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COGGING TORQUE REDUCTION IN A PERMANENT MAGNET WIND TURBINE GENERATOR

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Abstract - Most small wind turbines use permanent magnet (PM) generators. The generators are usually direct-drive (i.e., no gearbox is required). Direct-drive PM generators are characterized by low maintenance and high efficiency. Small wind turbines are usually self-starting and require very simple controls. Cogging torque is an inherent characteristic of PM generators and is caused by the geometry of the generator. Cogging torque affects self-start ability and produces noise and mechanical vibration. Thus, minimizing cogging torque is important in improving the operation of small wind turbines. In this paper, we investigate three design options to minimize cogging torque: uniformity of air gap, pole width, and skewing. Although the design improvement is intended for small wind turbines, it is also applicable to larger wind turbines.

Key words: wind turbine, small generator, permanent magnet, renewable energy, remote application, cogging torque

INTRODUCTION

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.[1,2] Some small wind turbines are connected to a utility. Figure 1 shows some typical small wind turbine applications. The market for small wind turbines (under 50 kW) is growing and is predicted to remain strong in the near future. Considering the market potential, many improvements in the technology can pay for themselves through superior quality, lower maintenance, and higher reliability.

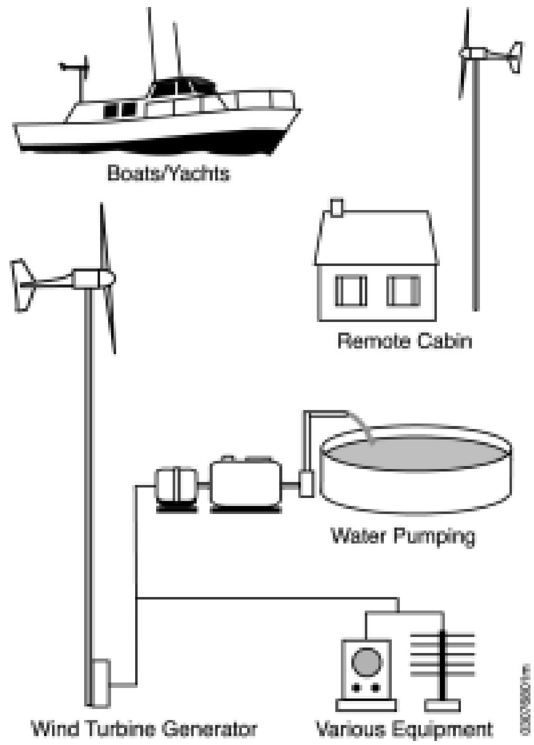

Figure 1. Different types of small wind turbine applications

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*[3] 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,[4,5] however; most of commercially available small wind turbines have the radial flux configuration.

Cogging 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. Cogging torque is an inherent characteristic of PM generators and is caused by the geometry of the generator. It is important to reduce the cogging torque in a PM generator, because cogging torque affects self-start ability and produces noise and mechanical vibration on wind turbines. Many methods have been reported to reduce cogging 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[6,7] and some papers predict cogging torque using analytical or MMF diagram approach[8,9]. A finite element analysis package program called ANSYS™ [10] is used to predict the cogging torque presented in this paper.

WIND TURBINE CHARACTERISTICS

The aerodynamic power generated by the wind turbine is:

$$P = 0.5 \rho A C_p V^3 \qquad (1)$$

where:

ρ = density of air
A = swept area of the blade
C_p = performance coefficient
V = wind speed.

The torque generated by the turbine is:

$$T = \frac{P}{\omega_s} \qquad (2)$$

where:

T = mechanical torque at the turbine side
P = output power of the turbine
ω_s = rotor speed of the wind turbine.

