Analysis on the Cogging Torque of Permanent Magnet Machine for Wind Power Applications

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***Abstract*—This paper deals with the analysis of cogging torque of permanent magnet machine for wind energy application. For the purpose of study, a 24-slot and 18-pole pairing of permanent magnet machine is selected. In order to reduce the cogging torque of permanent magnet machine based on the wind power requirement, a combining of shaping in magnet edge with three dummy slots in stator core of machine is studied in the paper. The combining of shaping in magnet edge with three dummy slots in stator core give a high value of cogging torque reduction of the model of PMM proposed. For the analysis of the entire machine structure, the finite element analysis is employed in the study. Using the finite element analysis based on FEMM, the cogging torque value of PMM models is analyzed. It is found that the cogging torque reduction value of the model of the PMM proposed can be increased to 98.74 % compared to the conventional PMM model. In conclusion, it can be said that the PMM can be developed and proposed in wind power application.**

Keywords: cogging torque, permanent magnet machine, renewable energy, finite element analysis

I. Introduction

The Permanent Magnet Machines (PMMs), has been widely applied in many applications not only with good in electrical and magnetic characteristics, but also it has any stronger construction compared with the other electrical machine type. As a result, the PMMs are widely be applied in many fields, such as medical equipment, robotic, electric transportation, pump, and as well as renewable energy applications. In renewable energy applications, the PMMs are used as generators, such as in wind-powered, water-powered, tidal-powered, and others related to the low speed applications. In wind power systems nowadays, many PMMs are applied in low power wind turbines to convert mechanical energy to become electrical energy. This is caused that the PMMs have some advantages over the other type electrical machine. For renewable energy system as in wind power applications, the PMMs usually is designed with higher number pole, compared with the other application in non-renewable energy. The reason is that the renewable energy sources usually move slowly compared to the energy from fossil, so that to adjust any movement of the rotation system, the pole of any PMMs should have a higher of pole number. According to the principal of electrical generating, the higher the number of poles of the PMM in rotor, the lower the mechanical energy is needed to feed any torque to the rotor to attain a certain frequency according to the customer requirement/need. For instance, to attain a frequency of 50 Hertz in electrical power system, a PMMs of 6 poles must make any rotation as much as 1000 per minute. It is difficult to obtain any force of wind power to provide such a high torque in order to increase the rotation speed of the machine. On the other hand, a micro or small wind power system usually uses direct driven to provide any rotation. For wind power application, a 10-pole or more of PMM may be reliable and acceptable, while stator number can be various. The advantages of PMMs over the conventional electric machines are efficient, simple, strong, and adaptable to the machine construction. For small wind power systems, the connection between PMMs and wind turbines can be simplified by direct driven connection. However, the most important issue related to the renewable energy applications, is cogging torque (CT). The CT in PMM is expressed in change of the torque on rotor in interaction of the magnet flux from rotor and stator slot of the PMM. The CT can generate vibrations, acoustic noise, and more complicated starting conditions, exploitation become more complex. As a consequence the CT effects to reduce the self-starting capability of the wind power, especially at low wind speed condition [1]. In any PMM with high CT value, even the rotor of the PMM can be driven by prime mover, and make any rotation, the electrical power output of PMM can be decreased. From the discussion it can be concluded the CT in PMM has become one of important indexes of PMM performance. Thus, for application in wind turbine system, the CT of machine should be set as low as possible in the design phase. However, the CT reduction becomes a difficult task when the requirement is very strict applications, as in wind power system. In order to minimize the CT of PMM regarding the wind power application, the CT peak value must be reduced as low as possible [1],[2]. In past researchers [1], the CT peak value in any PMM or other electrical machine cannot allowed more than 2 % of the rated torque. Unless, the blade of the wind power system cannot be rotated by the power of the wind except for the strong wind. For reducing the CT in any PMM, some researchers have developed and proposed some CT reduction techniques [1]–[7], and many more in worldwide. Some of CT reduction technique was done by adjusting the magnet pole arc [1],[8], full skew / step skew [9]–[11], magnet shape [1], [8],[12]–[14], magnet surface slot [2],[4],magnet edge slot [2],[3], dummy slots in stator teeth [8],[15],[16]. The Scholars in [5], [7] investigated the effect magnet structure on the magnetic flux distribution in air gap of PMM. In fact, the CT in any PMM is influenced by the stator core and magnet structure [7]. In addition, the CT peak values and frequency of CT are highly influenced by the magnet shape, magnet dimensions, magnetization pattern, and material of the permanent magnet. It has been investigated, that the number of slots and poles pairing in any PMM the CT of machine. The slot and pole pairing has any significant effect on value of CT. So that, the slot and pole combination must be considered to obtain magnet pole arc and determining the dummy slot in stator teeth regarding the reduction the CT of PMM. For purpose of study, a - 24 slots and 18 poles pairing of PMM is selected in the paper. This type of PMM can be adopted to apply in wind power since it has many number poles, leads can accommodate the low wind speed condition. In addition, to overcome the rotor weight, some axial channel can be employed in the rotor core. Two of PMMs studied have been investigated and compared in this paper. Firstly, the PMM model with conventional structure, which both of stator and rotor core without any optimization. Secondly, PMM model proposed with the edge of magnets are shaped with 3 dummy slots in the core of stator.

