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Improvement of Cogging Torque Reduction by Combining the Magnet Edge Shaping and Dummy Slot in Stator Core of Fractional Slot Number in Permanent Magnet Machine

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Abstract. A new technique in reducing the cogging torque by combining the magnet edge shaping and dummy slot in stator core of fractional slot number in permanent magnet machine was studied in this paper. The cogging torque is the most issue in permanent magnet application, since it effects to reduce the machine performance. A permanent magnet machine of fractional slot number with 24 slot /20 pole was presented in the paper. Firstly, the permanent magnet machine with conventional both of magnet structure and stator structure has been investigated as the basic reference of initial structure. Secondly, the magnet edge shaping with conventional stator core was investigated. Thirdly, in proposed structure, the combination of magnet edge shaping with dummy slot in stator was employed. The three different structures of the permanent magnet machine then analysed and compared. By implementation of magnet edge shaping combined with dummy slot in stator core has increased the interaction between magnet and stator core. This leads to increase the cogging torque frequency and reduce the peak value the cogging torque of the machine. Using the FEMM, the cogging torque value of the permanent magnet machine was analysed and computed. It was found that cogging torque reduction of the proposed structure as much as 99.47 % compared with the initial structure.

1. Introduction

Permanent magnet machines (PMMs) has been widely used in many applications such as a motor in pump, electric vehicles and others. In the context of renewable energy systems, the PMMs have been found as generator in wind turbine. For PMMs, the most important parameter in its application is in low speed condition which is the cogging torque (CT). The CT in PMM is complicated. The CT can be divided into two categories which are the stage of design and manufacturing. In the stage of design, the CT is investigated based on the interaction between the flux of magnet (material) in rotor and the slot opening in stator core. The CT is affected by material used in constructing the machine and have existed during the early stage of the machine development. According to researchers [1], it is known as natural CT. In the stage of manufacturing, the CT in permanent magnet do exist as it was caused by the imperfection of material handling when the PMM was fabricated, which is called additional CT. In this paper, authors only focus on the natural CT. As a matter of fact, the CT in PMM is hardly decrease towards zero value since it is influenced by many factors which are related to the PMM structures itself, except for the PMM with slot. On other hand, in renewable energy application such as in wind power system, usually requires a very low cogging torque peak value of the PMM. According to Handershot and Miller [2], a good design of machine is when the CT content of the machine lies between 1 - 2% of the rated torque. Up until now, to achieve a very low CT value in practical use is still a difficult task in electrical machine design. It is in fact that the CT in electrical machine can only be minimized but it cannot be totally removed from the machine, even in the industries a modern machine tools are being utilized for such issues. In the design stage, the CT of any PMM 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 stage. The purpose of this work is to offer and introduce a new technique to reduce the CT of permanent magnet machine by employing the combination of magnet edge shaping and dummy slot in stator core. The shaping of magnet edge and dummy slotting are two different CT reduction technique. Both CTs reduction techniques are combined, in order to achieve the CT reduction of the proposed PMM. In this paper, the CT reduction of the PMMs studied was analysed and focussed only in the design stage instead of manufacture stage. For purpose of study, the analysis the PMM structure, some assumptions have been made:

- The magnetic flux orientation was assumed to be radial.
- End effect of the permanent magnet generator is neglected.
- The magnet poles have the same characteristics.
- Saturation in both stator and rotor core of the machine is neglected.
- No current in stator winding or open circuit.
- The width and length of the stator teeth is not optimized.
- 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 PMM generic model have been adopted and studied. This type of structures was popular based on reference [2]. The permanent magnets used for the PMM structure proposed have been adopted to be bread loaf type. According Petkovska et al. [3], many commercially available machines drivers own a typical cogging torque ranging from 5 - 15% from the rated torque of the machine. And, due to the imperfection of manufacturing in mass production, the CT of machine may increase more than 25 % even it has been introduced a properly design permanent magnets.

