

Study the Influence of Edge Points of Magnet Surface and Stator Core on the Cogging Torque Reduction in Permanent Magnet Machine

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Abstract. Cogging torque in permanent magnet machine application effects to some undesirable vibration and noises. To minimize the cogging torque in permanent magnet machine's the most important issue recently. Influence the number of edge points in the magnet of one and two steps of magnet edge slotting was studied in this paper. For purpose of study, the structure of permanent magnet machine with 18 slot / 8 pole has been chosen, and the magnetic flux of all magnets was radial. The finite element of 2D based on FEMM 4.2 software was implemented to analysis the magnet flux distribution in air gap. Simulation results showed that by improvement of edge point at magnet edge of the two steps of slotting in magnet edge could reduce the cogging torque of permanent magnet significantly when compared with the initial structure. Employing the numerical simulation, both of the machine structures were analysed. It has been found that, the cogging torque reduction of edge points with 8 points has the highest reduction around 98.84 % compared with initial structure of the permanent magnet machine.

1. Introduction

Permanent magnet machines (PMM) have been widely used in many applications because of its compact feature, simple and low size mechanical construction, easy maintenance, and good reliability, high torque density and efficiency [1-3]. Nowadays the PMMs have been applied in many systems in our daily life such as in robotics, pumps, electric bike, wind power, water power and many more. However, the most important issue in PMM application is the cogging torque. The cogging torque is produced by the magnetic interaction between permanent magnet of the rotor and the stator teeth or stator core. It refers that by modify the magnet structure or optimise the stator core can minimize the cogging torque. To minimise the cogging torque in permanent magnet machine is one of difficult task in electric machine design and manufacture. Since the last few years, many cogging torque reduction techniques have been developed and proposed in worldwide. The cogging torque reduction techniques have been developed and proposed in world scientific, research and education. All of the cogging techniques mentioned above have advantages or may be drawback. The cogging torque techniques also can be employed with combination of two or more of the cogging torque techniques. In paper, the effect of edge points of magnet edge on the cogging torque reduction in permanent magnet machine was proposed. In the



beginning, to create the edge points of the magnet edge, the edge points were created through the aims of slotting in magnet structure. The slotting in magnet structure can be employed in any part of the magnet structure or in magnet surface, and it has been developed and proposed in past as in [1],[2],[4]. However, the most effective way to slotting the magnet structure is by placing the slotting in the magnet edge [3],[5]. In this study, the slotting was focussed only in the magnet edge. The advantages of slotting in magnet edge to create the edge points was laid in the fact that magnet part cutting is smaller compared with slotting in magnet surface. In general, reducing magnet volume in permanent magnet machine by cutting through the magnet surface can reduce the cogging torque [7]. However, this technique of cogging torque reduction may be not sufficient for special cogging torque reduction value requirement. Thus, using slotting in any part in magnet structure refers to reduce the magnet volume and effects to the cogging torque reduction. It is more efficient compared with reducing the magnet volume through cutting in the all magnet surface. But, even though by reducing more part of the magnet structure can effect to reduce the cogging torque, but the effect of cogging torque reduction may be more efficient by placing the slotting in magnet edge, instead in the centre of magnet. The reason is that, the magnet edge produces both normal and tangential flux density. When the slotting was employed in the edge of the magnet, the tangential flux density usually drops significantly compared with the magnet structure without any slotting, or the slotting magnet centre. As it has been understood, that tangential flux density is one of parameter which gives contribute to increase the cogging torque. Reducing the tangential flux density is more efficient by reducing the magnet edge. Effect of edge points of magnet structure on the cogging torque in permanent magnet machine was developed and proposed in our study. In this paper, the edge points in magnet surface were performed through the combining shaping and slotting in surface or magnet edge. A-two steps of slotting in magnet edge have been used and it was found that the number of edge points of the magnet increase ten times, compared with initial structure, while for the one step of slotting in magnet edge, the edge points were six times compared with the initial magnet structure. The presence of edge points or the number of points in magnet edge, leads to increase the number of contact points between magnet in rotor core and slot opening width in stator core. In addition, the interaction between magnet in rotor and stator more frequent and increase cogging torque frequency and reduce the peak of cogging torque. The presence of edge points also influences the magnetic flux distribution magnet edge, leads the total magnet flux flowing into the air gap become declined. The technique proposed in this study have been validated using numeric analysis based on finite element analysis. For comparison, the cogging torque reduction of different number of magnet edge points with 18 slot / 8 pole of permanent magnet machine have been studied and presented.

