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A New Technique to Reduce the Cogging Torque of Integral Slot Number in Permanent Magnet Synchronous Machine

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***Abstract*— This paper proposed a new cogging torque reduction technique of integral slot number in the permanent magnet synchronous machine (PMSM). The purpose of the proposed new technique simulated on the PMSM with 48 slot/6 pole structure. In the study, the magnet edge of the PMSM was slotted to minimize the cogging torque while the stator core has remained natural. Slotting in magnet edge is one of the techniques to reduce the cogging torque in PMSMs, which has been existed in the previous research. In the proposed structure, we employed the two steps of slotting in magnets edge as one of the cogging torque reduction techniques. In this paper, authors have investigated three permanent magnet synchronous machine with different magnet structure has been studied and compared. The proposed permanent magnet synchronous machine with employed two steps of slotting has shown to promise the best of cogging torque reduction. The performance of the permanent magnet synchronous machine studied has been computed and analyzed by finite element analysis. It is found that the smaller cross-section area of magnet pole results in the decrement of cogging torque and air gap normal flux density in the PMSM. The new slotting in the magnet edge reduces the magnet pole cross-section and the cogging torque. The cogging torque of the proposed structure could be reduced around 98.8 % compared with the initial structure. The two steps of slotting could reduce the cogging torque of integral slot number in permanent magnet synchronous machine significantly.**

***Keywords*— cogging torque; finite element method; permanent magnet synchronous machine; slotting.**

I. INTRODUCTION

The Permanent magnet synchronous machines (PMSM) have widely used in many applications since their advantages over another type of electrical machine. According to scholars [1]–[7], the advantages of employing any PMSM structure such as compact structure, simple construction, low size mechanical construction, easy maintenance, good reliability, high torque density, and excellent efficiency. However, for special applications such as in robotics and renewable energy system, the issue of CT in PMMs should be considered and analyzed in the stage of design. Naturally, the CT in PMSM structure is affected by the interaction of magnetic in rotor core with the slot opening width in stator teeth of PMSM. The CT in PMSM is the circumferential component of an attractive force that attempts to maintain the alignments between the slot opening in the stator slot in stator and the magnets in rotor core of the PMSM [1].

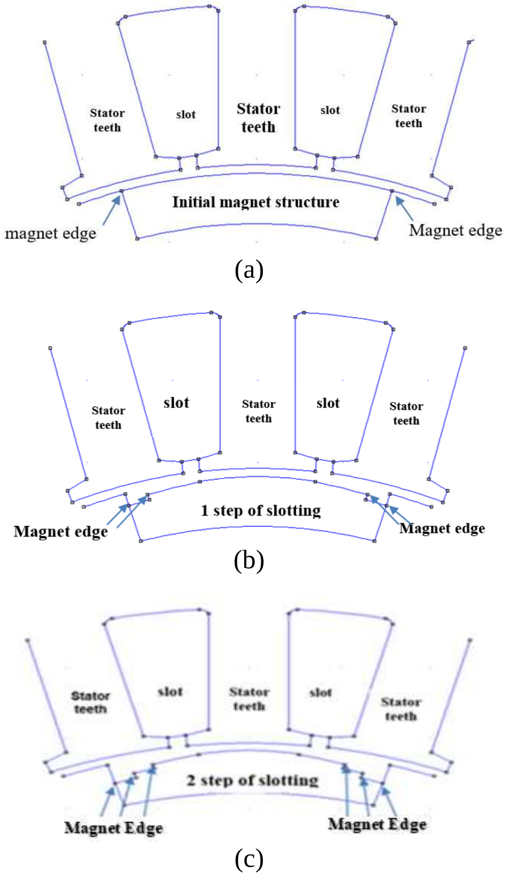
It has been understood, the presence of CT in PMSM must create noise and generate vibration, which leads to limit the applications to a high-precision control system. Based on the discussion, it can be concluded that the CT in PMSM is a crucial issue that must be considered and solved.

Many CT reduction techniques have developed and proposed for the last four years. The reports related to the CT reduction technique and its achievement also well documented in worldwide. Some CT reduction techniques has been applied in PMSM design such as such as to shift or segmented of the magnet pole [1], to skew or step skewing magnet [2]–[8], to optimize the magnet pole arc [7]–[14] magnet slotted [2]–[6][8][15] to shape the magnet [13][16]–[22], to employ dummy slot at stator core and dummy teeth at stator [11][15][23]–[26], combining the skewing with radial pole pairing method and skewing with axial pole pairing method reduces [27], CT reduction in Brushless Motors by a Nonlinear Control Technique [28]. However, the most effective technique to reduce the CT in PMSM with integral slot number of 48 slot / 6 pole is by employing two steps of slotting in the magnet edge of the machine. By slotting the magnet edge of any PMSM, it can provide a new flux path in the magnet surface to minimize magnet flux distribution in the air gap of the PMSM.

