Improvement the cogging torque reduction methods by combining the magnet slotted and gradually inclined surface end in permanent magnet generator

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ABSTRACT

Cogging torque (CT) in permanent magnet synchronous (PMS) machine, generator or electric motor should be reduced to increase the preperformance in application. Many CT reduction techniques has been proposed in the last few years. This research dealt with the study of techniques for reduction of the CT in PMSG. The PMS generator investigated in this paper is the integral slot number type with 18 slots and 6 poles. The CT has been analyzed to be reduced by employ the slot opening width variation, magnet edges slotting, and gradually inclined surface end. This paper also has analyzed the effect of combination of slot opening width and slotting permanent magnets. The finite element method magnetics (FEMM) is used in this work to perform electromagnetic simulations of the PMSG. Using the FEMM, the CT reduction of permanent magnet synchronous generators studied is analyzed and the CT peak value is compared. It is found that by combining of reduced of slot opening and slotting the permanent magnets can reduce the CT of PMS generator significantly abound 98.55% compared with the base line model.

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1. INTRODUCTION

Permanent magnet synchronous generators (PMSGs) are widely used in engineering and our daily life. Currently, these are commonly utilized in low power wind turbines due to their benefits, including high efficiency, reliability, and simplicity construction. The PMSGs also have a higher power density compared with excited type of machine. In renewable energy system, the PMSGs usually are directly linked to the wind turbine system. It is simpler and the wind turbine operates without gear box. However, one of main disadvantages have been found in application of PMSG is the presence of cogging torque (CT).

In PMSG, CT is defined as the variation in rotor torque because of contact with the tangential magnet force produced by the magnet edge at the rotor core and the stator slot opening. In this instance, additional vibrations, acoustic noise, and other things arose, making the exploitation more challenging due to CT [1]–[5]. In addition, the presence of CT in air gap of machine can make a breaking action which locks the magnet rotor at the beginning of rotation. This makes it more difficult for the primary mover to rotate the magnet rotor.

Based on the discussion, The minimization of CT in a PMG is crucial for attaining optimal performance. When using permanent magnet synchronous (PMS) for certain applications like robots and wind turbines, it is important to minimize the CT content to no more than 2% of the rated torque of the machine. To lower the coefficient of drag (CT) in a permanent magnet motor (PMM), one can decrease the interaction between the magnet edge flux at the rotor core and the slot opening at the stator core. Tangential magnet force created by the magnet edge influences the interaction between the magnet edge and slot opening. The tangential magnet force is determined by the gradient of the tangential magnet flux density at the magnet edge. At high tangential magnet flux density, the tangential magnet force is generated in the air gap of the machine, unless the slot opening width at the stator core is small.

In a PMG or PMM with narrow slot opening width, the quantity of tangential magnet force toward the slot opening become less. In other word, tangential magnet force (F_t) generated by magnet edge become low, so that it is not strong enough to tight the slot opening at stator core. For that reason, CT reduction in a PMG or PMM could reduce the tangential magnet force at magnet edge, reduced the slot opening width of stator core of machine or combining magnet edge slotting and reduce slot opening width. In the beginning of this paper, some CT reduction techniques in permanent magnet machine is highlight as follows [6]-[11]: (a) use the fractional slot number (*FSN*) type of PMG, (b) optimize the magnet size, (c) use magnet skew of stator core skew, (d) reduce the slot opening width at stator core. However, the most effective way to minimize the CT in integral slot number (*ISN*) type of PMG is by combining the magnet edge slotting and reduce the slot opening width at stator core. In this study, the influence of slot opening width at stator core, magnet edges slotting, and the combination of reduce slot opening width and magnet edge slotting are investigated. The purpose of work is to reduce the CT peak of PMG proposed at least 98% of the rated torque.

In the beginning, the CT of base line model of PMG is investigated. In the investigation, authors use NdFeB for magnet rotor without any slotting in the magnet structure. The slot opening of base line model is set to be 3 mm, 2.5 mm and 2 mm. The CT of three structure of PMG is compared. The CT peak comparison of the PMGs is presented in the paper. In the next stage, author investigated the PMGs with magnet edge slotting with one step of slot. In this stage, one step of slot applied to reduce the CT of PMGs. The presence of one step of slotting at magnet edge of machine, the magnet edges become thinner than in the center [12], [13]. The benefits of implementing magnet edge slotting include the immediate reduction of the tangential magnet thrust. Consequently, the interaction between the magnet edge placed at the rotor core and the slot opening decreases. The reduction of the slot opening can effectively distribute and generate magnet force within the slot aperture by preserving the tangential magnet flux density. Furthermore, the CT reduction technique suggested by the authors in this study offers the additional benefit of not only reducing the CT but also minimizing the commutation torque ripple. The present study examines the performance of PMGs by the application of finite element method magnetics (FEMM 4.2). The comparation structure of PMGs studied are shown in Figure 1 and Figure 2 (PMG proposed).