Since the last two decades, many CT techniques have been proposed by researchers. The results of the research on CT reduction methods have been reported and documented. Some of the CT reduction techniques have been proposed such as dummy slot in stator teeth [4-6], slotting in magnet edge [7-10], and magnet shaping [11-14]. However, the most effective way to minimise the CT in permanent magnet machine is by combining the magnet shaping and dummy slot in stator core. The advantages of this technique are the fact that the distance between the points at magnet edge to the slot opening might be adjusted to a proper value. This technique aims to improve the proper contact between magnet edge and slot opening in stator core. Moreover, the CT frequency would increase and hence decrease the peak of CT. In this paper, the PMM model of a-24 slots / 20 poles structure have been selected and studied [2]. In the beginning, the initial magnet structure of the PMM was analysed. It was expected the CT of the PMM can be reduced as low as possible and could be realized in real structure or practical. The CT of the PMM have been analysed with considering the possibilities to the real machine structure such as the bolts in the rotor and stator core.

In this paper, some axial channels in rotor core of the PMMs models also have been introduced. The effect of axial channels in rotor of the PMM do not have a significance effect on the value of CT of the PPMs studied. The effect of axial channels in rotor core on the PMM performance may rarely discussed in research. However, the presence of some axial channels in the rotor core may be influence the magnetic flux distribution in rotor core of the PMM. Thus, to investigation further the effect of axial channels in the rotor core on the CT peak value, one should pay attention on the type and size of the axial channels in the rotor core of the PMM. In this paper, 5 axial channels have been employed. In this study, the effect of combining the magnet edge shaping and dummy slot in stator core on the CT reduction in the proposed PMM was presented in this paper. In order to increase the accuracy of the CT measurement, some dummy line in the air gap of the PMMs studied have been introduced. Using finite element based on the FEMM, authors have found that by combining the magnet edge shaping and dummy slot in stator core, the CT of the proposed PMM could be reduced dramatically to around 99.47 % compared with the initial structure of the PMM.

2. Permanent Magnet Machine Structure

2.1. Initial Structure

The PMM structure proposed in this paper refers to the cogging torque reduction in the stage of design. In this paper, the cogging torque of the PMM of fractional slot number with 24 slot / 20 pole structure was selected to minimise the cogging torque. The cogging torque reduction developed in this paper was by combining two of existing techniques which is the 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 cogging torque reduction in fractional slot number type of machine. The effectiveness of proposed structure was validated using the finite element analysis. In this study, a 24 slot / 20 pole with conventional magnet structure as the initial structure has been considered. In general, the cogging technique reduction can be summarized as in Figure 1. In the stage of design, it shows that the cogging torque reduction in PMM can be achieved by optimizing the structure of rotor, stator or combined of both of stator and rotor structure. The initial structure of the PMM study in this paper as shown in Figure 1.

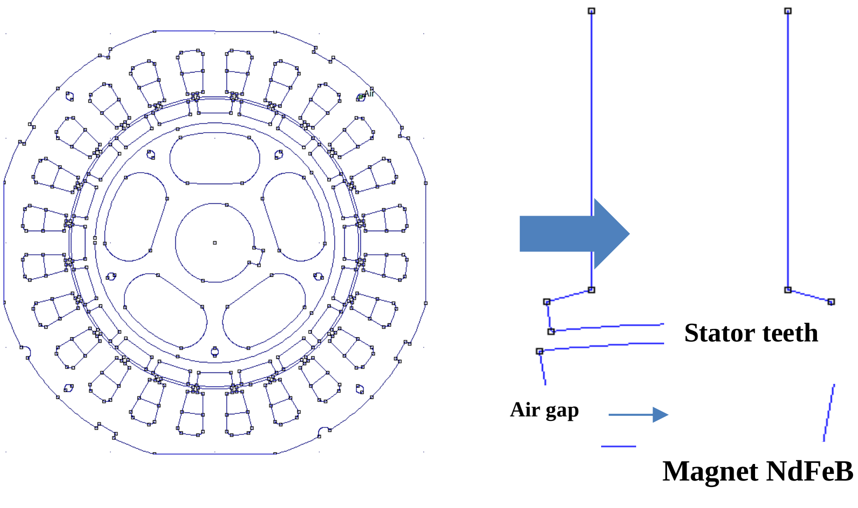

Figure 1. Model of PMSG studied a fractional slot of 8 slot /18 PMSG

3. Cogging Torque Reduction Classification

As have been mentioned in previous of this paper, many CT reduction techniques have been developed and proposed among researchers. The CT reduction technique can be summarized in Figure 2. It can be observed that the CT technique could be done by one or combination of two cogging torque techniques. Every cogging torque technique has advantages and disadvantages hence it could be stated that there is no exact best technique for the CT. In our proposed structure, a combination of dummy slot in stator core and shaping in magnet edge was developed and investigated.