In addition, leads to increasing the interaction between the magnet edge and the stator core and achieve the CT frequency. As the two steps of slotting have been employed in magnet edge, it effects to minimize the magnet flux to reach the stator slot in stator core becomes smaller compared with the conventional magnet structure. Then, the presence of the two steps of slotting in the magnet edge can reducing the air gap reluctance effectively, leading the CT peak value of the PMSM becomes decrease. In the paper, a-two steps slotting technique of have been employed to magnet edge of any integral slot number with PMSM of 48 slot/6 pole. For the study purpose, a slot opening width of the PMSM studied has been chosen to be 2 mm. In the beginning, the distance between the whole magnet rotor surface the distance between the whole magnet rotor surface and the stator core is 2.31133 mm. The computing the PMSM performance, the finite element method (FEMM) has been used in the paper. It has been found, the CT of PMSM with two steps of slotting (TSS) in magnet edge can be reduced effectively.

II. MATERIAL AND METHOD

In this study, we have investigated three permanent magnet synchronous machine with different magnet structure has been studied and compared. The Initial Magnet Structure and Propose of a New Model depicted in Figure 1. The performance of the permanent magnet synchronous machine studied has been computed and analyzed by finite element method [FEMM].



(a)

(b)

(c)

Fig. 1 Magnet Structure of the PMSM; (a) Initial Structure, (b) One Step Slotting (OSS), (c) Two Steps Slotting (TSS)

Figure 1 shows the magnet structure of the PMMs, (a) is the Initial Structure, (b) is the One Step Slotting (OSS), and (c) is the Two Steps Slotting (TSS). In Figure 1(a), it can be observed the initial magnet structure is a conventional magnet one, refers no slotting to be employed in the magnet structure. In Figure 1(b) [13], one step of slotting has been applied in magnet edge (model 1), while for the purposed structure, a two-step of slotting has been applied in the magnet edges of the PMSM (model 2) as shown in Figure 1(c). All the PMSM structures have studied and compared in this paper. A comparison of the three structure (model) of 48 slot/6 pole of the PMSM was compared and presented in this paper. In the beginning of the task, to achieve the CT reduction of the PMSM, the structure of the PMSM have been optimized using the response surface method (RSM).

The RSM is one of the optimization methods usually employed to achieve electric performance and other systems related to engineering, science, medicine and many more. Based on the RSM procedure, 5 (five) parameters of the magnet of the PMSM proposed to considered to be restructured, as presented in Table I, i.e.: A_1 is the First length of magnet edge Slotting, A_2 is the first height of magnet edge slotting, A_3 is the second length of magnet edge slotting, A_4 is the second height of magnet edge slotting, and A_5 is the pole arc of magnet edge slotting.

TABLE I
RESPONSE SURFACE METHOD

No	A_1(mm)	A_2(mm)	A_3(mm)	A_4(mm)	A_5(mm)
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	3	2
10	3	2	4	4	1
11	3	3	1	3	4
12	3	4	2	2	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

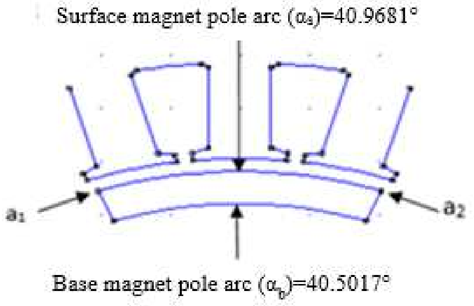
In Table I, the proposed structure of the PMM optimized using the RSM procedure. To simplify, only one row in Table I will be discussed, say in raw of the Table I, but the principle is the same for every raw. In raw, the parameters of A_1, A_2, A_3, A_4, and A_5 are 3 mm, 4 mm, 2 mm, 2.0 mm, and 3.0 mm, respectively. Based on these parameter values, the PMSM proposed was constructed. The performance of the proposed structure was analyzed using the finite element method. Since the magnet of the proposed structure has been slotted, the cross-section becomes decrease. The cross-section of proposed (model 2) PMSM was 0.000437468 mm, the one-step of slotting (model 1) was 0.000444829 mm, and the initial structure (initial model) was 0.000529746 mm, respectively.

Moreover, since the poles of the magnets occupying the same place in the rotor core, consequently, the air gap of two steps of slotting in magnet edge increase around be 0.000703784 meter^2. The increasing of air-gap cross-section leads to reduce the air gap reluctance, which intern effects of reducing the peak value of CT and increasing the frequency of CT. The physical parameters of the 48 slot/6 pole of the PMSM is analyzed and presented, as shown in as shown in Table II.