The purpose of this research is to propose a CT reduction technique of integral slot number (ISN) type of PMSG by combining the magnet edge slotting and gradually inclined surface end (GISE) at magnet edge and variation the slot opening. The structure of the PMSGs is shown in Figure 1. In beginning of study, the performance of PMSG of base line model are analyzed. The base line model of PMSG is the machine with 3 mm width of slot opening and conventional magnet structure. The magnetic flux orientation of PMGSs studied is radial flux, while parallel and Halbach flux orientation is not studied in the paper. The materials used for the PMSGs studied are M-19 for stator and rotor core. While for magnet rotor uses NdFeB. In Figure 1(a), one can observe that the magnet structure of base line model of PMSG is without any slotting at magnet, while Figure 1(b) explain the one step of slotting at magnet edge.

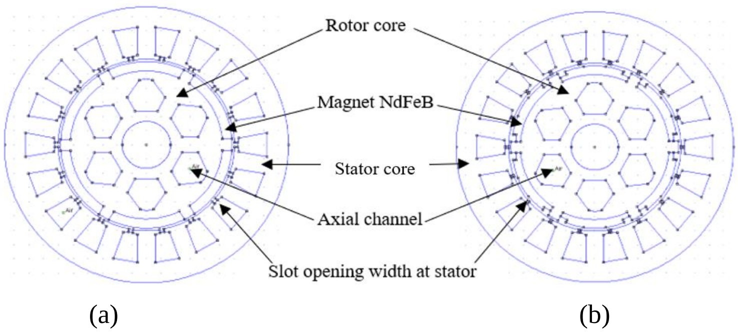


Figure 1. Structure of Inset-PMSG with 18 slots and 6 pole (a) without slotting of permanent magnet rotor (base line model) and (b) one step of slotting at magnet edge

2. MATERIAL AND METHODS

INSET-PMSG rotor structure: A typical inset-PMSG rotor is analogous to a widely used surfaced-mounted permanent magnet rotor, apart from the iron tooth or rotor teeth positioned between each pair of neighboring permanent magnets. The magnet rotor design of the Inset-PMSG can be seen in Figure 2. The inset permanent magnet rotor closely approximates the structure of the commercial surface permanent magnet generator. From a construction perspective, the inset-PMSG may exhibit greater strength in comparison to the surface PMSG. The primary source of flux in surface permanent magnet machines is produced by the permanent magnets (PMs) that are integrated into the rotor core of the machine. Furthermore, in Inset-PMSG, the rotor teeth induce a rotor anisotropy, a crucial factor for achieving accurate rotor position detection during machine operation. The rotor teeth are integral components of the rotor core, positioned between two magnets. An inherent benefit of Inset-PMSG is its extensive flux loop within the rotor core, which effectively minimizes the rotor iron saturation [14], [15]. Figure 2(a) shows the PMSG cross section and Figure 2(b) shows the PMSG stator teeth and magnet with two steps of slotting.

