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Improving the Performance of PM Wind Turbine Generator by Minimizing the Detent Torque Using Finite Element Method

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Abstract* – *Nowadays most of the wind turbines use permanent magnet (PM) generators. The generators are usually direct-drive which means no gearbox is required. Direct-drive permanent magnet generators are widely used because of low maintenance and high efficiency. Small wind turbines are usually self-starting and require very simple controls. Detent torque (cogging torque) is an inherent characteristic of PM generators and is caused by the geometry of the generator. Detent torque affects self-start ability and produces noise and mechanical vibration. The performance of the wind turbine generator is improved by minimizing detent torque. In this paper, we investigate different methods for the reduction of detent toque both stator side and rotor side techniques. Although the design improvement is deliberate for small wind turbines, it is also pertinent to larger wind turbines.

Key words: Detent torque, wind turbine generator, permanent magnet, renewable energy.

I. Introduction

A permanent magnet synchronous generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. Synchronous generators are the majority source of commercial electrical energy. They are commonly used to convert the mechanical power output of steam turbines, gas turbines, reciprocating engines, hydro turbines and wind turbines into electrical power for the grid. They are known as synchronous generators because the speed of the rotor must always match the supply frequency. In a permanent magnet generator, the magnetic field of the rotor is produced by permanent magnets. Other types of generator use electromagnets to produce a magnetic field in a rotor winding. The direct current in the rotor field winding is fed through a slip-ring assembly or provided by a brushless exciter on the same shaft. Permanent magnet generators do not require a DC supply for the excitation circuit nor do they have slip rings and contact brushes. However, large permanent magnets are costly which restricts the economic rating of the machine. The flux density of high performance permanent magnets is limited. The air gap flux is not controllable, so the voltage of the machine cannot be easily regulated. A persistent magnetic field imposes safety issues during assembly, field service or repair. High performance permanent magnets, themselves, have structural and thermal issues. Torque current MMF vectorially combines with the persistent flux of permanent magnets, which leads to higher air-gap flux density and eventually, core saturation. Detent torque of electrical machine is the torque due to the interaction between the permanent magnets of the rotor and the stator slots of a Permanent Magnet (PM) machine. It is also known as cogging torque or 'no-current' torque. This torque is position dependent and its periodicity per revolution depends on the number of magnetic poles and the number of teeth on the stator. Detent torque is an undesirable component for the operation of such a machine. It is especially prominent at lower speeds, with the symptom of jerkiness. Detent torque results in torque as well as speed ripple; however, at high speed the machine moment of inertia filters out the effect of detent torque.

Wind power has been used for many years to improve the quality of life. For example, ancient civilizations used wind power to help pump water, mill grains, and for many other uses.

In modern days, wind turbines are used for the same or similar purposes (e.g., water or oil pumping, battery charging, or power generation). One important aspect of a wind turbine is that it operates without the side effect of creating pollution.

Small wind turbines are economically attractive alternatives to conventional sources of energy. They can be used in many remote or dedicated applications, such as weather stations, remote cabins, camp sites, unattended radio stations, boats, etc. Some small wind turbines are connected to a utility. The market for small wind turbines (under 50 kW) is growing and is predicted to remain strong in the near future.

II. SYSTEM CONFIGURATION

There are two types of small wind turbine, permanent magnet (PM) generators, based on the location of the permanent magnet. One is called outside rotating and the other, inside rotating. As the name implies, the outside rotating generator employs magnet poles rotating outside the armature winding. The inside rotating generator is similar to conventional PM motors, in which the rotor rotates inside the armature winding.

Both configurations have been widely adapted and arguments can be made that one configuration is better than the other, but with proper design, both configurations can be optimized. Other configurations, such as axial flux, have been proposed for small wind turbine applications, however; most of commercially available small wind turbines have the radial flux configuration.

Detent torque is the torque produced by the shaft when the rotor of a PM generator is rotated with respect to the stator at no load condition. Detent torque is an inherent characteristic of PM generators and is caused by the geometry of the generator. It is important to reduce the detent torque in a PM generator, because detent torque affects self-start ability and produces noise and mechanical vibration on wind turbines. Many methods have been reported to reduce detent torque, including pole shifting, uneven distribution of stator slots, stator tooth notching, and others. This paper investigates the inside rotating PM generator configuration using finite element analysis. This investigation is based on an existing PM generator and is not intended for the design of a new generator.
Therefore, only potential modifications were investigated (i.e., stator skewing and magnet geometry). Many excellent textbooks are available for PM generator design and some papers predict detent torque using analytical or MMF diagram approach8,9. A finite element analysis package program called MAGNET is used to predict the detent torque presented in this paper.