II. STRUCTURE OF PMM MODELS STUDIED

The structure of PMM Model is presented in Figure 1. In PMM structure, some axial channels in the rotor have been introduced in the paper. For simplification, the influences of the axial channels on the CT reduction or other effect related to performance of PMM is not studied detailed in this study.

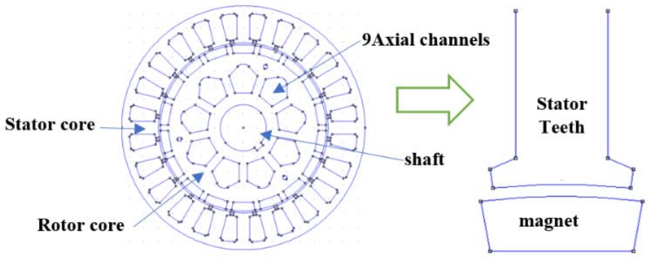


Figure 1. Initial PMM Model of 24 slots and 18 poles pairing

The structure of the Initial PMM Model is shown in Figure 1. As can be observed, the magnet structure of the PMM adopts a bread-loaf type. The stator teeth with conventional structure, without any dummy slot or dummy teeth. The stator and rotor core are made of M-19 steel, as it is popular in PMM or modern electrical machine structure nowadays. The M-19 steel has a good mechanical construction to support both mechanical and magnetic load. It can support any magnetic flux density as much as 1.5-1.6 Tesla. In order to increase the dynamic response of the PMM, some axial channels have been introduced. The rotor weigh can be reduced to 31.87 %, compared with non-axial channel rotor core. However, as can be seen from Figure 1, the stator teeth and magnet structure of the PMM is conventional, leads the CT of the machine tends to be high. To minimize the CT of machine, a combining of magnet edge shaping and dummy slot in stator core are developed in the paper. By shaping the magnet edge leads to reduce the magnet flux in the magnet edge flowing into air gap. In addition, the magnets occupy the air gap of PMM become decrease. The air gap cross section is then achieved by employing the dummy slots in stator core. Combining the dummy slots in stator and magnet edge shaping can increase any larger of air gap cross section and reduce the air gap reluctance of the PMM proposed model. The PMM proposed model as shown in Figure 2.

