IOP Conf. Series: Materials Science and Engineering **807** (2020) 012026 doi:10.1088/1757-899X/807/1/012026

Study of The Effect of Height and Length of Slotting in Magnet Edge on the Cogging Torque Reduction of Fractional Slot Number in Permanent Magnet Machine

Tajuddin Nur[1*] and Liza Evelyn Joe[2]

[1] Department of Electrical Engineering, Graduate School of Engineering,
[2] Faculty of Engineering, Atma Jaya Catholic University of Indonesia, Jakarta, Jl. Jend. Sudirman No.51 Jakarta 12930 Indonesia

Corresponding e-mail: tajuddinnur559@gmail.com

Abstract. Cogging torque generated in permanent magnet machine effects to some undesirable vibration and noises. In order to minimize the cogging torque in permanent magnet is the most important issues recently. This paper investigated the influence of the value of height and length of slotting in magnet edge on the cogging torque reduction. For purpose of study the structure of 24 slot/10 pole of permanent magnet machines have been chosen. The 2-D finite element based on FEMM 4.2 software was implemented to compute the permanent magnet machine performance. Simulation results showed that by optimising the height and length of slotting in magnet edge can reduce the cogging torque of permanent magnet machine significantly. The most effective way by employing a-two step slotting with 2.5 mm of height and 0.7 mm of length of the slotting in magnet in the first step of slotting. In the second step of in magnet edge, the length of slotting has been assigned as much as 2.3 mm and the height of slotting was 0.588635 mm. By employing the FEMM, three of different magnet structures of permanent magnet machine were analysed. It was found that the cogging torque of permanent magnet machine proposed magnet structure as much as 99.7 % compared with the initial structure of the permanent magnet machine.

1. Introduction

In renewable energy systems such as wind power, water power, wave power and other related to the special purpose of electrical machine, the utilization of permanent magnet machine (PMM) is one of the most important part in order to harvest the electric energy. The reason is that the type of electrical machine has some advantages over the other type of electrical machines such as high efficiency, lower maintenance, and high-power density. However, the most issues related to the PMM application is the cogging torque (CT). The cogging torque in PMM produces attractive force between magnet in rotor and stator core. In low speed wind situation, the blades are hard to be rotated and rotor experiences to be braked. The CT in PMM is produced by magnet flux in rotor core, then generates magnetic interaction or force between the stator core and permanent magnet in the rotor. Based on the above discussion, it can be concluded that the CT value in PMM depends on the structure and the material used in the PMM manufacturing. Hence, in order to minimise the CT value in PMM, an appropriated design of magnet structure in rotor core and stator core structured must be provided. In addition, the influence of the material used for the machine must be considered. Since the last few years, there have been increasing

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

IOP Conf. Series: Materials Science and Engineering **807** (2020) 012026 doi:10.1088/1757-899X/807/1/012026

the research on CT reduction techniques which have been proposed and reported in worldwide where the authors have paid attention at the slotting in magnet structure [1- 5]. In [1- 2], developed a cogging torque reduction technique by employing the slotting in the magnet surfaces of PMM. While in [3] and [5], proposed the slotting in the magnet edge to minimise the CT. and authors [5] investigated the effect of the length and height of slotting in magnet edge on the CT reduction in an integral slot number of 24 slot / 8 pole. Employing the magnet edge slotting technique, the CT of the machine could be reduced as much as 95 % compared with initial structure. This means that the CT content in the PMM was 5 %. In the study, the material used for magnet was NdFeB and for both of stator and rotor core, the M-19 steel have been used. Another scholar [4] employed one step of slotting in magnet edge to reduce the CT and it could be reduced significantly. However, for renewable energy application the CT in the CT contains in the permanent magnet machine must be as low as possible. Past researchers suggested the content of CT for special purpose, the CT content in the range 1 to 2 % of the rated torque.

In this study, the effect of length and height of slotting in magnet edge of a fractional slot number was presented. For the purpose of this study, a- 24 slot / 10 poles of PMM structure have been chosen. Three of different structures of magnet were analysed and compared. All the stator cores of the machines studied have the same structure, the different only in the magnet structures. In the beginning, the conventional of magnet structure or initial structure was analysed, which was no any slotting in magnet. Using the finite element analysis, the value of cogging torque was calculated and recorded. Further, for the second structure, a one step of slotting was employed in the magnet edge. As have been predicted, the cogging torque can be reduced. However, the cogging torque reduction was not significantly for renewable energy system requirement. For wind power application, the cogging torque reduction at least 99 % from the rated torque. Thus, in order to achieve the CT reduction of proposed structure, a 2 step of slotting in magnet edge has employed in this study. The advantage of using a 2-step slotting in magnet edge is the fact that more length and height of the slotting can be obtained. In this paper, the optimum of length and height of the slotting in the proposed structure has been found as much as 2.5 mm and 0.7 mm respectively, then in the second step of slotting the length and height have been determined as much as 2.3 mm and 0.5886 mm, respectively.