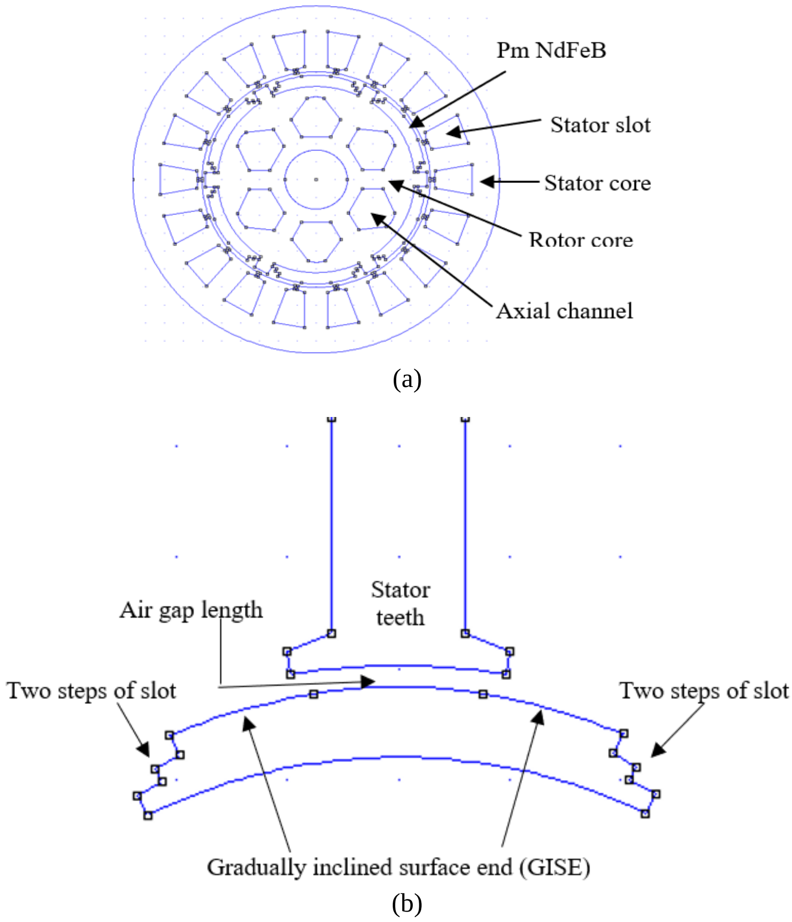


Figure 2. Magnet pole of PMSG with two steps of slotting at magnet edge (proposed structure) (a) PMSG proposed cross section and (b) stator teeth and magnet with two steps of slotting

3. RESULTS OF SIMULATION AND THE METHOD FOR CALCULATION

In the simulation, authors used the simulation procedure of FEMM based on the previous research [16]-[26]. To reduce the simulation by employing a LUA 4.0 script for simulation purposes the machine behavior based on the previous research [18], [19], [23], [24]. The distribution of the magnetic field within the generator is illustrated in Figure 3. Figures 3(a)-3(c) each explain the baseline model, one step of slotting, and two steps of slotting at the magnet edge, respectively.

In this investigation, we employ the virtual torque method to calculate the CT. In FEM analysis, it is essential to rotate the rotor of the generator in small increments, calculating the change in the total stored magnetic field energy at each position. It is possible to represent the torque produced in the machine as the partial variation in magnetic field co-energy with respect to the virtual displacement of the rotor. The CT equation is presented in the subsequent equation.

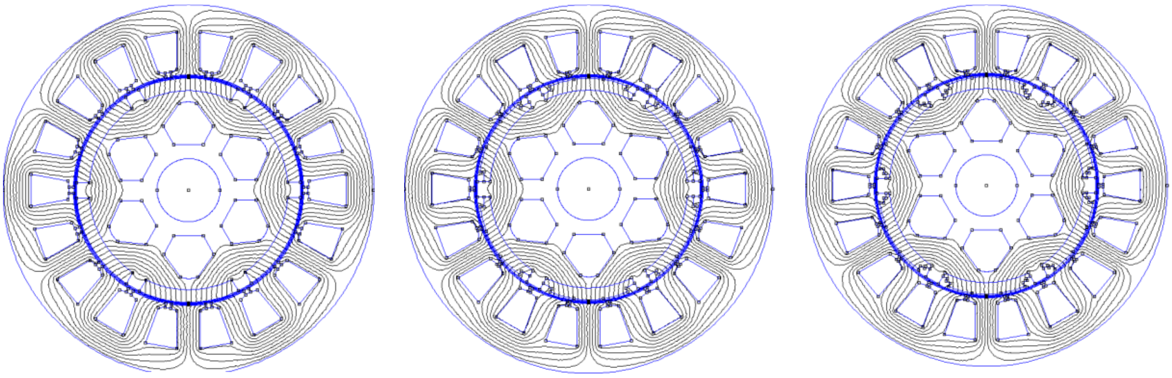
$$T_c = \frac{\partial W_C}{\partial \theta} \quad (1)$$

where θ: the rotor angular displacement and W_C: the stored co-energy of magnetic field. The (1), also can be formulated as shown in:

$$T_c = L_{stk} \int_0^{2\pi} F_t \, d\theta \quad (2)$$

Where :