2. Motivation of the Research

Nowadays, the users of electric machine have been increased rapidly as result of modern life. Most of the electric machine user require a production of a favourable ripple-free torque, low cogging torque peak are necessary. However, at the design stage and before the prototype of any permanent magnet machines are made, it is often difficult to construct any machine which produces satisfactory cogging torque reduction. In addition, there is not any specific criteria are found to determine the magnet rotor structure for such cogging torque reduction. Hence, in this study, a fractional slot number of 18 slot / 8 pole with certain of stator slot opening of 2 mm and magnet structure with more edge points was design to reduce the cogging torque in permanent magnet machine. In this study, a proposed structure of permanent magnet machine design was investigated to developed technique to minimize the cogging torque in permanent magnet machine. In order to increase the edge points of the magnet structure was performed with the aim of slotting in magnet edge. In this paper, authors focus to find a feasible number of edge points in magnet structure of fractional slot number of 18 slot / 8 pole to reduce the cogging torque. The cogging torque values of the permanent magnet machines with fractional were compared and presented.

3. Theories of the cogging torque in PMM

The cogging torque is caused by the interaction between stator core or slot opening width and permanent magnet in rotor core. Since the permanent magnet machine is constructed from various material such steel, iron, magnet and other, the cogging torque also is influenced by the material of the machine. It refers that the cogging torque in permanent magnet machine depend on the structure and material of the machine. In fact, the part of the magnet which contributes the most cogging torque in permanent magnet machine may be in magnet edge. For normal stator structure, where there is no any dummy slot, dummy teeth, shifting magnet or other, the cogging torque can be declined by reducing the magnet edge. The cogging torque reduction technique by reducing the magnet edge usually called magnet shaping. Another technique to reduce the amplitude of the cogging torque value is by reducing the volume of magnet [7]. By increasing the distance between magnet surface and slot opening width in stator core is another way to reduce the cogging torque [4]. The cogging torque in permanent magnet machine can be calculated as shown in equation (1). In this study, the magnet pole structure of the machines are assumed to be radial magnetization [2],[3],[7].

$$T_c = -\frac{1}{2}\phi_g^2 \frac{dR}{d\theta} \quad (1)$$

where ϕ_g^2 is the magnet flux in the air-gap, R_g is the passed air-gap reluctance, and θ is the rotor position of the machine. The cogging torque also can be formulated as a Fourier series shown in equation where m is the least common multiple of the number of stator slot (N_s) and the number of pole (N_p), k is an integer and T_{mk} is a Fourier coefficient as shown in equation (2).

$$T_c = \sum_{k=1}^{\infty} T_{mk} \sin(\theta mk) \quad (2)$$

For PMM with integral slot number, each pole of the machine has a whole number multiple stator teeth, so that the cogging effects of each magnet are in phase and added, leads the cogging torque tend to be higher compared with the fractional slot number. In contrast, for the permanent magnet machine with fractional slot number as proposed in this study, only some of the poles number multiple stator teeth, leads only some of the magnets in rotor core are in phase and added. This leads the permanent magnet machine with fractional slot number tends to have a lower cogging torque compared with the integral slot number. Another way to calculate the cogging torque can be done as shown in equation (3).

$$T_c = \frac{L_{stk}}{\mu_0} \int_0^{2\pi} r B_n B_t d\theta \quad (3)$$

where L_{stk} = stack length of the machine, B_n = normal flux density, B_t = tangential flux density, θ = mechanical degree of rotor rotation, r = dummy radius in air gap where the cogging torque values are measured. From Equation 3, refers that cogging torque is a function of the normal magnet flux density and tangential flux density. In order to increase the accurate of cogging torque computation in this paper, 4 dummy lines has been employed in the air gap of the machine [10]. The magnetic flux density of the three different of magnet structures was presented and compared.