2. Theories of the cogging torque in PMM

The CT in any PMM is caused by the interaction between stator core or slot opening width and permanent magnet in rotor core. In fact, the part of the magnet rotor which contributes the most of CT content in air gap may be in the magnet edge. So, in order to minimise the CT in air gap is by reducing the residual magnet flux in magnet edge. Reducing the residual can be done by shaping or slotting or compounding shaping and slotting in magnet structure. The CT can be calculated as shown in equation (1). In paper study, the magnet pole structure of machines was assumed to be radial magnetization [2],[3],[7].

$$T_c = -\frac{1}{2}\emptyset_g^2 \frac{dR}{d\theta} \tag{1}$$

where the $\emptyset_g^2$ is the flux in the air-gap, $\boldsymbol{R_g}$ is the passed air-gap reluctance, and $\boldsymbol{\theta}$ is the rotor position of the machine. The magnet flux in air gap in Eq.1, can be formulated as shown in Equation (2)

$$\emptyset_g = B_g A_g \tag{2}$$

where B_g=magnetic flux density in air gap and A_g = air gap cross section of the machine. The magnetic flux density is depended on the magnet flux remanence and air gap cross section is influenced by the distance between magnet in rotor core and the stator core. Another CT formulation for any PMM is

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

IOP Conf. Series: Materials Science and Engineering **807** (2020) 012026 doi:10.1088/1757-899X/807/1/012026

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. For the PMM with integral slot number, each pole of the machine has a whole number of multiple stator teeth, so that the cogging effects of each magnet are in phase and added, leads the cogging torque tend to be increased. In contrast, for the PMM with fractional slot number as in the 24 slot / 10 pole structure, only some of the poles number multiple stator teeth. This leads that only some of the magnets in rotor core are in phase and added. That is one of reason why the fractional slot number usually considered as CT reduction techniques. However, in order to fulfil requirement of low CT for renewable energy application, the fractional slot number technique should be combined together with other CT reduction technique to get a low CT according to the renewable energy system requirement. In this study, it has been found that value of length and height of slotting has affected on the CT reduction of the machine.

3. The proposed of PMM Structure

To study the effect of the height and length of slotting in the magnet edges on the CT reduction in a fractional slot number, a-24 slot/10 pole structure has been studied and proposed in this paper. The stator core structures are like the real machine, such as slot opening width, stator slot number, stator teeth height and stator teeth width were the same and have the same characteristics. The stator core for all permanent magnet machine studied were same, the only different is the magnet structures. As a comparison, in the beginning of this study, the magnet structure was initial t structure of magnet as shown in Figure 1. In Figure 2, a-one step of slotting in magnet with certain height and length have been employed to the magnet structure. While in Figure 3, the two steps of slotting were employed in magnet edge. The presence of slotting in magnet edge effect to the changing the distance between magnet edge and stator core. As a consequence, the magnet flux distribution in magnet edge also become changed.