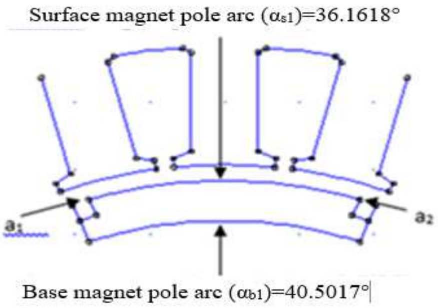
TABLE II
TESTED PARAMETERS FOR 48 SLOT/6 POLE STRUCTURE OF PMSM

No	Names of parameter	Initial Structure	One step slotting	Two step slotting
1	Stator diameter, d_{stator} (mm)	244	244	244
2	Air gap length, l_g (mm)	2.28	2.228	2.28
3	Rotor teeth angle, α_{rth} (deg.)	9.5	9.5	9.5
4	Slot opening width, w_{so} (mm)	2	2	2
5	Shaft diameter, d_{shat} (mm)	32.5969	32.5969	32.5969
6	Magnet length, l_m (mm)	59.348	59.348	59.348
7	Magnet height, h_{m} (mm)	8.34814	8.34814	8.34814
8	Airgap Cross Section, A_a (mm^2)	46.974	184.959	109.027

The detailed structure for all experimental machines depicted in Fig. 2. In Figure 2, the a_1 and a_2 denote the leading and trailing edge of magnet NdFeB in the simulation of the PMMs, and the base magnet pole arc (αb,) keep the same. The surface magnet pole arc (α_{s2}) decreases because of the presence of slotting in the magnet edge of structure 1 and structure 2 as shown in Fig. 4b, and Fig. 4c, respectively. It should be noted that the optimization of the magnet pole arc for the proposed model is 26.5 degrees. The lengths of the magnet pole arc for all PMMs are 0.0680600 meters, 0.0588716 meters and 0.0514854 meters for the initial structure, structure 1(OSS) and structure 2(TSS), respectively.



(a)



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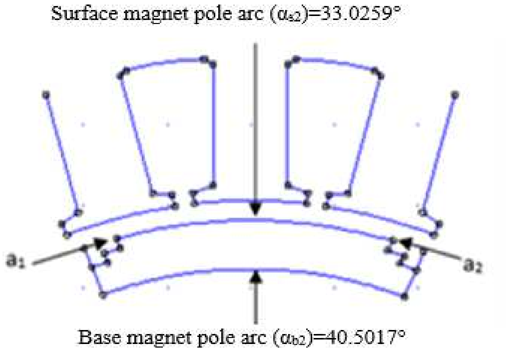


(c)

Fig. 2 Details of structure for the experimental PMM, (a). Initial Structure, (b) One step of slotting in magnet edge, and (c) Two Steps of slotting in magnet edge

The effect of slotting in magnet edge could optimize the magnet pitch and pole arc length. This leads and conducts a shorter route in the leading and trailing edge of the magnet edge. Another benefit by employing the slotting in the magnet edge increases the air gap cross-section area. The presence of slotting in the magnet edge also changes the rotor surface. It is noted that all machine structures investigated in the paper do not have any dummy slots in the stator teeth

The CT of PMSM has calculated with the assumption that there is no current in the stator winding of a permanent magnet machine. Therefore, the effect of the conductor in the stator slot in stator core and armature saturation is also negligible. In this paper, the magnetic saturation is negligible, and the magnetic flux distribution is assumed to be radial magnetization. The formula related to calculating the CT of PMSM has been used [3][4]. In the following section of this paper, the authors have used this formula (1) [3].

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

where $\boldsymbol{\emptyset_g^2}$ represents the magnetic flux in the air-gap, $\boldsymbol{R_g}$ is the air-gap reluctance through which the past, and $\boldsymbol{\theta}$ is the mechanical rotor position of the machine. It can be observed in Equation (1), that CT might be minimized by declining the air gap magnetic flux. However, the solution to reduce the CT by declining the magnetic flux air gap might be not a good choice if in PMSM design address in this parameter since the magnetic flux is one of the important parameters to increase the PMM output.