T_c	= cogging torque	(Newton.meter)
L_{stk}	= stack length of PMSGs/machine	(meter)
F_t	= tangential magnetic force	(Newton)
θ	= mechanical degree of rotor rotation	(degree)



(a) (b) (c)

Figure 3. Magnetic field distribution of a 18 slots and 6 pole Inset-PMSG using FEMM 4.2: (a) base line model, (b) one step of slotting, and (c) two steps of slotting at magnet edge

4. VALIDATION COGGING TORQUE REDUCTION METHODS USING FEMM

In part, the impact of CT reduction technique of the PSMGs studied is analyzed using FEMM. In the analysis it is divided in three steps:

a) Base line model of magnet and slot opening variation.

In base line model, both magnet structure and stator core has not any slotting or shaping. The PMSGs structure simulated refers to the Figure 1(a)

b) One step of magnet slot at magnet edge.

In this step, the PMSGs studied simulated refers to Figure 1(b). The aim of magnet slot is to increase the distance enclosed within the magnet edge slot aperture at the stator core. In addition, as distance becomes increase, the interaction between magnet edge will affect to increase the CT frequency, but reduction the peak of CT. The implementation of the two-step slotting at the magnet edge could decrease the CT by 95.146% in comparison to the baseline model. The CT reduction of a PMSG with a single slotting step at the is still not sufficient for special purpose.

c) Two steps of magnet slot at magnet edge.

The purpose of two steps of slot at magnet is achieve a higher CT frequency and further reduction of CT peak for special purpose application. Using the two steps of slotting at magnet edge combining with slot opening width of stator as length as 1.5 mm affect to decline significantly the tangential magnet force at magnet edge and reduce CT peak of PMSG proposed to around 98.54% of the base line.

This study presents a comparison of CT reduction of the investigated PMSGs.

4.1. Slot opening width versus base line model

In this step, the slot openings width at stator core of the machine are varied from is 1.5 mm (smallest), 2.0 mm, 2.5 mm, and 3.0 mm (largest) are analyzed. While the magnet structure of all machines is the same structure. The comparative result of CT using different slot opening width is presented. The CT value versus rotor position is shown in Figure 4.

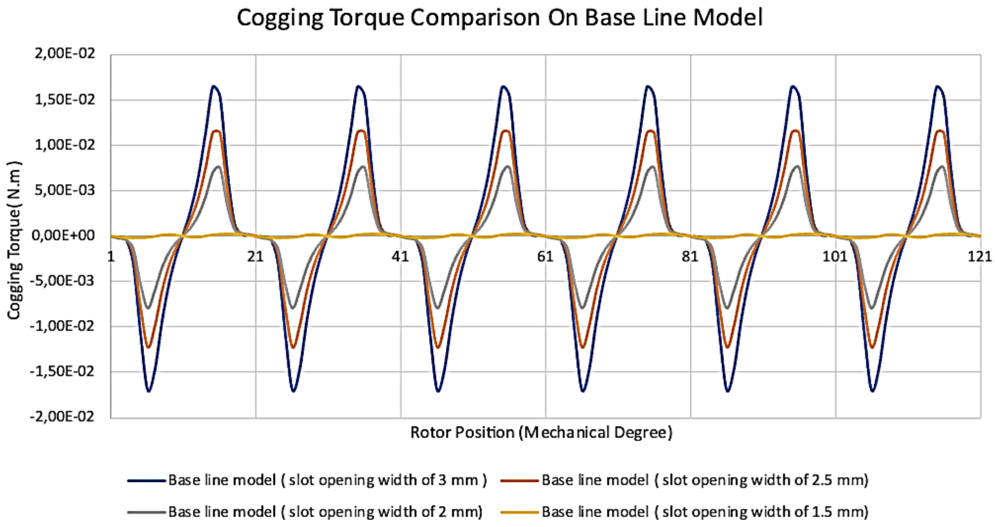


Figure 4. CT peak comparison of PMSG with base line model

4.2. Slot opening width variation versus one step of slot at magnet edge

The same method, in this step the PMSGs with one step of slotting with slot openings width at stator core of are varied from 1.5 mm (smallest), 2.0 mm, 2.5 mm, and 3.0 mm (largest) are analyzed. The comparative result of CT peak is presented. The CT values versus rotor position is shown in Figure 5.