III. STATOR SIDE CONTROL TECHNIQUES

Numerous methods for reducing the cogging torque, such as skewing the stator slots, optimizing the pole-arc to pole-pitch ratio of the magnets, employing a fractional number of slots per pole, etc., have been proposed. While some cogging torque reduction techniques, e.g., skewing, are applicable to any type of permanent-magnet machine, most papers on this topic are generally restricted to machines having surface-mounted magnet rotors [1]-[5]. However, machines equipped with interior magnet rotors generally have a higher torque density due to the saliency torque component and require less permanent magnet material. They also exhibit a higher demagnetization withstand capability, which is an important consideration under flux-weakening operation. However, relatively little has been reported on their cogging torque and its reduction.

This paper shows that the optimum pole-arc to pole-pitch ratio for achieving negligible cogging torque in surface mounted magnet machines is applicable to interior-magnet machines. It describes an investigation into the cogging torque that results in a four-pole interior-magnet brush- less machine having either six slots and a short-pitched non overlapping winding (i.e., concentrated coils) or 12 slots and a full-pitched overlapping winding, the rotor and stator diameters and the width of the slot openings being identical.

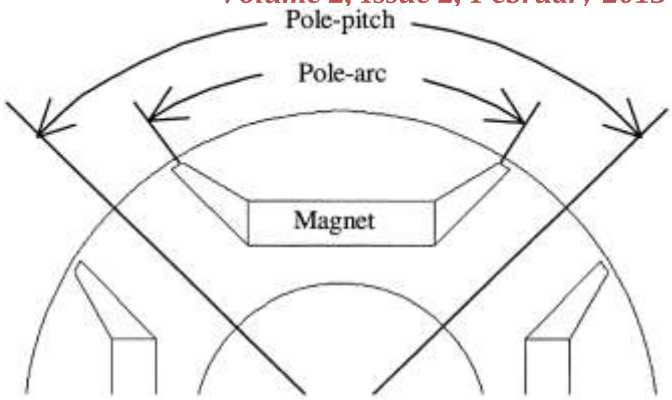

Fig. 1. Definition of pole–arc to pole–pitch ratio.

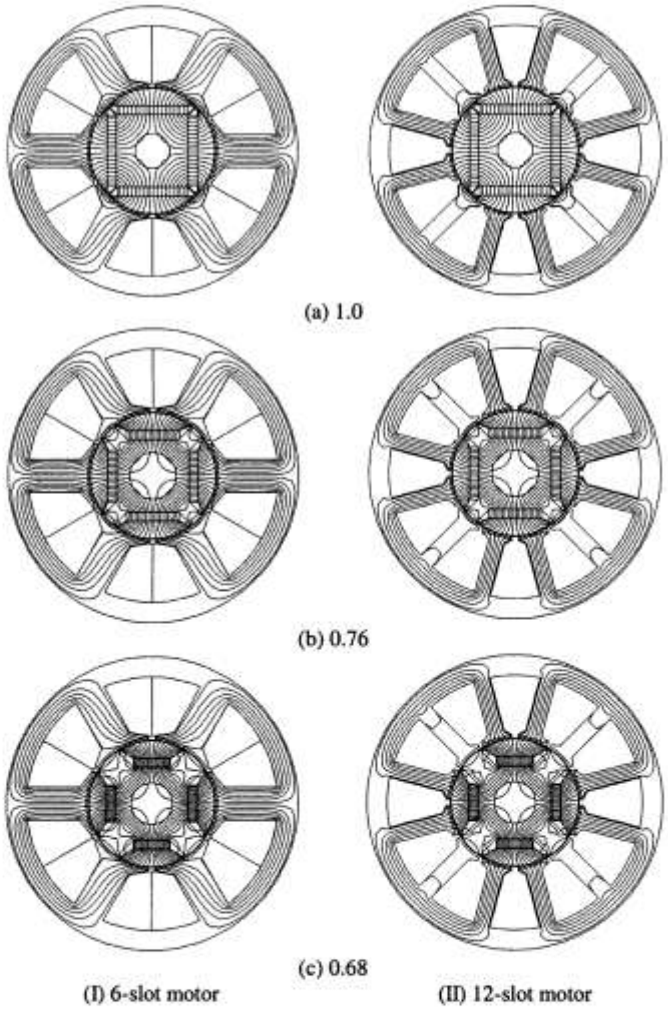

Fig. 2. Field distributions in four-pole interior-magnet brushless machines with pole arc to pole-pitch ratio as 1, 0.76 & 0.68.