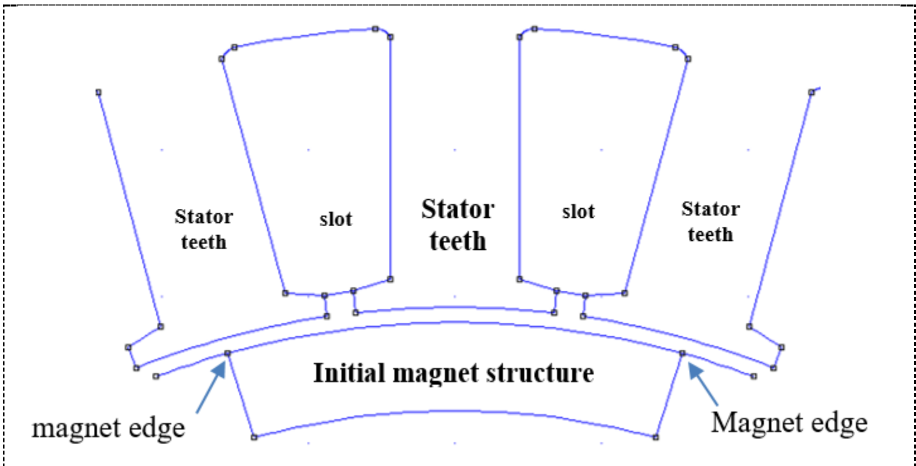

Figure 1. Initial Magnet structure

As can be seen in Figure 1, the structure of magnets is smooth and the distance between magnet rotor and stator teeth/stator core is homogenous. In Figure 1, the distance between magnet and stator core was 1 mm and the magnet flux were radially. Since there is no any slotting in magnet surface, in the initial magnet structure, only has two edges. The magnet edge of initial structure located in the right and left side of the magnet.

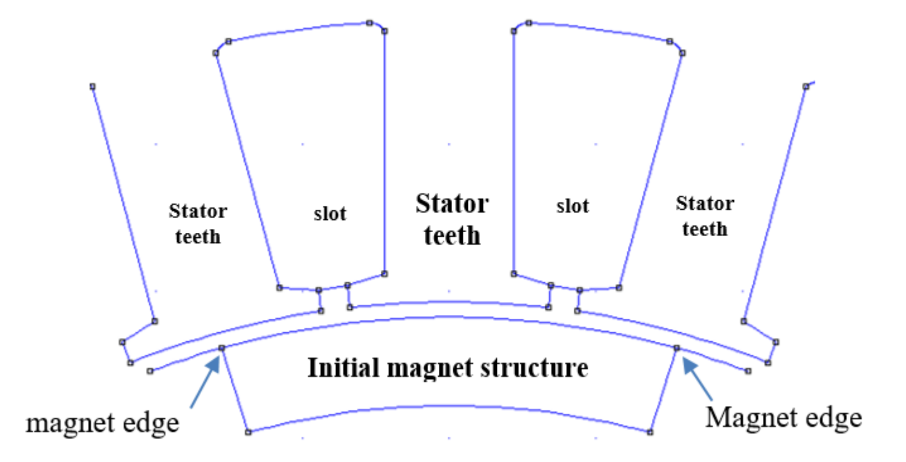

Figure 2. One step of slotting in magnet edge

In Figure 2, every side of the magnet has 2 edges so that there are 4 edges in magnet structure. The length and height of the slotting does not affect to the number of magnet edge, but it can change edge point of the magnet. It means that, the distance between magnet edge to the stator core depends on the length and height of the magnet edge slotting. The cross-section area or magnet volume also become changing caused by the length and height of the magnet slotting. As a consequence, it will affect to the total magnet flux flowing into the air gap and will reduce the cogging torque of the machine [7].