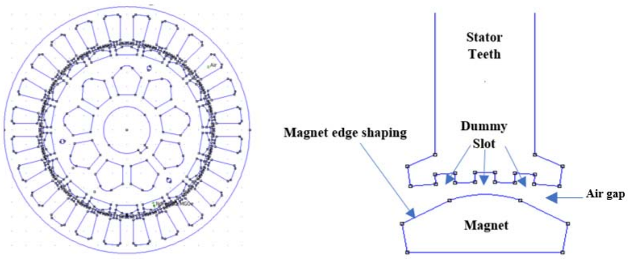


Figure 2. The PMM proposed model

As it can be seen in Figure 2, the magnet structure of PMM proposed model uses the magnet edge shaping, and a-stator teeth with 3 dummy slots. The presence of both magnet edge shaping in magnet, and the 3 dummy slots in stator teeth of machine can reduce both of normal and tangential force acting in air gap of the machine. The aim of magnet edge shaping of the PMM, is to minimize the value of tangential flux density of the magnet, leads as well as to minimize the tangential force in air gap of the machine. In addition, the presence in magnet edge, the space to be occupied by the magnets in air gap of machine become reduced. In other hand, the air gap cross section of machine become increase. As a rule of thumb, if the air gap cross section it effects to increase in any PMM or electrical machine, the air gap reluctance of the machine will decline. Providing one or more dummy slots in stator core is another benefit regarding to the reduction of CT. The reason is the presence of dummy slot in stator also increase the air gap cross section. It can be said, the effect of dummy slot almost the same as by employing magnet edge shaping of machine. The different is, the presence of stator teeth of machine with dummy slotted can reduce the peak of CT. This is caused, if the CT frequency of any PMM increase, the CT should be reduced. Thus, the combination of stator teeth with dummy slotted, with shaping in magnet edge can effectively minimize the CT of machine.

III. COMPUTING THE ELECTROMAGNET FORCE DENSITY IN AIR GAP OF PMM MODELS

The electromagnetic field analysis is the base of the computation of the densities of the electromagnetic force in air gap of PMM. Two kinds of electromagnetic force acting in air gap of PMM are the normal magnetic force, and the tangential magnetic force. Conventional analyzing technique can clearly indicate the relationship between function and variables, but it is not easy to solve the instantaneous value for satisfying the precision required [17]. And, as the structure of any PMM is complex, it is difficult to analyze accurately the electromagnetic phenomenon entirely the machine structure. For solving the electromagnetic field in PMMS, especially in the air-gap, numerical calculation technique have been used since the last few years. Some of numerical computation system have been used to analyze the PMM performance. In this paper, authors have applied the finite element method magnetics (FEMM). Another numerical system such as boundary element methods (BEM), finite different methods (FEM). However, nowadays the using of FEM have been widely applied compared with BEM and FDM. The advantages of FEM is the capable of the software to solve any complex structure of object, as in PMM or in other type electrical machine. However, the disadvantages of using FEMM will consume a lot of time. For that reason, in this paper a technique of analyzing PMM by combining FEMM and analysis technique. In this paper, a-numerical computation based on the FEMM has been used to investigate the electromagnetic performance of PMM structures studied. Currently, the basic technique to analyze the force and torque of electromagnetic is Maxwell Stress Tensor (MST). The MST is deduced from the mechanical theory of computing force and torque. From the electromagnetic flux density, such as radial and tangential force acting on the air gap of PMM can be formulated as [14]:

For the density of radial flux in air gap is

$$F_r = \frac{1}{2\mu_0}\left(B_r^2 - B_t^2\right) \quad (1)$$

where; B_r, and B_t is the density of radial flux and tangential flux in air gap, respectively.