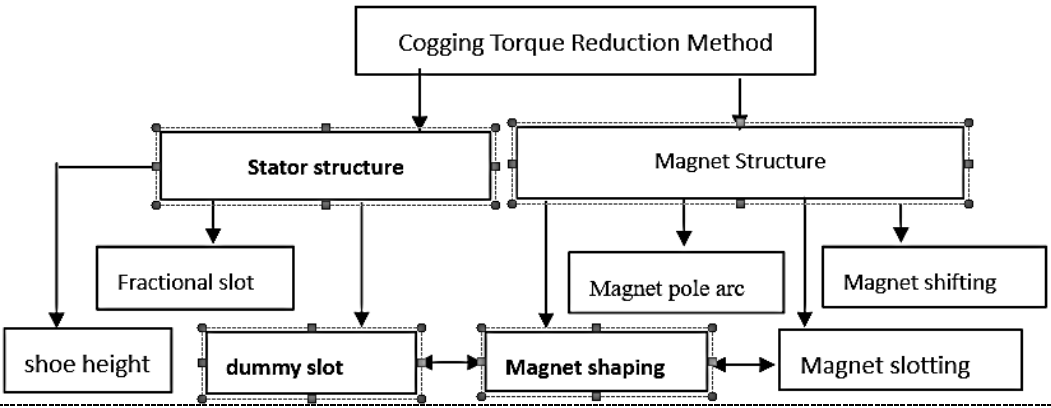

Figure 2. Cogging torque reduction technique classification [13]

3.1. Proposed Structure

As could be observed from Figure.2, the CT in any PMM can be reduced by modification the stator or magnet rotor. In this paper, a combination of dummy slot in stator core and shaping in magnet edge of rotor has been offered as one CT reduction solution in PMM. The advantage of this method may be lied in the fact that the source of CT in the edge of the magnet can be cut directly. It leads to minimize directly the source of the CT in magnet structure [15].

The stator teeth of proposed structure were much more similar with the conventional CT, the only main difference is in the proposed structure of PMM that has a dummy slot in every stator tooth. The slot opening in the stator core was set to be 2mm, which may be the most common in conventional stator structure. With the value of slot opening width of 2mm, 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 [16]. The PMM structure investigated in this paper was presented in Figure 2

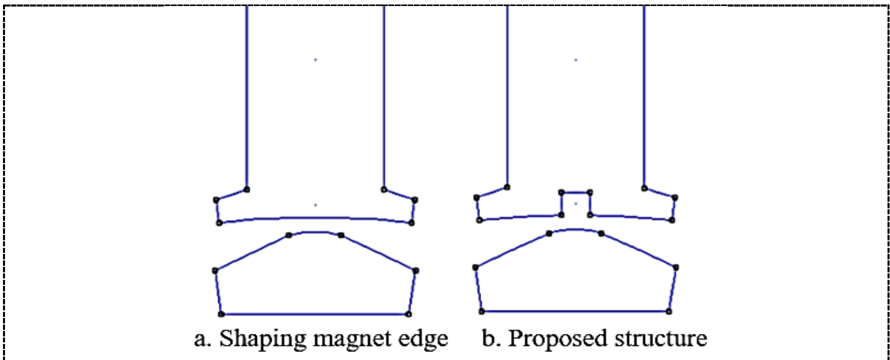

Figure 3. Cogging torque reduction technique classification [13]

From Figure 3 one can observe and compare that proposed structure of PMM with magnet edge shaping. The presence of magnet shaping increases the air gap area of the machine. In Figure 4, the stator core could be observed that the magnet shaping was paired with dummy slot.

