THE EFFECT OF SLOT AND POLE PAIRING WITH MAGNET EDGE SHAPING ON THE COGGING TORQUE REDUCTION IN PMSG

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Abstract

This paper dealt with the effect in magnet shape of permanent magnet synchronous generator (PMSG) with slot and pole combination on the cogging torque reduction. For purpose of study, combinations of 60 slots / 20 poles and 18 slot poles / 20 poles have been selected and investigated. First, the cogging torque of integral slot number and fractional slot number is computed. In addition, the stator core and magnet structure of fractional slot number is modified, and the cogging torque is analyzed. The slot parts of PMSG to be modified are slot numbers; curvature of base slot and slot opening height in stator. For the magnet structure, the magnet edge shaping length, magnet edge height and magnet edge arc are modified based on the Taguchi Table. Employing FEMM 4.2 (2-D) software, the proposed of PMSGs studied have been computed and compared. It has been found that cogging torque reduction as much as 99.96% compared with the original model.

Keywords: Cogging Torque, Slot Numbers, Curvature of Base Slot, Slot Opening, Magnet Edge Shaping, Taguchi Table

INTRODUCTION

Permanent Magnet Synchronous Generator (PMSG) is one of non-conventional synchronous generator types which widely used in many applications. As the name, in order to provide magnetic flux in the generator, the rotor is excited...
by permanent magnet [1]. In general, PMSG has some advantages such as weight lighter, compact, higher efficiency and easy to maintenance. Based on the attributes, it is convenient to be implemented in wind or another system in renewable energy application. For instance, nowadays the PMSG widely used in wind turbine system. In small wind turbine, the PMSG is usually connected directly to the turbine, leads the control system become simpler. However, one of the disadvantages of PMSG is that it has a high cogging torque (CT). The CT is affected by interaction between the fluxes of magnet structure in rotor core with the slot opening in stator core. In addition, the CT generated in any PMSG depends on the structure and material used for construction of the machine. In this paper, the material used for stator and rotor core is M-19 steel. The magnet rotor for the PMSG is NdFeB 32 MGOe. Both of the M-19 steel and NdFeB 32 MGOe are popular for electrical machine material. The advantages of M-19 steel is the ability to be loaded by high flux density as much as 1.5 tesla. The magnet NdFeB 32 MGOe has higher flux remmanent, compared to other permanent magnet. The characteristics of both materials can be read in the FEMM software. In PMSG, a higher amount of CTs can reduce the effectiveness of machine and system in applications. For instance, the presence of CT in PMSG has an effects on the brakes of rotor rotation, especially in conditions of low wind speed, and at the beginning of the rotor rotation. Based on the discussion, it can be concluded that CT is the most important issues and must be considered and overcome in the stage of design of PMSG, the issues of CT have also been investigated in [2],[3],[4],[6],[7],[8],[9]. In the stage of design, the CT is influenced by the structure of machine. The CT in the stage of design cannot be neglected, since it comes from the characteristics of material for construction and the structure of machine. The CT can be minimized. In fact, the CT in PMSG also can be effected by the human error when manufacturing. In this study, investigation will be based on the stage of design. For this purpose, it will be focused on the material and the machine structure. Since the last few years, many scholars have dealt related with CT reduction issue.

The CT reduction method in permanent magnet machine can be grouped into:
1. Modify the stator structure,
2. Modify the magnet rotor structure
3. Combining modify 1 and 2

Past research in [2],[3], there were many CT reduction methods have been developed and proposed in any scientific papers, such as modification of slot/pole combination to be fractional slot number [4], modification of stator curvature, and slot opening height in stator core [4],
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modification of magnet edge slotting length, magnet edge height, and magnet edge pole arc in rotor [2], as shown in Figure 1 and Figure 2.

In this paper, there are sixteen of PMSG structures with different structure based on Taguchi Table, as shown in Table 1.