4. The Proposed Magnet Structure for Permanent Magnet Machine

To study the effect of the edge point in magnet surface on the cogging torque reduction in permanent magnet machine of fractional slot number with 18 slot / 8 pole was proposed. In our study, the slot opening width of all machines studied were 2 mm. In addition, some axial channels in rotor of the machines study also have been introduced. However, the effect of axial channels on the cogging torque reduction was not studied detail in this paper. In the beginning, in order to achieve the number of edge points in magnet surface, the slotting in magnet edge has been done firstly. After assigning the slotting in each of magnet edge, the position of the edge can be observed in Figure 1a, 1b and 1c respectively. As can be observed, the presence of one step of slotting in magnet edge, automatically creates 6 six edges in magnet and does a – 80 in magnet for the two steps of slotting (proposed structure). The presence of edge points also effects to distance between magnet surface and slot opening width or stator core. The magnetic flux distribution also become changed in the magnet edge. The magnet cross section or magnet volume become declined. It can be predicted that total flux in to flow into air gap through the edge of magnet may be reduced significantly. At the same time, the air gap cross section of the machine become increase, since the volume of the magnets become decreased. This leads the reluctance air gap become higher and the air gap reluctance become smaller compared with the initial structure (see Fig.1a). According to the Equation 1, this effect to decreasing of the cogging torque of the machine. The cogging torque reduction then was computed using finite element analysis based on FEMM 4.2. The cogging torque reduction for three different of magnet structures were presented and compared in this paper.

In Figure 1, one can observe the stator core for all PMMs are same, the only different is the slotting in the magnet structures as shown in Figure 1a and 1b respectively. The magnet for initial structure has no slot (see Figure 1a) and only has 2 edge points. In Figure 1b and 1c, the presence of magnet edge slotting generates 6 edge points. For two step of slotting, the edge points are 8 edge points. In addition, the points contact also effects to variation of the distance between magnet in rotor and stator core. This leads to increase the interaction between the magnet edges and the stator slot. As a result, the cogging torque frequency of the machine more frequent and the peak value of cogging torque can be declined.