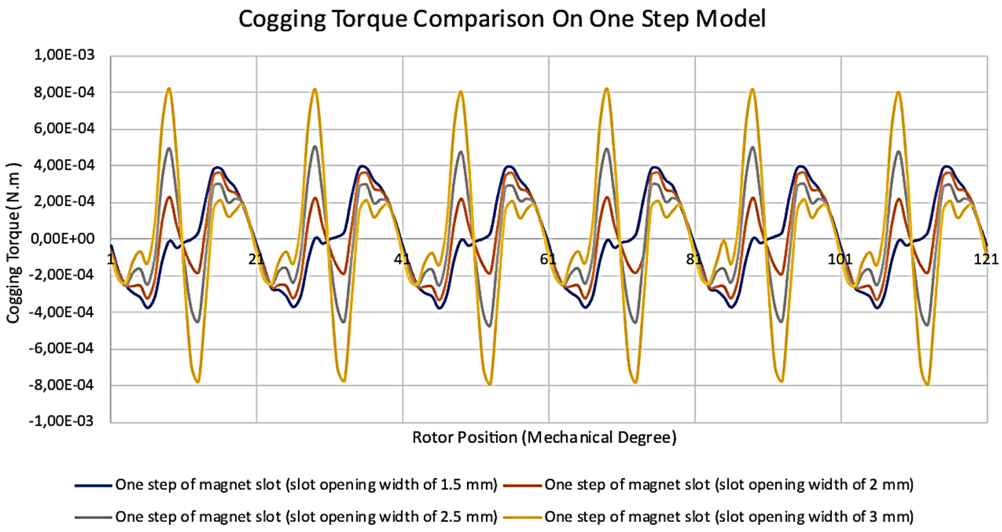


Figure 5. CT peak comparison of PMSG with one step of slotting at magnet

4.3. Slot opening width variation versus two steps of slotting at magnet edge

The same method, in this step the PMSGs with one step of slotting with slot openings width at stator core of are varied from 1.5 mm (smallest), 2.0 mm, 2.5 mm and 3.0 mm (largest) is analyzed. The comparative result of CT peak is presented. The CT values versus rotor position is shown in Figure 6.

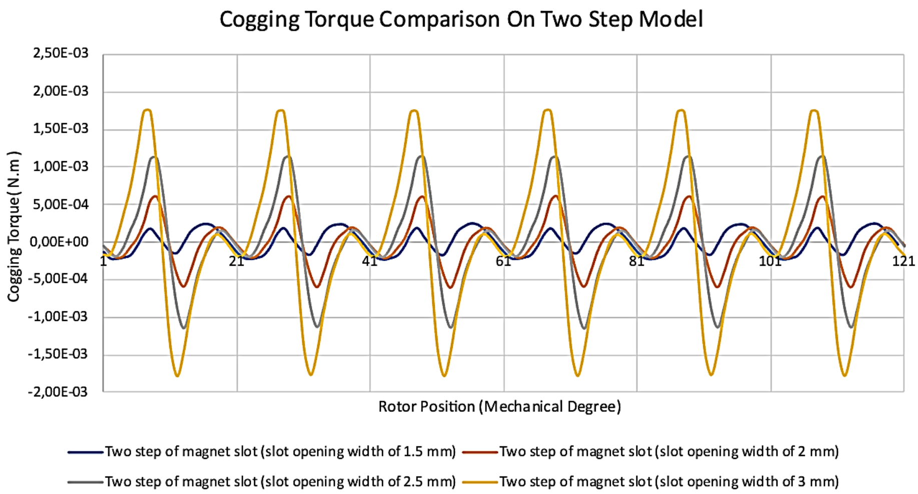


Figure 6. CT peak comparison of PMSGs with two steps of slot at magnet edge

5. CONCLUSION

Improving the CT reduction of PMSG with 18 slots and 6 poles of ISN using the combining of two steps of slotting at magnet, gradually inclined surface end at magnet edge, optimized slot opening width at stator core have presented in this paper. In this study, an analysis and comparison of three PMSGs featuring distinct magnet structure CT reductions has been conducted. Research indicates that decreasing the slot opening width to 1.5 mm can lead to a reduction in the CT peak of the machine to approximately 0.0002457 N.m, compared to the baseline model's CT peak of 0.0169000 N.m. The findings indicate that the CT reduction of PMSG is notably significant, achieving approximately 98.54% when compared to the baseline model. For future research, it is suggested to investigate the affect two steps of slotting on the unbalance magnetic pull (UMP).

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