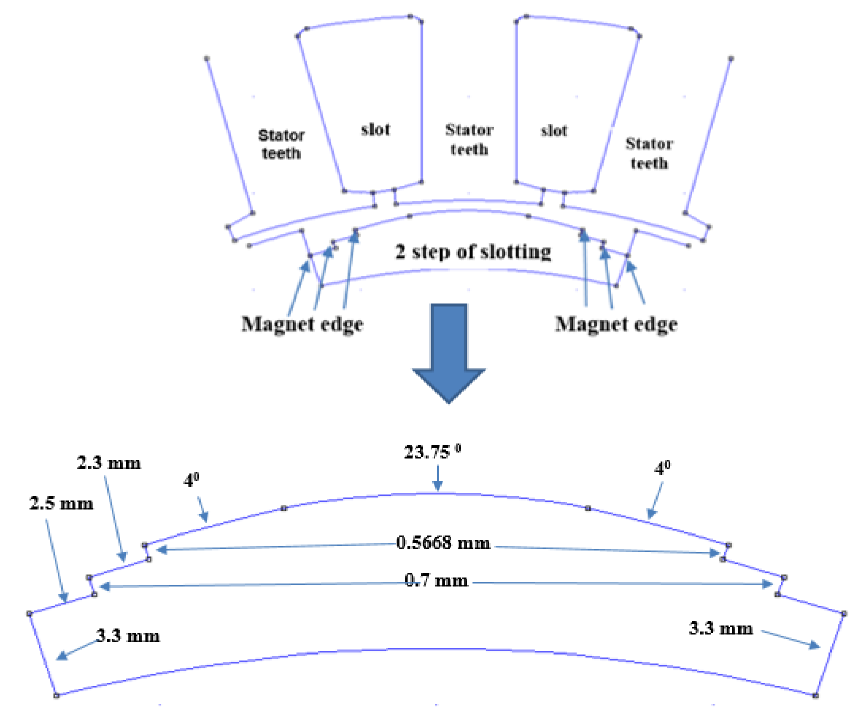

Figure 3. Two steps of slotting in magnet edge

In Figure 3, the presence of 2 steps of slotting in magnet edge with certain value of length and height effect to change magnet structure. As can be observed in Figure 3, there are 3 edges in each side of magnet. Compared with the initial structure, the magnet cross section area is smaller. As a result, the total flux flowing into air gap become decreased sharply. Also, the presence the 2 steps of slotting in magnet edge, effect to the increasing of the air gap cross section since the magnet cross section occupying the rotor core was reduced. This leads to reduce the air gap reluctance of the machine. Thus, the effect of employing 2 steps of slotting with first length of 2.5 mm, first height of 0.7 mm, second length of 2.3 mm, and 0.588635 mm, respectively, have given the best contribution in achieving the CT reduction of the PMM. In this study, the most effective value of length and height of slotting in magnet edge on the cogging torque reduction of the machine, as presented in Table 1.

Table 1. Height and Length of magnet edge slotting

No	1st length of (mm)	1st height of (mm)	2nd length of (mm)	2nd height of (mm)	T_{cmax} (N.m)
Initial structure	No magnet slotting	No magnet slotting	No magnet slotting	No magnet slotting	0.2352206
1 step of slotting	2.5	0.6	No magnet slotting	No magnet slotting	0.0675994
2 steps of slotting	2.5	0.7	2.3	0.588635	0.0006774

The presence of slotting in magnet edges effect to increase the number of edges in magnet structures. The magnet cross section or magnet volume also become decrease. This effect to magnetic flux distribution in magnet edge into air gap of the machine decline which leads to reduce the total flux magnet in air gap. For magnet structure in Figure 3, the magnet edge has been achieved to be 6 edges. The CT was calculated and compared with the initial structure. By employing the one step slotting in magnet edge became reduce. In Figure 3 (proposed structure), the two steps of slotting in the magnet edges was employed to increase the CT reduction. The different between one step of slotting in magnet edge and the two steps of slotting is the fact that the distance between magnet become variable. Also, the air gap cross section of the machine become larger compared with the one step of slotting. As a result, the air gap reluctance become decreases and declines the peak of cogging torque of the machine. The one step of slotting was illustrated in Figure 4 below and the effect of the slotting in magnet edge of the three structure of machine was calculated.

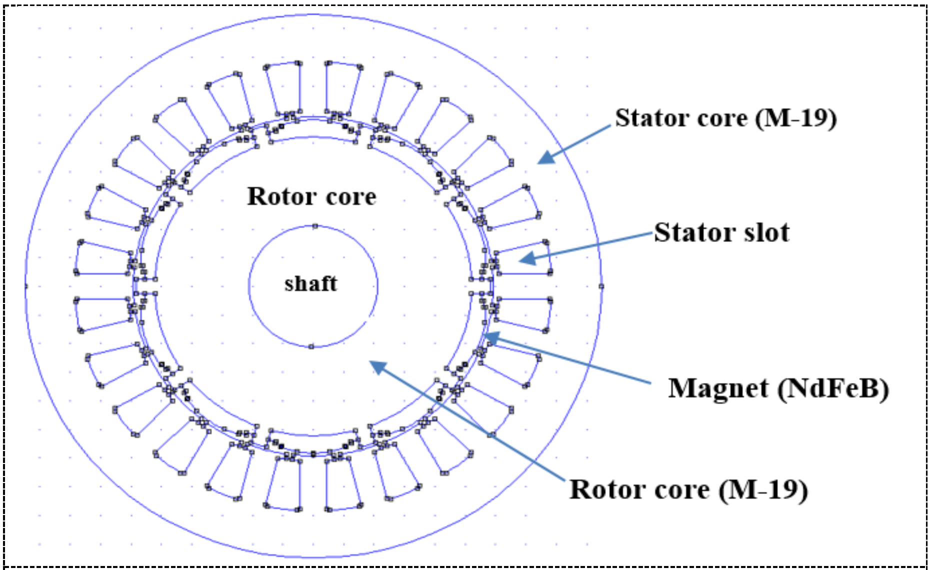

Figure 4. One step of slotting in magnet edge

4. Simulation of Magnetic Flux Distribution and Cogging Torque

4.1. Magnetic Flux Distribution in machine core

In order to predict the performance of the machines effected the CT reduction technique, the flux distribution in the core of the machine has been presented and compared, in this paper. The flux distribution in the part of the machine was performed by FEMM. The FEMM is one of powerful software which can calculate all the parts of the machine. The magnetic flux distribution of the all machines studied as shown in the Figure 4a, 4b and 4c, respectively.