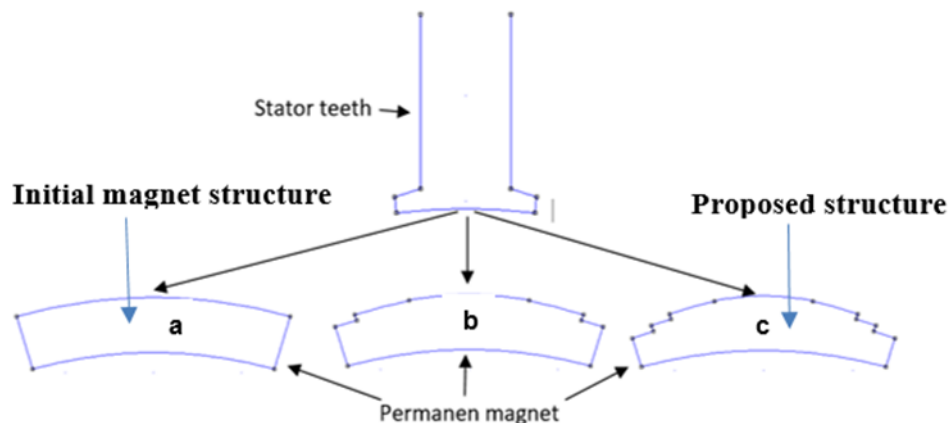


Figure 1. Three different magnet structures

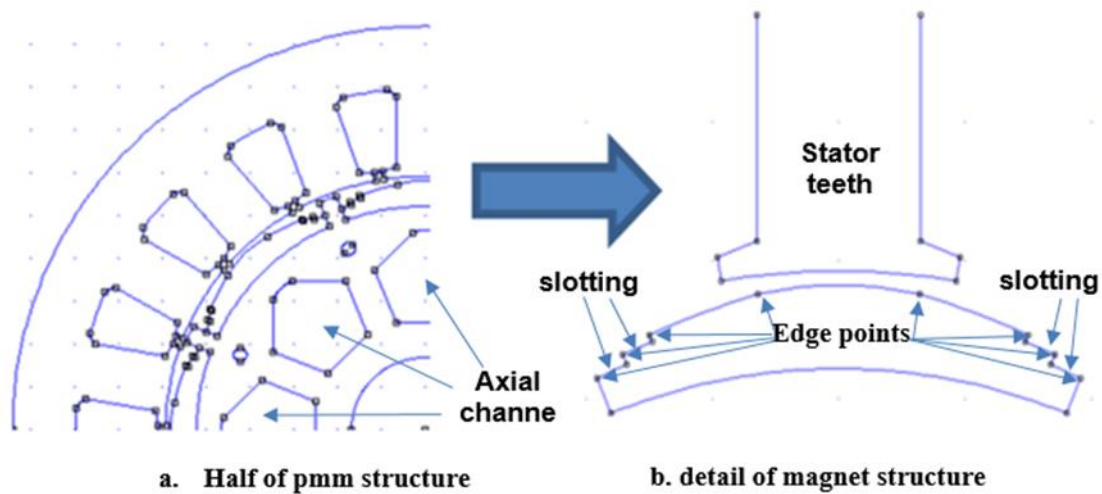


Figure 2. Structure of Permanent Magnet Machine Proposed

From Figure 2, one can observe that the edge points were exist as the slotting was employed. The number of slotting effect to number of edge points. For a-two step of slotting in magnet edge, resulting some of 8 edge points in magnet structure. The structures of PMM with 18 slots/8 pole with three different magnet structures were studied and compared. As a comparison, the initial magnet structure is popular magnet structure of permanent magnet without any slotting in magnet. It also shows that the magnet has only has 2 edge point which located in magnet edge (see Figure 1a). This conventional type of magnet structure has the highest peak of cogging torque compared with the 6 edge points and 8 edge points.

5. Effect of edge point on the magnet volume

The presence of more edge points in magnet surface effects to increase the contact point between magnet rotor and stator slot. It can be expected, that the more the number of edge points in magnet the more frequent the interaction between magnet rotor and stator core, leads to increase the frequency of cogging torque. In other hand, it also effects to reducing the magnet volume of the machine. But, from cost effective of magnet material view, it can be stated that it is one of advantage. The drawback of slotting the magnet edge may be, the magnet volume become reduced and effect to declining the power output of the machine.

6. Computing the Magnetic Flux density and Cogging Torque

6.1 Analysis the magnetic flux in air gap

In the beginning, authors computed and presented the normal flux density and tangential flux density in air gap of the initial and proposed structure, as shown in Figure 3a, 3b respectively.