Simulation Result and Calculation Method

In this paper, the PMSGs structure studied are simulated by employing numerical based on FEMM 4.2 (2-D). The FEMM (Finite Element Method Magnetics) is free software, where has been used to analyze the electrical machine structure or PMSG [2],[3],[4],[10]. Moreover, since the last few years, many scholars have analyzed electric machine structure based on this software in world wide. The FEMM software is one of simple tool, and easy to operate by researchers. The procedure of working with FEMM on the electric machine analysis has been reported in previous scholars [2],[3]. LUA 4.0 script is compatible with FEMM, and it can be used to mitigate the simulation. The procedure of combining FEMM and LUA based on the previous scholars [2],[3],[4]. The advantage of employing LUA in mitigation is lied in the fact that the computing process can be more accurately, compared with only FEMM. In addition, the parallel computation of PMSG can be increased. In this study, since the proposed of PMSG is for wind power system, the CT peak reduction targeted is at least 98 % compared with the initial structure. For minimizing the core losses in the machine, magnet flux density in both of stator ($B_s$) and rotor core ($B_r$) should be limited. Considering the material used for both of stator and rotor core is M-19 steel, the magnetic flux density in machine core should be $< 1.5$ tesla. If the magnetic flux density is 1.5 Tesla or higher, the eddy current losses of the machine will increase. In

**Figure 2.** Magnet edge length (A), magnet edge height (B), magnet edge angle (C) and height of dummy slot (D)

**MATERIAL AND METHOD**

The aim of this paper is to design and propose a new PMSG structure with any higher CT reduction for wind power application. The CT reduction for the purpose is expected to be at least 98%, compared with the load torque.

Table 1. Taguchi Table generated from Respond Surface Method (RSM).

<table>
<thead>
<tr>
<th>No</th>
<th>Magnet edge length (mm)</th>
<th>Magnet edge height (mm)</th>
<th>Magnet edge angle (°)</th>
<th>Slot opening height (mm)</th>
<th>Stator curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.04</td>
<td>2</td>
<td>0.0105</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
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<td>3</td>
<td>0.0106</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0.06</td>
<td>4</td>
<td>0.0107</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0.07</td>
<td>5</td>
<td>0.0108</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>0.225</td>
<td>0.04</td>
<td>3</td>
<td>0.0107</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>0.225</td>
<td>0.05</td>
<td>2</td>
<td>0.0108</td>
<td>35</td>
</tr>
<tr>
<td>7</td>
<td>0.225</td>
<td>0.06</td>
<td>5</td>
<td>0.0105</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>0.225</td>
<td>0.07</td>
<td>5</td>
<td>0.0106</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>0.025</td>
<td>0.04</td>
<td>4</td>
<td>0.0107</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>0.025</td>
<td>0.05</td>
<td>5</td>
<td>0.0108</td>
<td>25</td>
</tr>
<tr>
<td>11</td>
<td>0.025</td>
<td>0.06</td>
<td>2</td>
<td>0.0107</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>0.025</td>
<td>0.07</td>
<td>3</td>
<td>0.0106</td>
<td>35</td>
</tr>
<tr>
<td>13</td>
<td>0.1354167</td>
<td>0.04</td>
<td>5</td>
<td>0.0106</td>
<td>35</td>
</tr>
<tr>
<td>14</td>
<td>0.1354167</td>
<td>0.05</td>
<td>4</td>
<td>0.0105</td>
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<td>0.1354167</td>
<td>0.07</td>
<td>2</td>
<td>0.0107</td>
<td>30</td>
</tr>
</tbody>
</table>
In the beginning, the CT peak of original model has been computed using FEMM. It has been found that CT peak value of Initial Model with 60 slot / 20 pole as much as 0.0938244000 N.m. In general, the CT of all PMSG models studied is computed based on the Equation (1) [5],[6].

