Investigation of the forces acting on the coils of a Modular Slotless Permanent Magnet Generator

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The paper investigates the forces acting on the coils of a modular permanent magnet generator. Two different cases are studied. First, the magnetic forces on the coil are computed in the case, when each coil is separately replaceable. Second, the forces are computed for one solid modular system, which is formed by three coils. It is shown that there is a strong force fluctuation acting on the coil when it is replaceable. When a modular system is used, the force fluctuation is reduced, but this configuration results in an increase of the cogging torque.

***Index Terms*—Permanent magnet generator, modular system, slotless design, coil forces, cogging torque**

I. INTRODUCTION

Wind energy has grown to be a significant factor in the electrical generator industry. This puts also higher demands on the system reliability and maintenance cost. One solution to increase the wind turbine system reliability is to use directly driven permanent magnet generators. By removing the gearbox from the drivetrain system, the system reliability will increase and the maintenance cost will decrease, but it will lead to low rotational speed of the generator. The low rotational speed results in an increase of the generator diameter, where the MW class machines diameter tends to be very large in size, expensive and difficult to build, transport and install [1].

One possibility to improve the machine maintenance and reliability is to use modular design of these machines. The modularity of the machine system will improve fault tolerance and reduce downtime in case of failure. In the generator system, the stator winding failures account for about 20-30% of all generator failures [2]. These failures are expensive to fix and take considerable time, according to [3], generator failures average to about 150 hours of downtime. Thus, the use of segmentation would reduce the time and cost of fault for winding replacement [4].

However, using the modular topology will also introduce additional air-gaps in the machine flux path. These additional air-gaps can lead to higher machine cogging torque, reduction in the back EMF, change in the winding factor etc. [5-6]. In this paper, the modular concept is introduced for the slotless permanent magnet machine. The study is concentrated on the local forces accruing in the module section.

II. CONSTRUCTION OF THE MACHINE

In the paper, the slotless PM generator for wind turbines has been taken under investigation. The description of this machine type can be found from the authors' previous works [7]. The principal design of the machine is given in Fig. 1, where it can be seen that the machine consists of surface mounted permanent magnet rotor and the stator consists of concentrated air-gap winding and back iron. The machine parameters are given in Table 1.

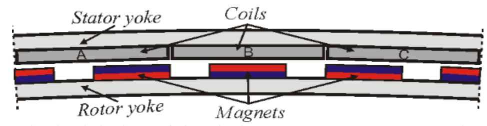

Fig. 1. The principal design of the slotless PM generator presenting one section of it.

In the given design, the number of poles and number of coils is chosen so that for each three coils there are four poles, meaning that the three coil system is forming one symmetrical three phase generator system, later referred to as one coil section.

TABLE I
SLOTLESS PM GENERATOR PARAMETERS

Name	*Unit*	*Value*
Electrical power	*kW*	3000
Rotational speed	*rpm*	13
Torque	*kNm*	2090
Air-gap radius	*m*	6.3
Air-gap hight	*mm*	10
Magnet dimensions	*mm*	20x100x800
Coil dimensions	*mm*	20x200x800
Number of coils per magnets		3/4

III. FORCES ON THE COILS

To make a modular machine with replaceable windings, two possible solutions can be looked at. First, the case where each coil is a separate system (Fig. 2 a) and can be replaced. Second is the option, where three coils are forming a section which is detachable (Fig. 2 b). Making the coils detachable means also that there will be additional air-gaps in the machine flux path. These air-gaps cannot be reduced to zero, because of manufacturing tolerances and also coil removal would be easier when a certain gap is left between the sections. For the given machine, the total gap on the coil perimeter was chosen to be 0.5 mm × number of coils.

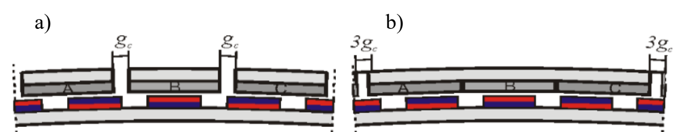

Fig. 2. Modular system of the generator. a) modular system where each coils are replaceable, b) modular system where a coil section is removable

Making the additional air-gaps in the machine flux path will also result in additional forces in the coil system. In the machine, the electromagnetic traction can be divided into two parts. First, the share stress (Fig. 3 a) that produces a useful force in an electrical machine and second, the normal component of Maxwell stress, directed across the air-gap, so that the facing iron surfaces are attracted towards each other. Without the modularity, the normal force component would only be between the stator and the rotor, but when adding the air-gaps between the coils, additional force component occurs between the coils assemblies.