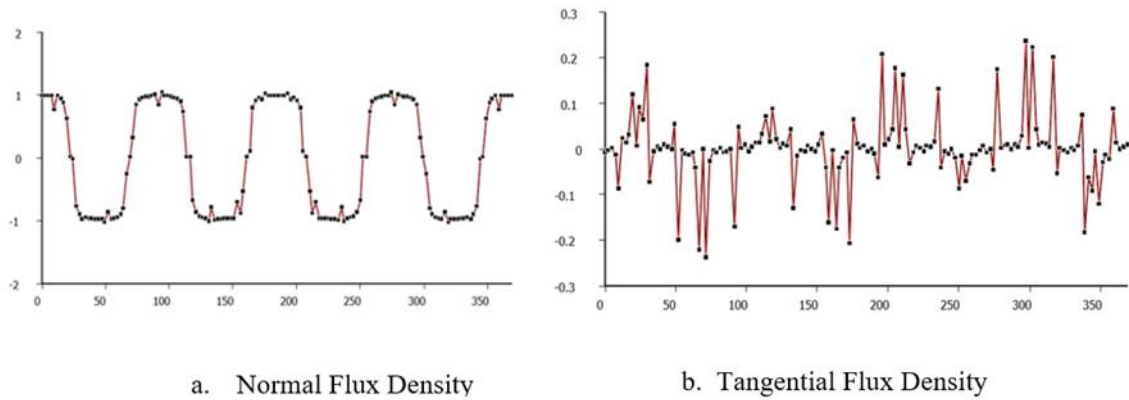


Figure 3. Magnetic Flux Density of Initial Magnet Structure

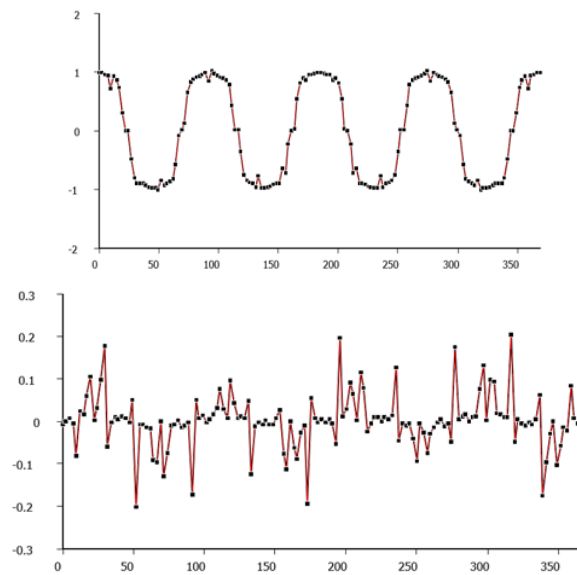


Figure 4. Magnetic Flux Density of Magnet Structure with 6 edge points

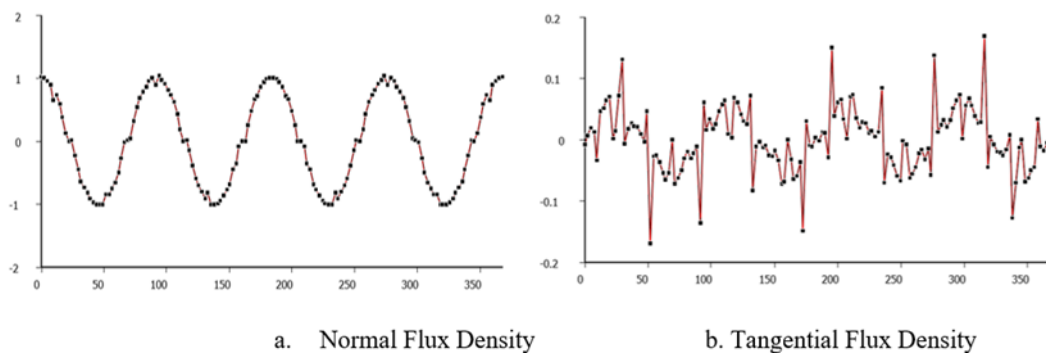


Figure 5. Magnetic Flux Density of Proposed Structure (8 edge points)

From Figure 3 and Figure 4, shows the magnetic flux density in air gap of the machine. Figure 3a and 3b, represents the normal and tangential magnetic flux in air gap of initial magnet structure. It can be observed that normal magnetic flux density distribution is square, while the tangential flux magnet density in Figure 3b is dense. In Figure 4a, the normal magnetic flux density peak is remaining stable is around 1.0 Tesla and the same as the initial magnet structure does. The only different the shape of the normal flux density wave is more sine, compared with the initial magnet structure. The tangential flux density in Figure 4b tends to decrease compared with the tangential of the tangential flux density of initial magnet structure. The peak tangential flux density also declined to as much as 0.18 Tesla.

6.2. Computation the Cogging Torque using finite element

In this study, the FEMM 4.2 was used to compute the cogging torque values of the permanent magnet machines studied. The procedure of cogging torque computation was based on past researchers [2],[3],[5],[7],[8]. The comparison of cogging torque reduction for three different magnet structures of 18 slot / 8 pole was presented and compared in Figure 6.