Another parameter that might be considered to reduce the CT is the air gap reluctance of the PMSM. In addition, the CT is independent of the magnet flux direction in the air gap since the amount of the magnet flux is squared, as shown in. As can be observed in Equation (1), if the air gap reluctance *R* does not vary with the rotor rotation positions, the cogging torque will zero. It is impossible to realize in all conditions, since the air gap reluctance of all-electric machines always varies as the magnet rotors rotating, except for slot less of the electrical machine only. In addition, the CT of any PMSM is influenced by material used for constructing the machine. The most effective technique to reduce CT is to optimize the magnet pole structure, as proposed in this paper. In this study the Two Steps slotting (TSS) in magnet edge is investigated and proposed in this paper. The advantages of this technique laid in the fact that by employing the TSS technique in magnet edge, another CT reduction technique might gather. The other CT reduction technique could be included in this method by implementing this method, such as bread loaf [17], optimize magnet pole arc [19], reducing magnet volume [17], increasing air gap length between the stator core and magnet pole [27].

According to the author's experience, this combination technique is very powerful to limit the value of air gap reluctance when the rotor magnet is rotating. The effectiveness of the proposed technique investigated in this paper refers to the CT reduction in PMSM was presented. The air-gap reluctance in Equation (1) varies periodically, and it causes the CT of the PMSM to be periodic. The total magnetic flux in air-gap is influenced by the normal flux density and cross-section area of air-gap, as shown in Equation (2):

$$\emptyset_g = \int B.dA \qquad (2)$$

The CT also might be formulated as a Fourier series shown in (3):

$$T_c = \sum_{k=1}^{\infty} T_{mk} \, sin\,(mk\theta) \qquad (3)$$

In Eq. (3) m is the least common multiple of the number of stator slot (N_s) and the number of the pole (Np), k is an integer and T_{mk} is a Fourier coefficient. As the structure of the PMSM with 48 slot/6 pole or in an integral slot number, this leads that each pole of the machine sees a whole number of multiple stator teeth so that the cogging effects of each magnet are in phase and added [1]. The CT values contribution for each magnet can be described by Equation (4):

$$T_c = N_p \sum_{k=1}^{\infty} T_{pN_sk} \, sin\,(N_s k\theta) \qquad (4)$$

Where T_{pNsk} is a coefficient CT per every magnet. The air-gap reluctance in Equation (1) also could be analyzed by using equation (5):

$$Rg = \frac{g}{\mu_0 A_g} \qquad (5)$$

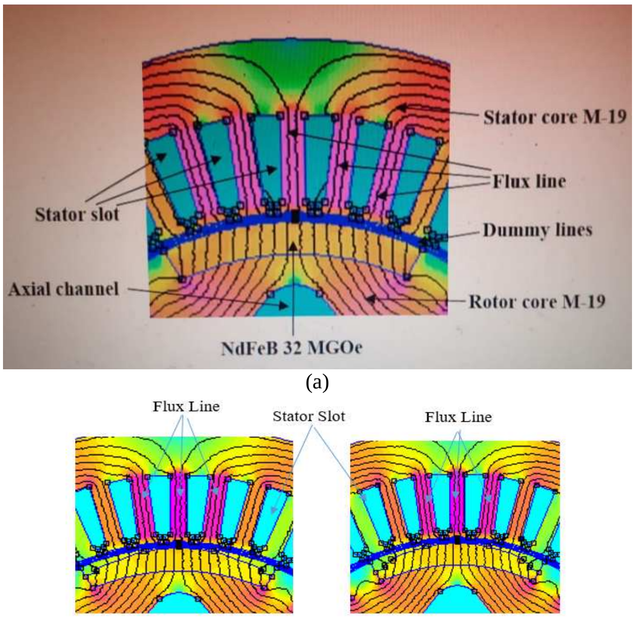
where R_g, g, A_g are the air gap reluctance, air gap length, air-gap cross-section area, and $\boldsymbol{\mu_0}$ magnetic permeability in air gap respectively. In this paper, the magnets of PMSMs studied have been assumed to be unity and the effect of machine has been neglected. The flux magnetic density in the air gap of PMSMs are coupled with remnant flux density B_r, and calculated as in Equation (6) [27], [17].

$$B_g = \frac{B_r l_m}{(r_r + l_g)\ln\frac{r_r + l_g}{r_r - l_m})} \qquad (6)$$

In Eq. (6) B_r, l_m, r_r, l_g is the magnet remanence, magnet length of magnet, radius of rotor and length of air gap of the machines respectively. All the relevant parameters used in the study are shown in Table 1. For permanent magnet remnant of NdFeB, Br is about 1.2 Tesla. Based on equation (1), the CT peak value for all experimental machines can be calculated. The impact of the magnet on the two steps of slotting in magnet edge to the CT could be analyzed using Equations (1), (2), and (3). The comparison of CT reduction for all PMSM structures with different magnet structure presented in the paper.