For the density of tangential flux, it can be formulated as;

$$F_t = \frac{1}{\mu_0}\left(B_r B_t\right) \quad (2)$$

Both the radial force and tangential affect to contribute the PMM performance. The radial force flows toward the stator teeth of the PMM, while the tangential force toward the slot opening in stator core of machine. It refers that tangential flux density effect to the CT of machine. The higher the tangential force acting on air gap of machine distributed into the stator slot, the higher the CT can be occurred. Based on the phenomenon, the CT in any PMM can be formulated as a function of tangential force, as:

$$T_c = L_{stk} F_t \oint r^2 d\theta \quad (3)$$

By substation the Equation (2) into (3), the CT value in air gap of PMM can be rewritten as:

$$T_c = L_{stk} \frac{1}{\mu_0}\left(B_r \cdot B_t\right) \oint r^2 d\theta \quad or$$

$$T_c = \frac{L_{stk}}{\mu_0} \oint r^2 B_r B_t d\theta \quad (4)$$

Where, L_{stk} the stack length of the PMM is, μ_0 is air gap conductance, r is dummy radius in air gap where the CT value is measured. From Eq. (4), one can observe that tangential force in air gap effects to the CT value of any PMM. As has been stated in beginning of the paper, the CT is generated by the interaction between magnet flux in the magnet edge and slot in stator core. Thus, in reducing the CT of PMM proposed model is based on the reducing the tangential force acting on the stator slot. For the purpose of reducing the tangential force acting in the air gap of machine, the magnet edge of the PMM model are shaped with a certain degree to minimize the value of tangential flux density in air core. The benefit of the technique is lied in the fact that the parameter effect to the tangential flux density and be minimized directly. Other issue to minimize the CT, is by increasing the air gap cross section. Some techniques to increase the air gap cross section is by employing some of the following parameters such as :(1) to increase the distanced between stator slot and magnet surface. (2). employing dummy slotting in stator core. (3). By employing slotting in magnet edge. (4). employing shaping in magnet edge. With combining the dummy slot in stator core, it contributes to increase the air gap cross section of machine, which in turn can reduce the CT peak value of machine significantly.

IV. Computing the Magnetic Flux Distribution in PMM Models Studied

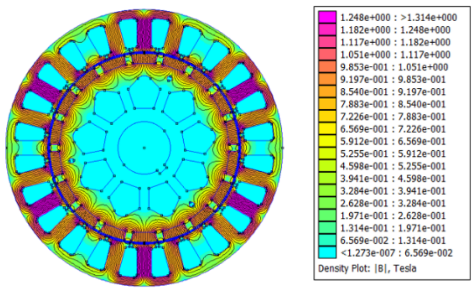


Figure 3. Distribution of Magnetic Flux Density of PMM Initial model studied

From Figure 3, one can observe the magnetic flux distribution of the PMM Initial Model. The axial channels in rotor core is not disturb the flux barrier in the rotor core of the PMM initial model. In addition, it has advantage in order to reduce the rotor weight around to 31.86 % compared with the conventional rotor core. It means that the dynamic response of the machine will increase as much as 31.86 % compared with non-axial channel. The magnetic flux density maximum in the PMM initial model core is around 1.248 Tesla.

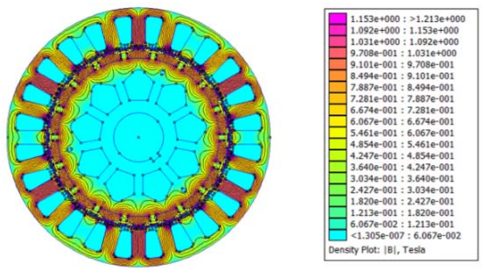
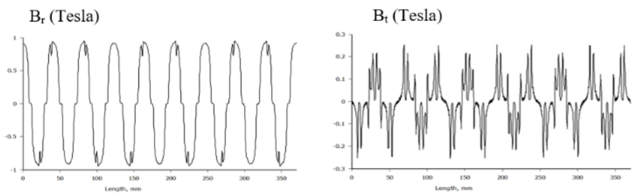


Figure 4. Distribution of Magnetic Flux in PMM proposed model

By combining the shaping in magnet edge, with a-3 dummy slots in stator teeth, can reduce the magnetic flux density in the machine. Using the finite element analysis, it has been found as much as 1.153 Tesla. The reduction of magnetic flux density in the machine core of PMM proposed model is around to 7.6 % compared with initial model. Density of magnetic flux reduction in the PMM proposed model refers to the reduction of core losses of the machine.

