the air-gap of machine, R_g is the passed air-gap reluctance, and $\boldsymbol{\theta}$ is the rotor position of the machine. Based on Equation 1, this technique may be having two advantages over the other techniques, reduce the total flux flowing into air gap and reduce the air gap reluctance as well.

The air gap reluctance become reduced since the magnet occupy the air gap the machine become smaller, compared with the initial structure. In fact, the source of CT in PMG and in all permanent magnet machine depends on the tangential magnet force generated by magnet structure as shown Figure 3. While normal magnetic force does not influence the CT directly, but it might be effect on the vibration of machine. However, the vibration issue is not discussed detailed in this study. The relation between tangential magnet force and CT as shown Equation (2) [15]

$$T_c = L_{stk}\int_{0}^{2\pi} r^2 F_t d\theta \quad (2)$$

Where ; L_{stk} = stack length (mm), r = rotor radius (mm), F_t= tangential force (Newton), θ = rotor position in degree. The tangential magnetic force is the function of normal magnet flux (B_n) and tangential magnet flux density (B_t). The normal magnet flux density produce a normal magnetic force as shown in Equation (3) :

$$F_n = \frac{1}{2\mu_0}[B_n^2 - B_t^2] \quad (3)$$

And the tangential magnet force can be formulated as:

$$F_t = \frac{1}{\mu_0}(B_n . B_t) \quad (4)$$

Based on the Equation (4), the CT can be rewritten as:

$$T_c = \frac{L_{stk}}{\mu_0}\int_{0}^{180} r^2 B_n B_t \, d\theta \quad (5)$$

The calculation procedure based on the past researchers and based on the Equation (5) [5],[7],[8]. By using the combining of shaping in magnet edge with dummy slot at stator core can reduce the tangential magnet force directly. To achieve the computation accuracy, 5 (five) dummy lines have been introduced in the air gap of PMGs studied. The value of the CT of the three different structures was presented and compared in Figure 5.

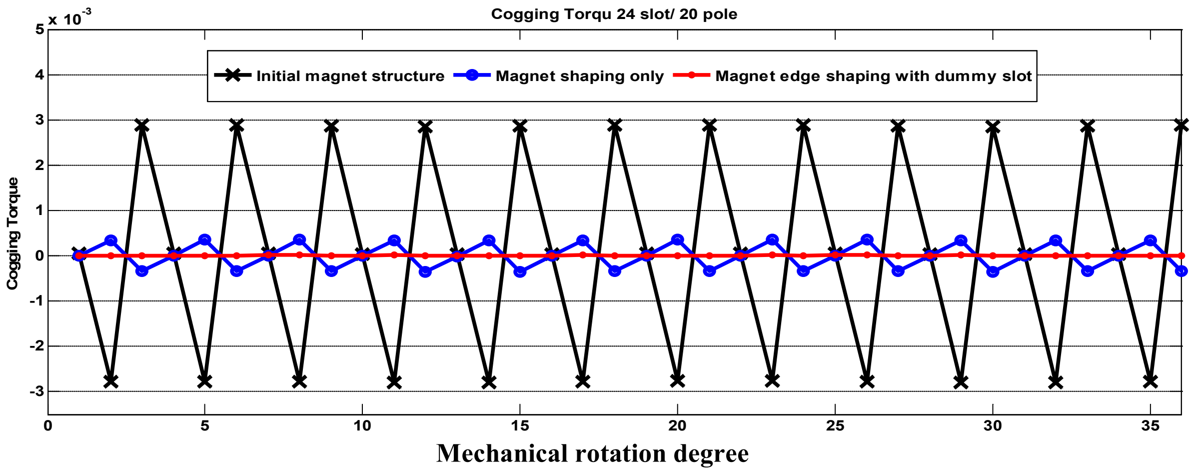

Figure 5. Comparison of cogging torque reduction of PMGs studied

The Figure 5 represents the comparison of CT reduction of the PMGs studied in this paper. It can be observed that by applying the combination of magnet edge shaping and dummy slot at stator core can reduce the CT of machine dramatically (**red line**), compared with initial structure (**black line**). The black line of shown in Figure 5 refers to the CT peak of base line model. In this study, the FEMM has been used to analysis the CT of PMGs. Using the FEMM we have been found that CT peak of base line model is 0.0028554 N.m. When the magnet of PMG is shaped the CT can be reduced around 0.0003471 N.m. This can be predicted as the magnet shaping is one of CT reduction technique. Next, in the proposed structure of PMG, combining the magnet edge shaping and dummy slotting at stator core is applied. The combination of the two CT reduction technique can the machine dramatically i.e 0.0028554 N.m (base line mobel) to 0.0000165 N.m (proposed model). This could be concluded that the CT reduction of PMG proposed is very significant as CT reduction standard in PMG application for renewable energy.

5. CONCLUSION

Effect of combining magnet edge shaping and dummy slot at stator core on the CT reduction of PMG has been studied and presented in this paper. The combination of magnet edge shaping and dummy slot at stator core has proved that the CT of machine can be reduced dramatically.

With the aim of FEMM, it was found that the maximum CT peak value of proposed structure as much as 0.0000156 N.m, while the initial CT peak value of the permanent magnet machine structure is around 0.0028554 N-m.

It can be concluded that the CT reduction of the proposed PMG declined as much as 99.42 **%** compared with the base line model. The combining of magnet edge shaping and dummy slotting at stator core is one of t effective way to improve the CT reduction in fractional slot number (FSN) of 24 slots and 20 poles.

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