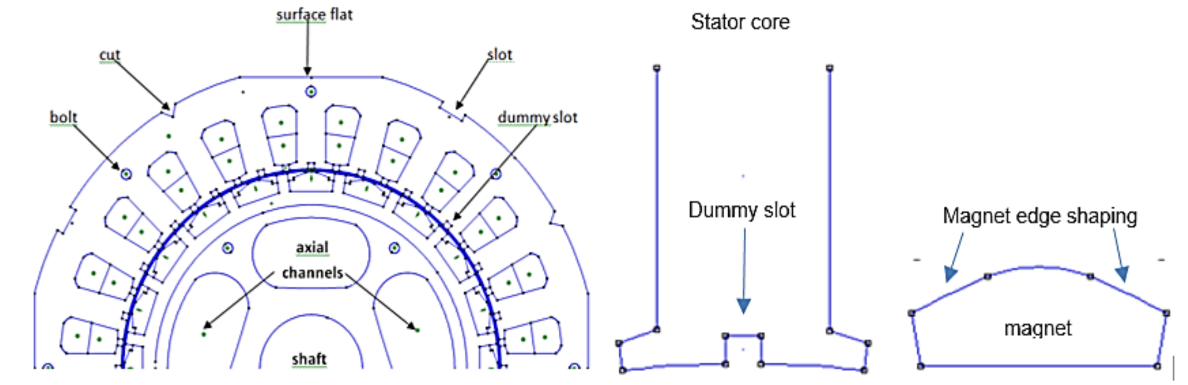

Figure 4. Combining magnet edge slotting and dummy slot in stator core

As has been stated in the beginning of this paper, one of effective technique to minimize the CT in PMM is by combining the shaping in magnet edge with dummy slot. The structure of PMM which employs the dummy slot in magnet edge and dummy slot in stator core. This type of CT technique has been studied and proposed by the previous authors as in [12]. However, the shaping magnet edge may be slightly reduced on the CT reduction of the machine. This research observes the CT reduction of the PMM achieved by employing the shaping in magnet edge paired with dummy slot in stator core. This technique effectively reduces the residual magnet flux in magnet edge which can minimise the CT of the PMM, as has been reported in [7],[10]. By combining the magnet edge shaping and dummy slotting in stator core.

4. Material for Structure Proposed Permanent Magnet Machine

In this paper, as in the initial structure and other structure, material used for the PMM proposed is M-19 steel**,** both for stator and rotor core. The advantage of using this material is the fact this kind of very material are common be used and very popular in PMM design nowadays. Also, the material could support the high magnet flux density in both stator and rotor core of the PMM. The material M-18, is expected to operate at the flux density not more than 1.5 Tesla, unless the PMM core losses could be increased rapidly. For the magnet in rotor core, the permanent magnet of Nd-Fe-B has been used in this study.

5. Analysis of Magnet and Stator Structure

The CT of the PMM is reduced by minimization of residual magnet flux in the magnet edge or in the magnet surface studied in references [7-10]. In order to achieve the CT reduction of the permanent magnet machine, the combination of shaping in magnet edge and dummy slot in stator teeth were introduced. As can be seen in the Figure 1, by employing the dummy slot in the magnet and dummy slot in stator could reduce the CT of the PMM more effectively as compared to the initial magnet structure and magnet shaping without no dummy slot. In the study, the pole arc of the shaping magnet has been optimized using design of experiment. However, the procedure of design of experiment was not studied detail in this paper. The machine structures then analysed using finite element method magnetics (FEMM).

6. Cogging Torque Calculation

In this paper, the magnets in PMM study are assumed to be unity and there is no current in the stator slot. The magnetic flux density in air gap was generated by the permanent magnet in rotor core. The magnet flux flows into the air gap of the machine radially. The CT reduction is calculated based on equation (1),[4],[9-10].

$$T_c = -\frac{1}{2}\emptyset^2{}_{\varepsilon}\frac{dR_\varepsilon}{d\theta} \tag{1}$$

where $\emptyset^2{}_{\varepsilon}$ is the magnet flux in the air-gap, R_ε is the passed air-gap reluctance, and θ is the rotor position of the machine. The calculation procedure based on the past researchers [7],[9-10]. By using the combination of shaping in magnet edge with dummy slot in stator core could eventually reduce both magnetic flux in air gap and air gap reluctance. Based on equation 1, this technique would yield two advantages over the other techniques which are 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. However, to achieve the cogging torque reduction, the magnet shaping degree must be assigned with a certain degree. In this paper, a 4^0 of pole arc of the magnet edge shaping has been assigned in order to achieve the CT reduction of the propose PMM [17]. The CT reduction of the three PMMs were presented and compared in this paper. The value of the CT reduction of the three different structures was presented and compared in Figure 5.