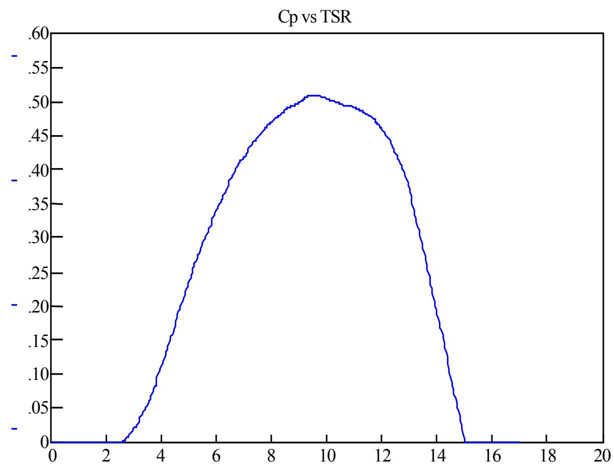

Figure 2. A typical C_p versus tip-speed ratio curve

A typical C_p curve is shown in Figure 2. This characteristic defines C_p as a function of the tip-speed ratio (TSR) given by equation 3:

$$TSR = \frac{\omega_s R}{V} \qquad (3)$$

where R is the radius of the wind turbine rotor.

Wind turbine operation is limited by its TSR. The upper limit of the TSR is based on noise generated by the wind turbine. A larger wind turbine operates at a lower rpm. As an example, a typical 10-kW wind turbine operates at about 300 to 500 rpm rated, while a 300-kW wind turbine operates at about 50 to 60 rpm.

COGGING TORQUE CONSIDERATION

Wind Turbine Start-up:

From the power equation shown in equation (1), it is apparent that the wind turbine should operate at the highest Cp at any wind speed. During start-up, when the rotor speed (ω_s) is very low, as shown by equation (3), the TSR is also low. From Figure 3, at low TSR, the resulting Cp is very low, thus the aerodynamic power is low. Therefore, it is desirable that during start-up the cogging torque of the PM generator is low enough that the aerodynamic power can overcome it. Otherwise, with a large cogging torque, the wind turbine may never come out of stall mode and may never start.

Wind Turbine Running Condition:

Small wind turbines typically have lower rotor inertia than large turbines because of their shorter blades and lower mass. Thus, the cogging torque excites the structure of the wind turbine and the smoothing effect of inertia is not very dominant. This is particularly apparent in a small wind turbine during low wind speeds when the rotor rotational speed is low. Noise and mechanical vibration may be excited by the cogging torque. This type of vibration may threaten the integrity of the mechanical structure of an improperly designed small wind turbine. In high wind speed, the amount of torque and the kinetic energy stored in the rotor is sufficiently large that the cogging torque is insignificant.

Uniform Air Gap versus Nonuniform Air Gap:

The rotational speed of a direct-drive electric generator for a wind turbine is usually lower than conventional grid-connected electric machines. With direct-drive operation, the rotor rpm is slow, requiring many poles to operate. With many poles, the width of the magnet pole is very short. Thus, even with a flat magnet surface, the rotor has almost uniform air gap. The magnet can also be shaped to get a uniform air gap.

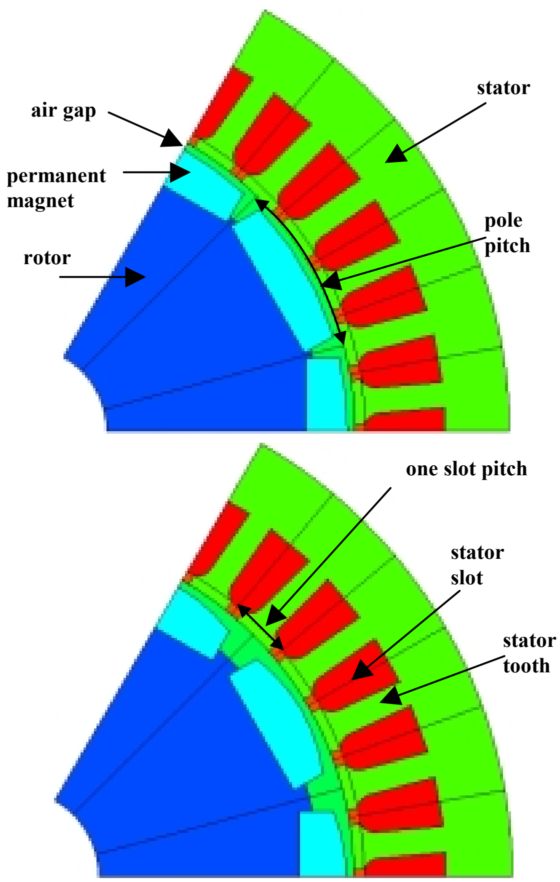

Figure 3. Permanent magnet with different shapes
a) Top = uniform air gap
b) Bottom = nonuniform air gap (bread loaf)