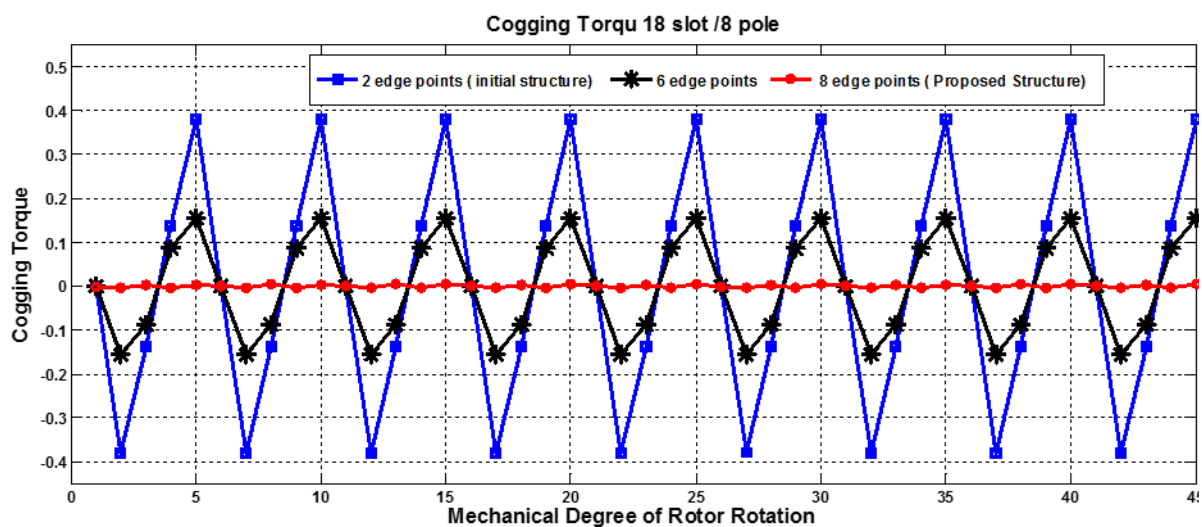


Figure 6. Comparison of Cogging Torque for different magnet structure of 18 slot / 8 pole

7. Discussion

Figure 6 represents the comparison of different magnet structure based on the edge points number of 18 slot / 8 pole. From the Figure 5, one can observe that the cogging torque for initial structure which the number of edge points 2 has the highest of cogging torque peak value. It has been analysed and it been found as much as 0.3793488 Tesla (as shown in blue line). After performing the slotting and improving the number of edge points in magnet edge, the cogging torque tends to be reduced (as shown in black line). This is caused by the interaction between magnet edge and stator core become more frequent leads to increase the cogging torque frequency. The presence of more slotting in magnet edge, automatically increases the number of edge point of the magnet structure, compared with initial magnet structure. As a result, the peak value of the cogging torque become decreased sharply. The cogging torque of the proposed magnet structure could be reduced to 0.0044001 Tesla. The cogging torque reduction of permanent magnet has been found in this paper was significant. Also, the cogging torque reduction of the proposed machine is a little bit higher compared with the previous research [1]-[5]. It means the cogging torque content of the proposed permanent magnet machine is lower, and it can be accepted to implement for any specific requirement.

8. Conclusion

Influences of edge points in magnet surface and stator core structure in permanent magnet machines of fractional slot have been investigated in this paper. The relation between the edge point number in magnet edge or magnet surface on the cogging torque for three different number of edge points were presented and compared. The edge points of permanent magnet machine with 8 edge point has the highest cogging torque reduction, compared with initial structure of 2 edge points and 6 edge points, respectively. Using the finite element analysis, the cogging torque has been computed and it was found that peak of cogging torque as much as 0.0044001 N.m. The cogging torque reduction of magnet structure with 8 points in magnet surface was found as much 98.84 %.

9. References

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