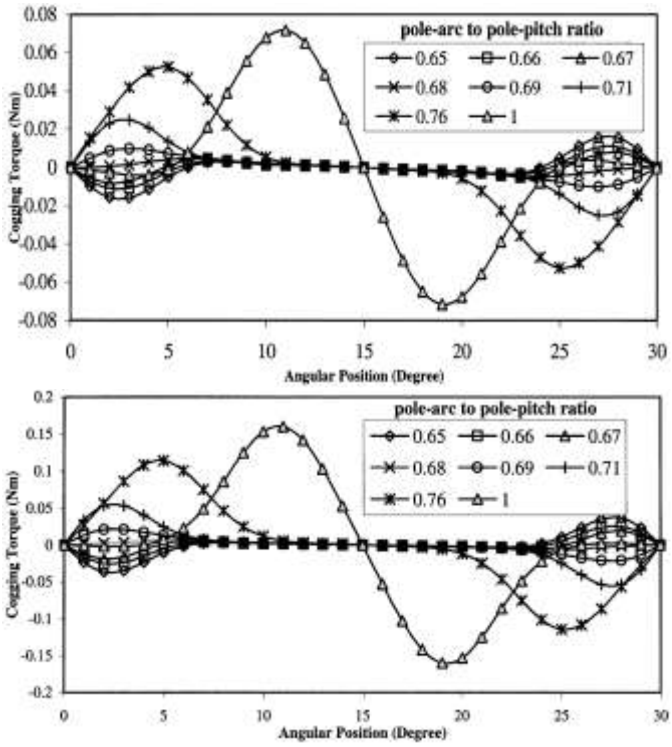

Fig. 3. Variation of cogging torque waveform with pole–arc to pole–pitch ratio. (a) 6-slot motor and (b) 12-slot motor.

The pole-arc of an interior magnet rotor is defined as the arc, which is subtended between the rotor lamination bridges (see Fig. 1). This definition is equivalent to the magnet pole–arc in a surface-mounted magnet machine. The variation of the cogging torque with the "pole-arc" is investigated by finite element analysis. Fig. 2 shows the field distributions that result when the pole arc to pole pitch ratio is equal to 1.0, 0.76, and 0.68, values of 1.0 and 0.68 resulting in the maximum and the minimum cogging torque, respectively, as will be evident from Figs.3.

IV. ROTOR SIDE CONTROL TECHNIQUES

Rotor side control techniques are mainly based on the rotor design by maintaining non uniform air gap between the stator and rotor. The cogging torque can be minimized if the shape of the magnetic pole is formed like a loaf of bread, thus creating a non uniform air gap. A comparison between uniform air gap and Non uniform gap (bread-loaf and sinusoidal type) permanent magnet surface is illustrated in Figure 4.

In Figure 5, a comparison of the normalized cogging torque between uniform air gap and non uniform air gap (bread-loaf magnet shape) is shown. The rotor is rotated in a fraction of the slot pitch and the resulting torque was calculated. It is apparent that the cogging torque reduction can reach about 50%. Note that all values are normalized to the peak torque of uniform air gap.