\[ T_c = \frac{1}{2} \phi_g \frac{dR_g}{d\theta} \quad (1) \]

where
\[ \phi_g = \text{total magnetic flux in air gap}, \]
\[ R_g = \text{reluctance in air gap}. \]

In order to reduce the CT peak value of any PMSG, the air gap reluctance should be optimized. In reality, for purpose of CT reduction one can minimize the tangential force acting in air gap. The effect of tangential force to increase the peak value of CT can be seen in Equation (2).

\[ T_c = L_{stk} F_t \int_0^{2\pi} r^2 d\theta \quad (2) \]

where
\[ L_{stk} = \text{PMSG stack length}, \]
\[ r = \text{dummy radius in air gap of machine}, \]
\[ F_t = \text{tangential force in air gap}. \]

The tangential force can be formulated as in Equation (3):

\[ F_t = \frac{1}{\mu_0} B_n B_t \quad (3) \]

By substitution of Equation (3) into Equation (2), the CT of PMSG can be written as:

\[ T_c = \frac{L_{stk}}{\mu_0} B_n B_t \int_0^{2\pi} r^2 d\theta \quad (4) \]

where
\[ L_{stk} = \text{stack length of PMSG}, \]
\[ B_n = \text{normal flux density}, \]
\[ B_t = \text{tangential flux density}, \]
\[ r = \text{dummy radius in air gap of machine}. \]

From Equation (4), the tangential force is the function of CT in permanent magnet machine. Considering the \( B_n \) and \( B_t \) always vary with the rotor rotation, the Equation (4) can be rewritten into Equation (5):

\[ T_c = \frac{L_{stk}}{\mu_0} \int_0^{2\pi} r^2 B_n B_t d\theta \quad (5) \]

The feature of \( B_n \) and \( B_t \) are presented in this study. One can observed that CT depends on the value of parameters in Equation (2). However, the most important issue to contribute CT in any permanent magnet machine is the tangential flux density (\( B_t \)). The tangential flux density tends to flow into slot opening of the machine, leads the machine is difficult to be rotated by prime mover. It is caused the tangential flux density generates tangential force acting in air gap. The presence of tangential force acting in air gap can block the rotor rotation. In standstill or the low wind speed condition, the rotor cannot be rotated. So that, for reducing the CT in any permanent magnet machine, one should consider to optimized the tangential force, instead of the normal magnet force. In order to decline the tangential force, one can focus on minimization the interaction between magnet structure and slot opening. In this paper, CT minimization has been studied and developed by combining three CT reduction methods, such as magnet edge shaping and dummy slot in stator core at fractional slot number (FSN). The novelty of this research is the fact that combining magnet edge shaping and dummy slotting in stator core of FSN with a very CT reduction. It has been studied that FSN is one of CT reduction methods, and effective in any permanent magnet machine [3]. However, less reports have found the CT reduction more than
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99%, compared with the initial model.

In Figure 3, it can be seen that the CT of any PMSG can be reduced by modify the structure of stator core, magnet rotor, or both of them. In FSN, both of stator and rotor are involved in CT reduction, shown in Figure 1.

Figure 3. Cogging Torque Reduction Classification

In combining the CT reduction method, the advantages and disadvantages of CT reduction might be complement each other. However, from manufacturing perspective, this may be more difficult to be implemented. In this study, an investigation and analysis of sixteen machines with different magnetic rotor topologies was carried out as shown in Table 1. As can be observed from the table, the structure of PMSG are developed. In magnet rotor, there are 4 parameters have been optimized, while in the stator core is one parameter. For simplify, only the best structure of PMSG is presented and compared with the initial model, as shown in Figure 3.

Figure 4 represents with the best of PMSG structure based on the Taguchi Table. In that figure, some axial channels in rotor core have been introduced. The effect of axial channels on the CT value is not study detailed in this paper. However, it should be mentioned, the effect of axial channel can reduce rotor weigh.