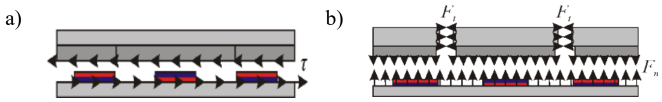

Fig. 3. Structural forces in the machines. a) the share stress, the useful air-gap force that gives the machine torque, b) normal component of Maxwell stress, the forces trying to close the gaps

A. *Modular replaceable coil*

To find the additional forces acting on the coil assemblies because of the air-gap between them, a FEM simulation was carried out in the case when all coils are replaceable. In the simulation a 0.5 mm air-gap between each coil was used. In the simulation the assumption was made that the air-gaps between the coils are equal. Also, as the generator radius is very large compared with the pole length, the simulation model was considered as a straight model. In the simulation, the rotor was shifted over the length of one pole. For different rotor positions, the forces acting on the coil assembly were computed from the field solution.

The simulation was carried out at no load. It means that the forces on the coil are created by field from the permanent magnets only. In Fig. 4a the radial force acting on the coil assembly is given and in Fig. 4b the tangential force is shown.

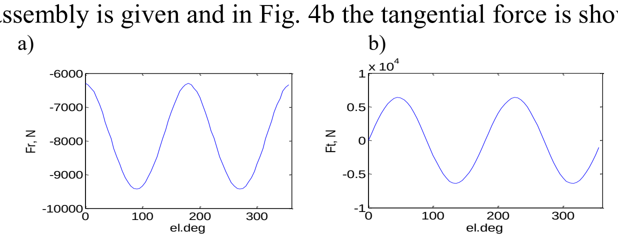

Fig. 4. Forces acting on the coil assembly. a) is the force in the radial direction and b) is the force in the tangential direction

From Fig. 4 it can be seen that at this situation the coil will suffer a strong force fluctuation on radial and tangential direction. If this force is compared with the neighboring coil, the force has the same amplitude but is shifted by 120 degrees. Here can be noted that when summing up all coil forces, the force fluctuation will disappear as long as the air-gaps are equal.

The structure in the generator has to be stiff and robust to maintain the small air-gap clearances. This additional force applied to the coil will put the coil support structure into higher stress, which may cause additional problems and has to be carefully designed.

B. *Modular replaceable coil section*

One possible solution to avoid these additional forces is to use three coil sections without an air-gap between the three coils, instead of one replaceable coil. In this situation, there will be an air-gap after each section. In the simulation of the given case, the air-gap width of 1.5 mm between the coil sections was used. For the one coil section, the forces at no load situation are given in Fig. 5.

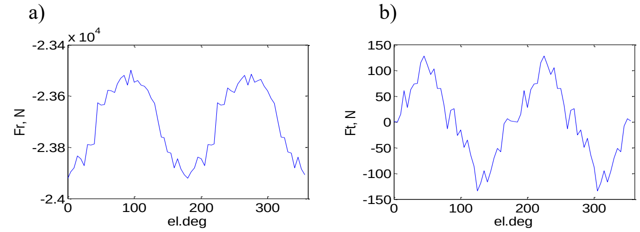

Fig 5. Forces acting on the coil section. a) force in the radial direction and b) the force in the tangential direction

As it can be seen from Fig. 5, there is still some fluctuation in the coil section forces but it is reduced drastically compared with the one coil modular system. On the other hand, this solution will lead to another problem. In one coil modular system the fluctuation in the coils sum up to zero and can be neglected form the machine performance point of view, when averaged over the full machine circumference. But when using the modular coil section solution, the fluctuating forces will not sum up into zero as all coil sections are in phase with each other. Instead, these forces will increase each other and a strong cogging torque will appear.

IV. Conclusion

In the paper the modular design of the slotless PM generator for wind turbines was introduced. Two different modular solutions were investigated and FEM simulations were carried out to find the forces acting on the modular system. It was shown that when using one coil modular system, problems with local forces in the coil will emerge, but these forces do not affect the machine performance. The local force can be reduced when using three coil sections as one module, instead of one coil modular system. Yet, this solution, emerges in a cogging torque that can be anticipated. Computation details will be given in the extended paper together with further analysis of the results and suggested solutions.

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