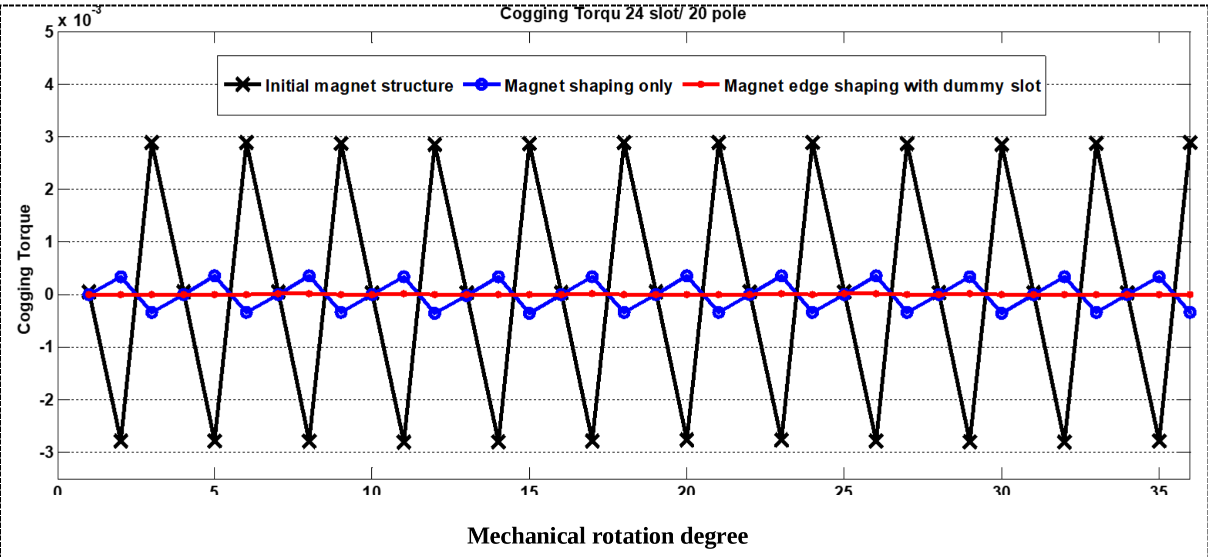

Figure 5. Combining magnet edge slotting and dummy slot in stator core

7. Result and Discussion

Figure 5 represents the comparison of CT reduction of the PMMs studied and investigated in this paper. As can be seen from the Figure 5, the CT value of the initial structure has the highest peak of CT among them of the three different PMM structures. Using the finite element analysis, all the PMMs studied were analysed and the CT reduction were compared. Initially, it has been found that the CT peak of the initial structure of PMM was approximately 0.0028554 N.m. In order to study the effect of the proposed CT reduction technique, the magnet edge shaping was employed in the PMM. The CT peak of the shaping in magnet edge was decreased to 0.0003471 N.m (blue line). The CT reduction is 84.44% compared with the initial structure. In the proposed PMM structure, the combining the magnet edge shaping and dummy slotting in stator core was employed. It was found that the CT peak of the proposed dropped to 0.0000165 N.m (red line). It can be concluded the CT peak reduced significantly, compared with initial structure of the PMM. This can be concluded the CT reduction of the proposed PMM was 99.47% compared with the initial structure.

8. Conclusion

Improvement of CT reduction by combining the shaping in magnet edge and dummy slot in stator core of the proposed PMM has been presented in this paper. The combination of magnet edge shaping with dummy slot in stator core has been developed to reduce the CT of the PMM. The comparison of CT value of each PMM structures was compared as shown in Figure 4. The CT of the proposed PMM reduced significantly, when the shaping in magnet edge was combined with dummy slot in stator core. Using finite element of FEMM 4.2 tools, the CT reduction of the PMM were calculated and compared. 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 declined as much as 99.47% compared with the initial magnet structure. The combining of magnet edge shaping with dummy slot in stator teeth was the effective way to improve the CT reduction in fractional slot number of 24 slot / 20 pole.

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