III. Results and Discussion

By Implementing the finite element of FEMM 4.2 combined with LUA 4.0 scripting the PMSM characteristics has been investigated [1][3][17][18][19][27]. The advantage of combination of FEMM and LUA increased a quick execution for the implementation of a complete simulation of a specific PMSM. Another benefit of LUA script application is the capability of parallel computation might be achieved significantly. At the beginning of each simulation, the simulated PMM structure is generated in Auto-CAD then exported to the FEMM file. The proposed Structure (OSS and TSS) is 2D planar, and the simulation results are available for stators and rotor of the PMSM with slotting at the edge of magnet poles. The result as the comparisons of air gap magnetic flux distribution and cogging torque for the simulation machines are investigated and shown as follows.



(a)

(b)

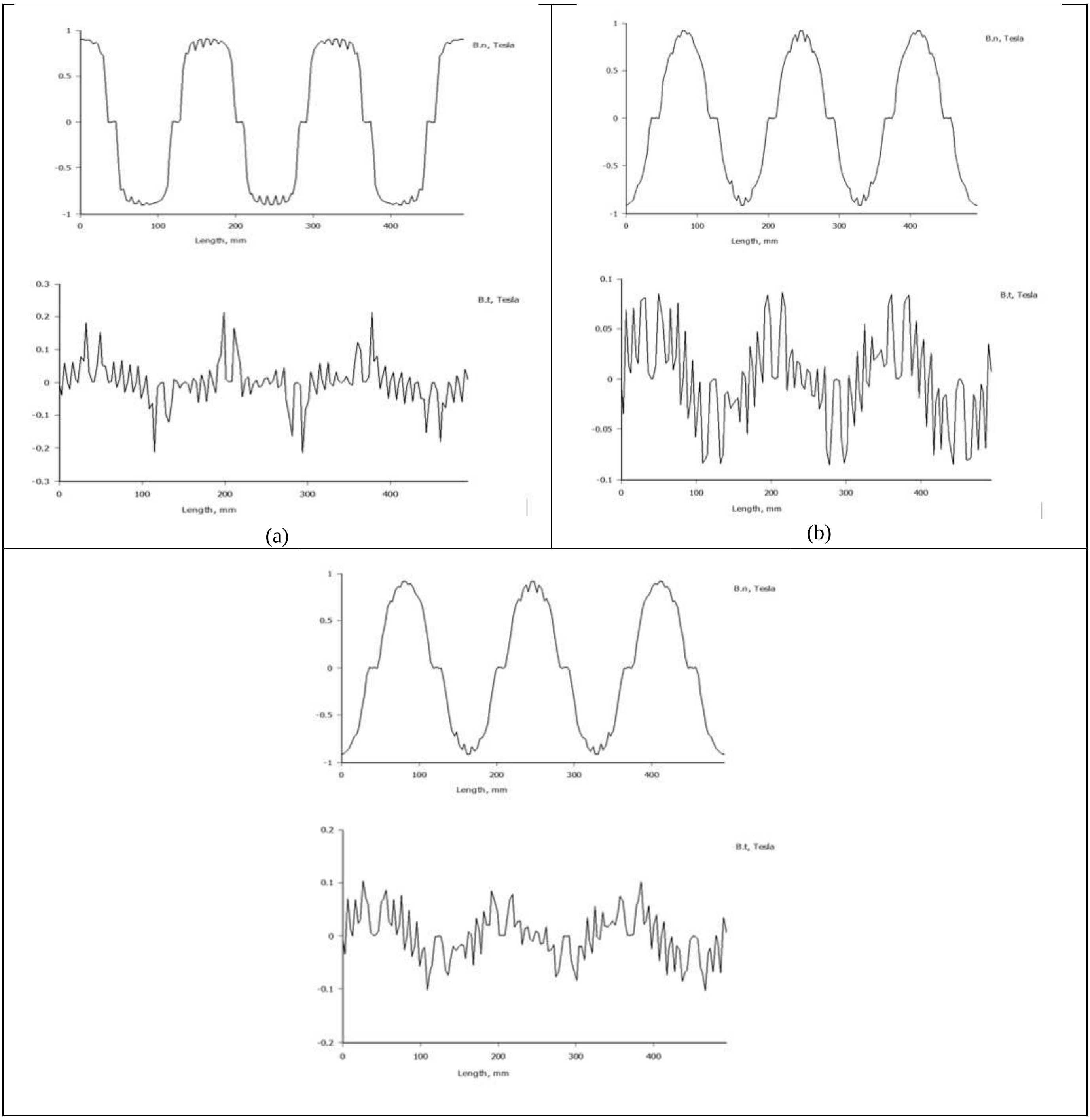
Fig. 3 The Magnetic Flux Density Distribution for PMSMs, (a) Magnetic Flux Density of Initial Structure, (b) Magnetic Flux Density Distribution proposed structure.