Figure 4. PMSG with 18 slots / 20 poles (proposed Structure)

DEVELOP COGGIN G TORQUE REDUCTION

The CT reduction was developed based on the integral slot number (ISN) of 60 slot / 20 pole. The CT peak value of this type of ISN structure is usually high. This caused that all magnetic flux distribution is added in phase, leads it is difficult to reduce the CT of this kind of machine structure. However, one of good CT reduction of ISN type of PMSG as have been reported in [2],[3]. In [2], scholars employed the two steps of slotting technique in magnet edge to reduce the CT in ISN with 24 slot / 8 pole. The air gap length of the machine is 2 mm and the slot opening width is 2 mm. The CT of the machine could be reduced to around 95 %, compared with conventional machine structure. In 2018, the CT reduction of machine is achieved by optimized the magnet edge parameters. The CT could be reduced to 98.35% compared with conventional machine structure [3]. In the beginning, the ISN of 60 slot/ 20 pole is converted to FSN with 18 slot / 20 pole. The CT values of the initial model of PMSG is computed. Using the FEMM, it has been found that CT value of the
initial model as much 0.0938244000 N.m. In order to achieve the measurement accuracy, the dummy lines in air gap of machine should increase [5]. In this study, 5 dummy lines has employed in the air gap for all PMSGs studied. The process of CT computation using FEMM as presented in the following Figure 5.

$$100\% - \frac{0.0001091440}{0.0938244000} \times 100\% = 99.88\%$$

It can be seen that the CT reduction of FSN is significant. It caused by combining of three CT reduction methods. The comparison of CT reduction between 60 slots / 20 poles and 18 slots /20 poles can be observed in Figure 6, and Figure 7 respectively.

In Figure 5, the PMSG structure by means of drawing can be imported from AutoCAD or drawn in the FEMM system. In this study, the PMSGs drawing are conducted in the FEMM systems. The material used in PMSGs structure is assigned in the stage of drawing. All the materials used in this study are listed in the FEMM software [3], [4]. To verify the CT reduction of FSN, the CT of FSN is compared with the ISN as follows:
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To improve the CT reduction of PMSG proposed, the structure of magnet is optimized based RSM. In this method, the structure of PMSG of ISN optimized. In the optimization, some 5 parameters in the PMSG proposed have been selected. The 5 parameters have been investigated in this study.

From Figure 9 and 10 respectively, the tangential flux magnet has any higher fluctuation wave, and has less dense compared with original model. In addition, the normal flux density also become more sine.

DISCUSSION

The CT reduction of PMSG with 60 slot /20 pole (integral slot number) to fractional slot numbering with 18 slot/ 20 pole is = 100% - [(0.0001091440 / 0.0938244000) x 100%] = 99.89%. To obtain better design qualifications for wind power applications, PMSG structured has been optimized by select 5 parameters in the machine. The parameters located in critical region in the machine structure, where the CT presents.

The CT reduction from the optimization design based on the Taguchi Table compared to initial model is calculated as = 100% - [(0.0000384239 / 0.0938244000) x 100%] = 99.96%. Both of the modifications produce tangential flux density ($B_t$) graphic with flatter shape and normal flux density $B_n$ graphic with more sinusoidal shape.

CONCLUSION

Effect of slot and pole pairing with magnet edge shaping on the CT reduction has been presented in the paper. One can observe that, CT in fractional slot number of PMSG is lower compared with the CT of integral slot number. Fractional slot number and shaping in magnet edge have been successfully on reducing the CT of PMSG. Modifying slot numbers of PMSG from integral slot numbering (ISN) to fractional slot number (FSN) can result in higher CT reduction, compared
to the ISN with modification of magnet rotor and stator teeth. By using magnet edge shaping based on the Taguchi Table, the CT reduction of PMSG promises a significantly higher CT reduction, compared with initial model. Based on the CT reduction of the PMSG proposed, it can be concluded that the machine can be used in wind power application.

REFERENCES