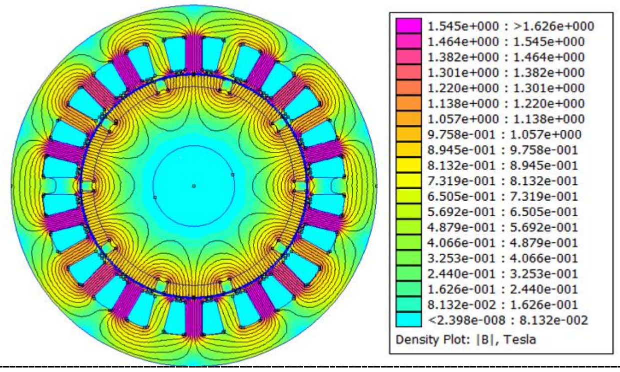

Figure 4a. Initial Magnet Structure

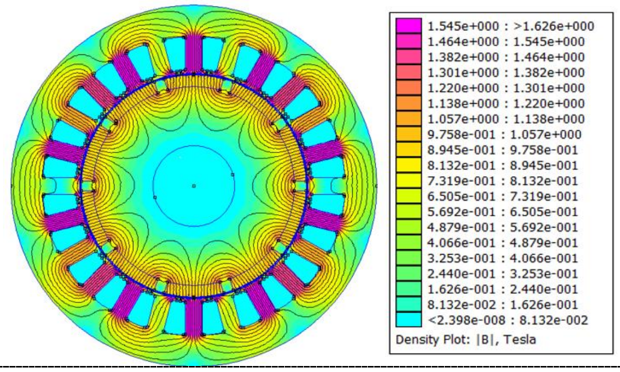

Figure 4b. One step of slotting in magnet edge

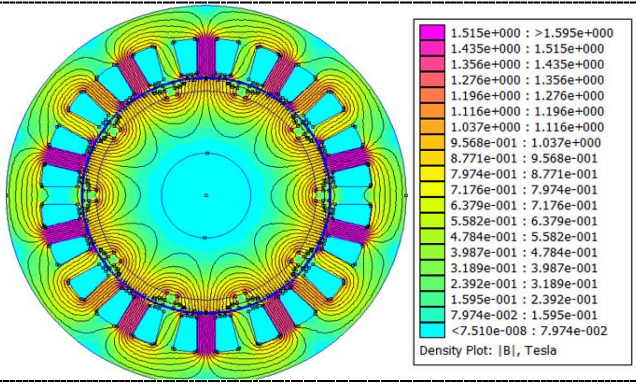

Figure 4c. Two steps of slotting in magnet edge

In Figure 4a,4b,4c, we can observe that the effect length and height of slotting only give a small contribution on the changing the magnetic flux density in the machine core. For proposed structure, the magnetic flux density in the core have been investigated using finite element and it has been found as much as 1.515 Tesla, while for the 1 step of slotting the magnetic flux density was 1. 535 Tesla and 1.545 Tesla for the magnetic flux density of the initial structure.

IOP Conf. Series: Materials Science and Engineering **807** (2020) 012026 doi:10.1088/1757-899X/807/1/012026

4.2. Calculation the Cogging Torque

In this paper, the FEMM 4.2 was used to investigate the PMM characteristics based on finite element analysis [2],[3],[5],[7],[8],[9]. The FEMM 4.2 is one of a-2D finite element analysis which has been widely used for analysis for any electrical machine performance since the last few years. The procedure of FEMM 4.2 operation based on three steps [8]. In order to achieve the accurate of CT computing in air gap, 5 dummy lines have been employed in the air gap the PMMs studied. Every structure of the machine was analysed and the CT of the PMM was recorded. Through the analysis of FEMM 4.2, CT of the PMMs studied were presented and compared, as shown in Figure 5.