A. Distribution of Magnetic Flux

Figure. 3 depicts the flux distribution path and the flux flow from the magnet rotor into the stator surface in the PMSM studied. Because of the TSS in magnet, the flux lines from the magnet rotor follow the general minimum of air gap reluctance low, which interpreted as a tendency of the lines of flux passing through the air along the shortest possible route. The magnet edge slotting also demands the minimum magneto-motive force for these actions. It affects the presence of any leakage flux in the magnet rotor and decreases the air gap normal flux density.

B. Normal and Tangential Flux.

The comparison of the Normal and Tangential Flux density for proposed structure depicted in Figure 4. (a), (b), and (c). Fig.4 shows the simulation results for the magnetic density flux performance in the air gap on all the PMSM studied. As can be observed the flux density curves distorted because of the slot opening in the stator core. This may be accepted and naturally occurred in all PMSM structures.



(a)

(b)

Fig. 4 The Comparison of Tangential and Radial of PMSMs studied; (a) Tangential and Radial flux density of PMSMs initial structure, (b) Tangential and Radial flux density of PMSMs OSS structure, (c) Tangential and Radial flux density of PMSMs TSS structure

The simulation results show that the shape of the magnetic flux distribution in the air gap of the proposed TSS is not distorted, while the peak of normal flux density remains constant. The shape and peak of magnetic flux density in the air gap of an electrical machine are the significant parameters predicting the output power. The proposed TSS can achieve better power performance and characteristics than the other PMSM structures studied. The comparisons of flux density for the three structures of PMSMs, as shown in Fig. 6.

Also, from Figure 6 it can be observed the flux density curves distorted because of the slot opening in the stator core. This may be accepted and naturally occurred in all PMSM structures. The simulation results show that the shape of the magnetic flux distribution in the air gap of the proposed TSS is not distorted, while the peak of normal flux density remains constant. The shape and peak of magnetic flux density in the air gap of an electrical machine are the significant parameters predicting the output power. The proposed TSS can achieve better power performance and characteristics than the other PMSM structures studied. The comparisons of flux density for the three structures/models of PMSMs, as shown in Fig. 6.

The simulation result shows for the air gap normal flux density in every magnet shown as follows: Two Steps Slotting (TSS) is 0.539500 Tesla, One Steps Slotting (OSS) is 0.538946 Tesla, Original Model is 0.674042 Tesla.

The distribution of air gap normal flux density at different mechanical rotor positions in the experimental machines can be predicted by Equation (6) as shown in Fig. 5. It is noted that the air gap magnetic density flux wave is a little bit distorted. It is caused by the slot opening in the core of the stator of all machine. It might be caused by the effect of slot opening in the core of the stator of all permanent magnet machines.

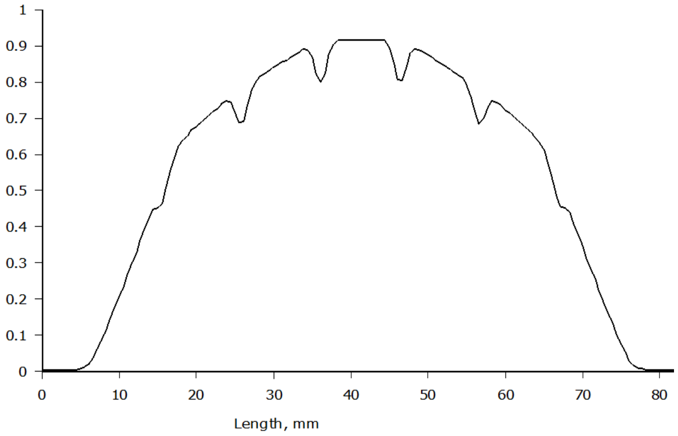
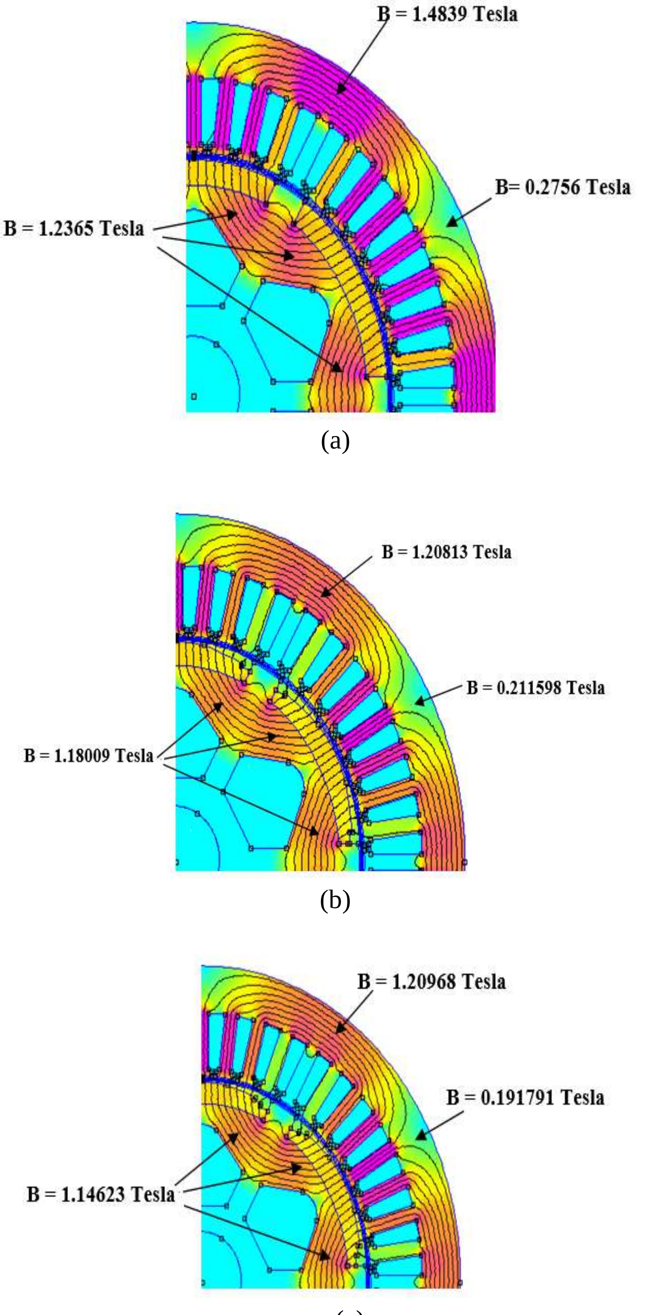