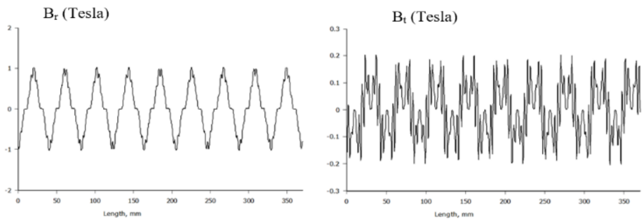
V. COMPUTING MAGNETIC FLUX DENSITY IN AIR GAP OF PMM MODELS

The density of magnetic flux in PMM or other electrical refers to the characteristics of machine. In analysis the characteristics, some parameters related the magnetic field should be considered. Two of most important parameters related to the electromagnetics issues are normal and tangential flux density. Both of them effect to the increasing of magnetic force acting in air gap of machine. The radial flux density and tangential flux density of the PMM models studied is investigated and presented, as it can be seen in Figure 5 and Figure 6, respectively.



a. Radial flux density   b. Tangential Flux density

Figure 5. Flux density of initial PMM model



Radial Flux Density   Tangential Flux Density

Figure 6. Flux density of initial PMM proposed model

Both the density of radial and tangential flux as shown in Figure 5 and 6 are measured located between magnet surface in rotor core and stator core of PMM with the help of FEMM. For minimizing the error, and to increase the measurement accuracy of CT of PMMs studied, 5 dummy lines have been used between the magnet surface and stator for all PMM models studied.

VI. ANALYSIS THE COGGING TORQUE OF PMM MODELS

In order to compute the CT of the PMM models, the finite element method magnetics (FEMM) has been employed in the paper. The procedure of PMM models analysis based on the past researchers [2], [3], [5], [14], [18]. The initial PMM models have been computed, and it has been found the CT peak value around to 0.0056221 N.m. By employing the combining of magnet edge shaping and 3 dummy slots in stator core, the CT peak value of PMM proposed model around to 0.0000701 N.m.

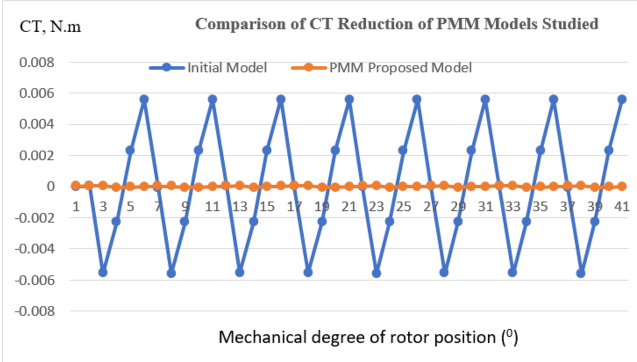


Figure 7. Comparison of CT of PMM Models Studied

VII. CONCLUSION

Analysis for CT reduction of PMM for wind power application has been presented in the paper. For computation of CT value of PMM models, the finite element method and analytical have been used. The CT reduction of PMM proposed model can be minimized significantly by application of shaping in magnet edge, with dummy slot in stator core of the machine. Using the finite element analysis, the CT peak value of PMM Initial model have been found around to 0.0056209 N.m. After performing CT reduction in the PMM proposed model, the CT peak value can be decreased to 0.0000708 N.m. Based on Fig.7, the percentage of CT reduction for the PMM proposed model is around 98.74 %. It can be concluded the CT reduction technique by applying the combining of shaping in magnet edge dummy slots in stator teeth is effectively to reduce the CT of PMM regarding the wind power application. For achieving the CT reduction of the PMM proposed model to more than 98.74 %, another CT reduction techniques, such as step skew in magnet rotor will conducted in our future research.

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