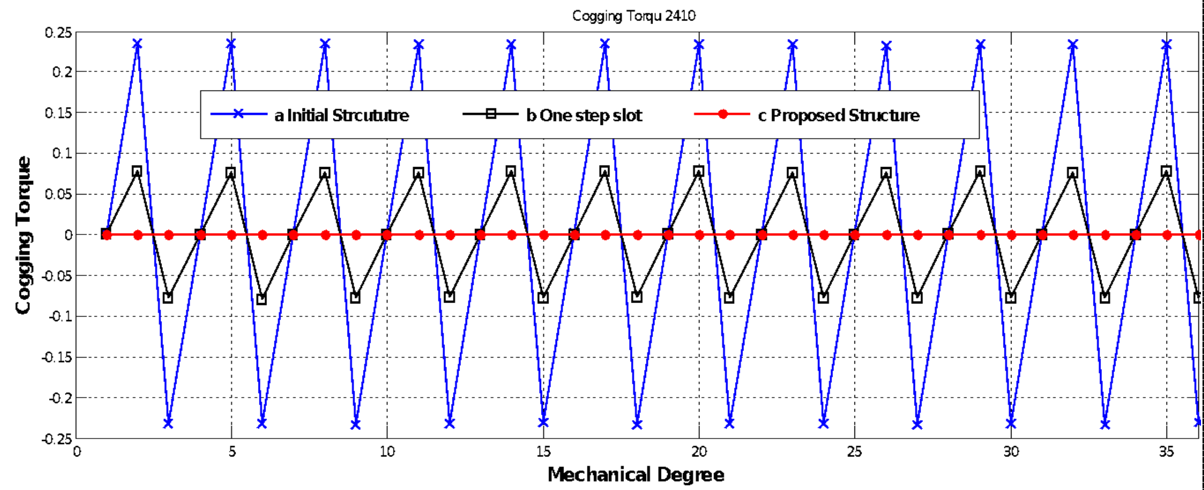

Figure 5. Comparison of Cogging Torque for different magnet structure (24 slot / 10 pole)

In Figure 5, one can observe that the CT for initial structure of PMM 24 slot / 10 pole is the highest. The CT peak value has been analysed and it was found around 0.2250818 Tesla. After employing the appropriate length and height of slotting in magnet edge, the magnet structure of proposed structure has the most edge points among the three different magnet structure. As a result, the magnet flux interaction between magnet surface and stator slot opening become frequent. This leads the achieving the CT frequency and reduce the peak of CT of the machine. The CT reduction was validated with finite element analysis and it has been found as much as to 0.0016483 Tesla. Based on the initial structure, the CT reduction of the machine was calculated as 100 % - (T_{cmax} of proposed structure/T_{cmax} of initial structure)100 % =100 % - (0.0006774 / 0.2352206) % =100 % - 0.29 % = 99.7 %. It could be concluded that the CT reduction for the proposed structure was around 99. 7 %.

5. Conclusion

In the present work, the effects of height and length of slotting in the magnet edges on the CT reduction in fractional slot number of 24 slot /10 pole has been presented. The CT reduction of the three different magnets of slotting have been compared. It was found that the two steps of slotting with 2.5 mm of length and 0.7 mm of height, while in the second step, the length and height of slotting was 2.3 mm and 0.588635 mm, respectively. The CT reduction for the proposed structure was computed using FEMM and it was found as much as 99.7 % compared with the initial structure. It can be concluded that the length and height of slotting in magnet edge of fractional slot number of 24 slot/ 10 pole effects significantly on the CT reduction of the proposed PMM.

References

[1] Chen N, Ho SL and Fu WN 2010 *IEEE Trans. on Magnetics* Vol.**46,** No.6, pp. 2478-2481
[2] Scuiller F 2014 *IEEE Trans. on Magnetics* Vol. **50,** No.4, pp.1-9
[3] Chabchoub M, Salah B. I, Krebs G 2012 *First International Conference on Renewable Energies and Vehicular Technology*, Hammamet pp. 206-211
[4] Wu L, Jin W, Ni J, Ying J 2007 *Internal conference on Electrical Machine and Systems (ICEMS)* pp.769-773
[5] Ling,J.M and Nur,T 2016 *Advanced in Mechanical Engineering*, Vol.**8**, No.8, pp.1-9
[6] Rahideh A, Korakianitis, Ruiz P, Keeble T, Rothman MT 2010 Vol.**322**, pp.3680-3687
[7] Srisiriwanna T, Mongkol K 2012 *ECTI Trans. on Electrical Engineering, Electronics and Communications* Vol. **2012**; 10: 146-152.
[8] Meeker D.2018 *Finite Element Method Magnetics* Version 4.2 User’s Manual
[9] Nur,T Mulyadi,M 2018 *IEEE ICASI conference*.