Fig. 5 Normal Flux Density of Proposed Model

From Fig.6, it can be investigated that the slot at the edge of the magnet rotor in Model 2 and Model 1 does not affect the changing of the variation rate of the magnetic flux density wave for all experimental machines. This refers that proposed machine Model 2 is promising for the presence of two steps of slotting in the magnets that do not distort to the balance of the magnetic force in the air gap of the machine of Model 2. A PMSM machine under eccentricity, which is the magnetic force in the air gap is unbalancing, and the variation rate of air-gap magnetic flux density is likely higher compared with a health PMSM machine [18].

The magnetic flux density in the core of the stator and rotor investigated using finite element simulation. It has been found that the maximum values in the stator core of PMSM are around 1.4839 Tesla, 1.20813 Tesla, and 1.20968 for the Initial Model, one step slotting, and two-step slotting, respectively. To clarify the performance of the PMSMs studied, three of maximum magnetic flux density in the stator teeth shown in Figure. 6.



(a)

(b)

(c)

Fig. 6 The Magnetic Flux Density of inside the three Structures/Models of machines, (a) Magnetic Flux density in the core of stator and rotor of Initial Model, (b) Magnetic Flux density of One Step Slotting, (c) Magnetic Flux density of Two Steps Slotting.

The Simulation using finite element method showed the slotting in the magnet edge of 48 slot / 6 pole did not affect the magnetic density flux seriously in the core of the rotor and stator. However, structure/model 2 has a little bit higher density flux in the stator core compared with structure/model 1. For the magnetic flux density in the rotor core, the proposed structure 2 has the highest around 1.2 Tesla among three machines structures, and the Initial structure is 1.4839 Tesla, and for structure 1 and structure 2 is 1.20813 Tesla, 1.20968 Tesla, respectively.

Considering the limit of density flux magnet in the core of the rotor is around 1.5-1.6 Tesla, it can be noted that the presence of slot at the edge of the magnets may affect to decreasing of magnetic flux density in the rotor core. If the density magnet flux in the core of the rotor more than 1.6 Tesla, the performance of the machine is bad, since the core of the machine will high saturation. In this condition the cross-section of the PMSM studied should be resized. The density flux in the stator, as shown in Figure 5, it can be observed that the slot at the edge of the magnet rotor does not affect or only a little bit the increasing of magnetic flux density in stator core and rotor core for the three PMSMs. As mentioned, the CT of any permanent magnet machine is influenced by material. So, for the purposed this research, authors have considered to use M-19 for stator and rotor core.