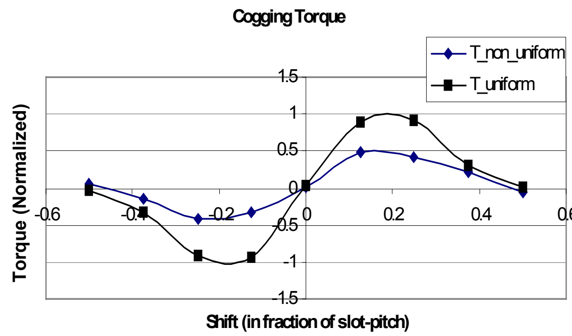

Figure 4. Cogging torque for uniform air gap and for nonuniform air gap

The cogging torque can be minimized if the shape of the magnetic pole is formed like a loaf of bread, thus creating a nonuniform air gap. A comparison between uniform air gap and bread-loaf type permanent magnet surface is illustrated in Figure 3. As shown in Lao et al.[11], the shape of the pole surface (i.e., bread loaf) can be optimized to reduce the cogging torque.

In Figure 4, a comparison of the normalized cogging torque between uniform air gap and nonuniform 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.

Pole Width to Pole Pitch Ratio:

In this paper, the original shape of the pole surface and the design of stator lamination are kept unchanged for the entire investigation. While maintaining the pole-pitch and the shape of the pole surface, the width of the