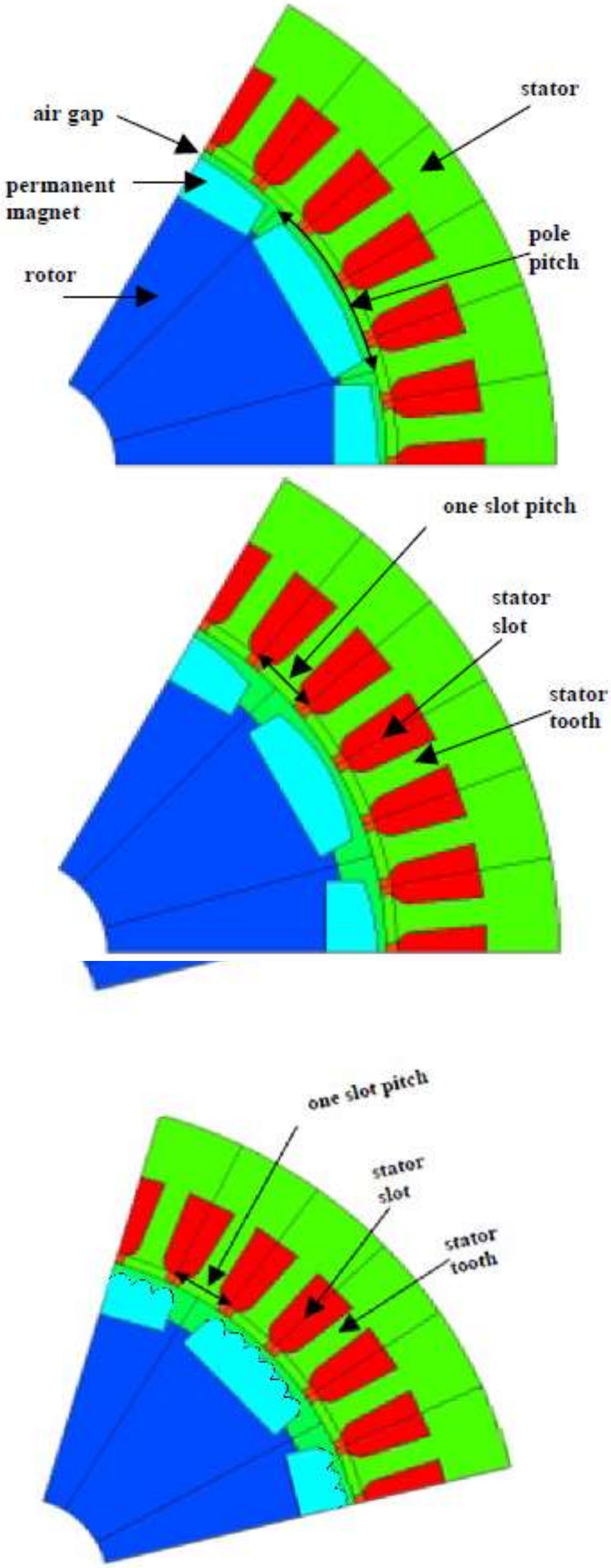

Figure 4. Permanent magnet with different shapes

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a) Top = uniform air gap
b) Bottom = nonuniform air gap (bread loaf)
c) Bottom = nonuniform air gap (sinusoidal)

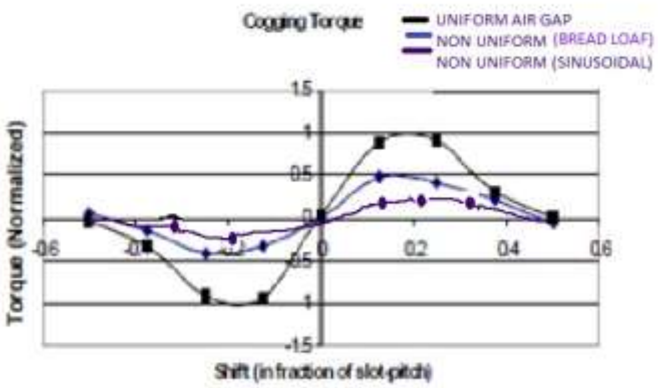

Figure 5. Cogging torque for uniform air gap and for non uniform air gap

V. CONCLUSION

This paper presents an overview of permanent magnet wind turbine generators and the importance of minimizing detent torque. The Detent torque, which results in a four pole interior magnet brushless machine having either a six slot stator with a short pitched non overlapping winding or a 12 slot stator with a full pitched overlapping winding, has been investigated by finite element analysis. The dimensional aspects determining the cogging torque of a PM generator are investigated. Finite element analysis is used to quantify the cogging torque in the design process.

Factors contributing to the cogging torque include the following:

- Pole shape: the non uniform (bread loaf & sinusoidal) pole shape of the permanent magnet appears to reduce detent torque.
- Pole arc to pole pitch ratio: it is apparent that there is a minimum cogging torque as the pole arc to pole pitch ratio is varied.
- Skewing: a perfect skew can nearly eliminate cogging torque. While skewing can potentially eliminate cogging, other design approaches may be lower in cost and/or easier to manufacture. These approaches may result in a finite residual cogging torque. The wind turbine designer must then compare this residual torque to the aero dynamic start-up torque to ensure acceptable performance of the wind turbine. We also note that this paper is not an exhaustive study of all the available cogging reduction options.

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