This kind of material can be loaded by magnetic flux density around 1.5-.1.6 Tesla. Using the finite element analysis (FEMM 4,2), the CT have been investigated within 180^0 (mechanical degree) with 1^0 every step of rotor rotation. For purpose of clear demonstration, only 60^0 depicted in Figure 8. It found that the CT for all PMSMs have two pulsations for every 60^0 mechanical rotation degrees. The CT for Initial Structure is around 0.5912996 N-m (peak value), it has considered to be the highest of CT peak value among the PMSMs investigated in the paper. It can be understood and accepted since the Initial Structure has the largest air-gap reluctance among the PMSMs studied. The CT peak for OSS is 0.069824 N-m, which is lower a little bit compared with the Initial Structure. The decrement sourced from the effect of TSS in magnet and the air-gap reluctance. The CT peak for Structure of PMSM 2 is 0.0072210 N-m.

C. *Cogging Torque Calculation*

The cogging torque comparison for the CT of PMSM depicted in Figure 7. The proposed Structure of PMSMs with six poles and 48 slots reduces the CT effectively. The significant improvement of performance for the proposed PMSM as shown in Fig. 7 can be identified by the smallest cogging torque in the beginning 12 tested points in the mechanical rotor degrees (0^0~22^0), and the last 12 tested points in the mechanical rotor degrees of 38^0~60^0). The maximum cogging torque of the proposed structure TSS occurs at the rotor rotates to about 26^0 from the initial rotor mechanical position, while the value for the Original Model is about 15^0 and Model 1 for 22^0. It means that at the beginning of rotation from motionless or at low speed, the Original Model, and the Model 1 need more mechanical energy to attain the same speed rotation compared with the proposed Model 2. The fluctuation distribution of cogging torque for proposed Model 2 can be achieved by its smoother characteristics. From Figure 6, it is obtained that the maximum value of CT of Initial Structure 0.5912996 N-m. One step Slotting 0.069824 N-m, and Two steps slotting 0.0072210 N-m. So, the proposed model provides the CT reduction as much as 98.8% compared with the Original Model (Initial Structure)

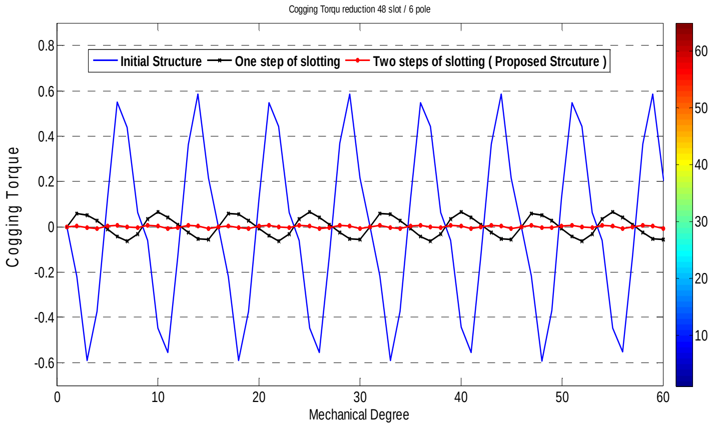


Fig. 7 Comparisons of the CT at the different mechanical angular position

The proposed two-steps of slotting (TSS) in the magnet edge reduce the effect of reducing the cross-sectional area of the magnet but did not change the rotor diameter. The presence of the two-step slotting in the magnet can be inferred to modify and reduce the magnetic flux strength without any change in the magnetic material of the inset PMSM. The proposed two-step of slotting in the magnet edge decreases the reluctance of the air gap, which refers to reduce the CT of the PMSM. Meanwhile, the magnetic flux density of the proposed inset PMSM in the stator and rotor cores also decreases when compared with the initial magnet structure (original model). The proposed TSS technique in magnet edge refers to the variations in the magnet arc length varying, which affects the magnet pitch and surface area of the permanent magnet. In other words, the cogging torque can be reduced

IV. CONCLUSION

The influence of the slot opening width on the pole magnet area was investigated. From the simulation results, it concluded that the smaller cross-section area of magnet pole results in the decrement of cogging torque and air gap normal flux density in the PMSM. The new slotting in the magnet edge reduces the magnet pole cross-section and the cogging torque. The novelty of the proposed Model 2 (TSS) achieves to adjust the magnet pole arc and distance without changing the rotor diameter and stator construction. From the point of mechanical construction, the proposed machine is strong enough because there are rotor teeth between the magnets to avoid centrifugal force. On the other hand, the air gap between the stator and rotor core can be increased to reduce the air gap reluctance in the machine. Moreover, from the point of the magnetic circuit, the crucial flux circulation in the surface of rotor teeth reduces the cogging torque in the air gap effectively.

The proposed PMSM Model 2 (TSS) promises to achieve CT reduction and applied to the renewable energy system, with limited mechanical energy source, such as in wind power or geothermal system.

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