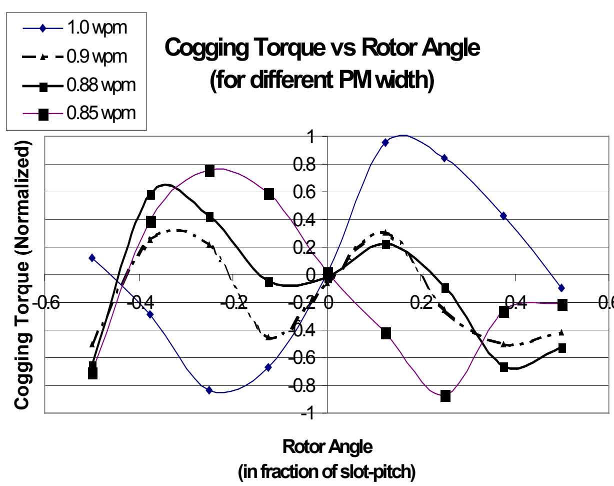

Figure 5. Cogging torque for different magnet width for nonuniform air gap

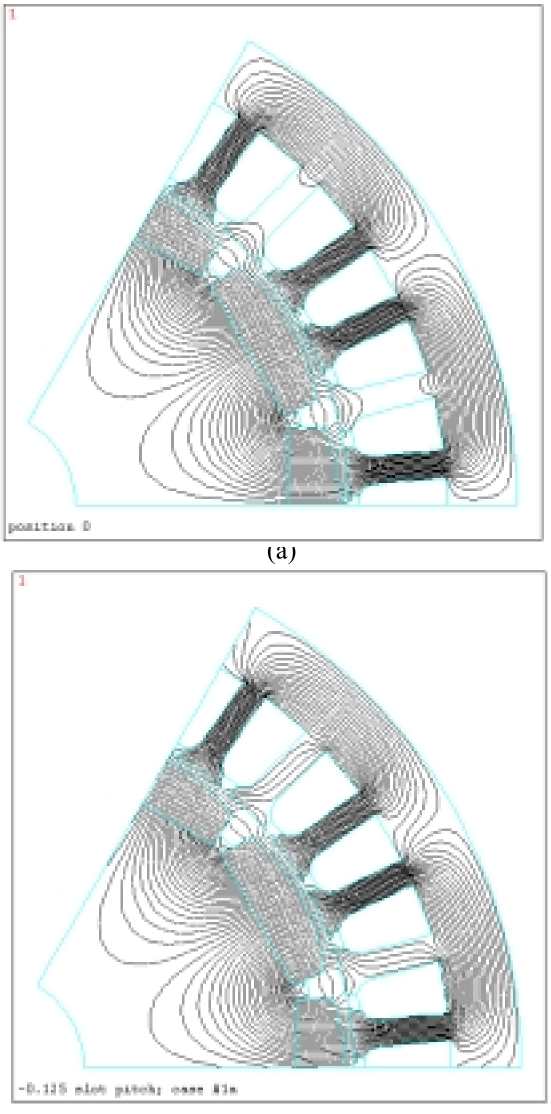

Figure 6. Flux lines in the generator

a) Minimum cogging torque position

b) Maximum cogging torque position

magnet pole is truncated with respect to the original width. The cogging torque is computed for different rotational angles (in fraction of slot pitch). The width of the pole is normalized to the original width of the pole.

Figure 5 shows how the cogging torque varies with the rotational angle as the width of the pole is changed. It is shown that there is a size of the pole at which the cogging torque is minimized. It is interesting to observe that as the width of the pole is close to the optimum width, the shape of the cogging torque changes. The frequency of the cogging torque doubles at optimum width. As the width is reduced lower than the optimum width, the cogging torque starts to increase in magnitude again and the frequency is back to the frequency of the cogging torque at the original width.

As an illustration, the flux lines in the generator for two different rotor positions are presented in Figure 6. In Figure 6a, the flux lines are shown for minimum cogging torque position. The flux lines are symmetrically distributed. Figure 6b represents maximum cogging torque position.

Skewing Effect:

Cogging torque can be reduced by skewing the stator stack or skewing the magnet pole. Skewing the stator stack is to spatially skew one end of the stator stack a few degrees with respect to the other end of the stack. Usually a full skew of one slot pitch is implemented to reduce the cogging torque. One slot pitch is an arc covering one slot and one tooth of the stator. In general, skewing PM generators can eliminate the cogging torque. However, skewing can add complexity to the manufacturing process, thus additional cost of the final product can be expected. Skewing the magnet requires that the magnet be shaped properly, which may add to the manufacturing cost. Skewing the stator may complicate the winding installation, reduces the effective slot area, and increases the conductor length (e.g., increases the stator resistance).

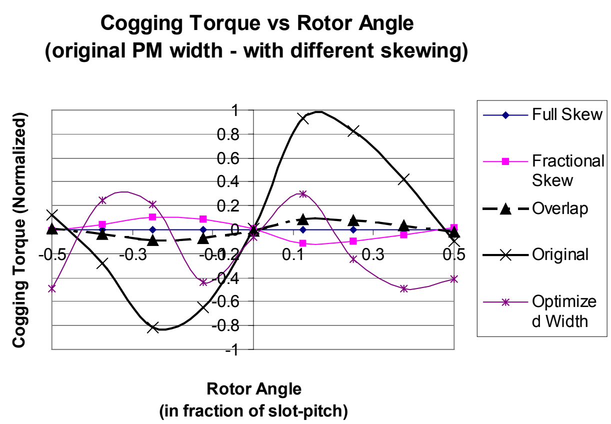

Figure 7. Cogging torque as a function of rotor angle at different skewing angle

Figure 7 shows the variation of cogging torque when the stator of the generator is skewed in a fraction of the rotor slot pitch (fractional skew). The nonuniform air gap is used and different degrees of skewings are presented. The cogging torque is normalized to the peak cogging torque of the original width without skew. A full skew of one slot pitch is presented as the reference. Fractional pitch covers only 87.5% of the full skew, while overlap covers 112.5% of the full skew. As a comparison, the optimized magnet width is also presented on the same graph. The graph shows that the skewing angle plays an important role in reducing the cogging torque. The closer the skewing angle to a full skew, the smaller the resulting cogging torque. It is shown that controlling the magnet width does not eliminate the cogging torque completely.

CONCLUSION

This paper presents an overview of small wind turbine generators and the importance of minimizing cogging torque. 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 nonuniform (bread loaf) pole shape of the permanent magnet appears to reduce cogging 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 aerodynamic 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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