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Cogging torque reduction by optimal design of PM synchronous generator for wind turbines

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ABSTRACT

In this study, design and optimization of a surface-mounted permanent magnet synchronous generator (PMSG) have been carried out for use in low power wind turbines. In the successive optimization steps based upon the parametric solution method, design parameters of skew, pole embrace, and pole arc offset are chosen to be optimized so that the cogging torque is reduced. Cogging torque is a type of torque ripple coming from the machine design and causes undesired vibration and acoustic noise during the operation of machine. Moreover, although the effect of cogging torque in high power surface-mounted PMSGs is not sensible, it becomes important in low power applications to maintain good dynamical behavior. Analytical and finite element analysis (FEA) are conducted after obtaining the magnet structure that provides minimum cogging torque. Electrical and electromagnetic distributions are presented according to the changes in the corresponding design parameters. While the cogging torque in the initial design is 522.7 mNm, it has been reduced to 49.1 mNm in the optimized generator, which in turn means an improvement of about 90%. The generator under consideration has the specifications of 2.5 kW, 120 V, 14-pole with an inner type-rotor.

Introduction

The need for energy sources to meet energy requirements emerged from growing-population and developing technology is going up day by day. Nowadays, due to the reduction of fossil fuels in electricity generation and increase in environmental awareness, popularity of renewable energy sources (RESs) has increased. Renewable energy is basically defined as energy coming from resources which are naturally replenished on a human timescale, such as wind, sunlight, rain, waves, tides, and geothermal heat. Due to being cheap, local, environmentally friendly, and for energy diversification, many studies and intensive work have been devoted to this field all over the world to benefit from RESs [1–4]. It can be said that renewable energy barters conventional fuels in four different fields: electricity generation, air and water heating/cooling, motor fuels, and rural (off-grid) energy services. RESs do exist over wide geographical areas, unlike other energy sources, which are gathered in a limited number of countries. Crucial energy security, climate change mitigation, and economic benefits are the cause of rapid deployment of

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renewable energy and energy efficiency issues. According to international public opinion surveys, encouraging to use RESs, such as solar power and wind power, is strongly supported. Among RESs, wind energy plays a significant role in solving energy crisis and environmental problems, and there has been a notable increase in the use of wind energy for the last ten years [5–7].

Wind energy is a kind of energy extracted from solar energy. Winds forming the wind energy are produced by the unbalanced heating of the atmosphere by the sun, the abnormal shapes of the earth's surface, and rotation of the earth. The resulting air flow or motion energy can be used to generate electricity, when captured by means of wind turbines, which are capable of converting the kinetic energy in the wind into the mechanical energy. As a result, this mechanical power is then converted into the electrical power by using generators. As the generator electrical characteristics have significant impact upon energy quality and efficiency, this issue should be taken into account during the design process of generators [3,6].

Various kinds of generators can be used in wind turbines and each has advantages and disadvantages on its own. The details related to those generators can be found in Ref. [8]. Having a high energy density in parallel with permanent magnet (PM) technology, PMSGs are increasingly used in renewable energy applications. In addition, more than half of the world's top 10 turbine manufacturers are interested in permanent magnet generator technology or already selling PMSGs to the market because of permanent magnet technology offers advantages such as low speed without gearbox which is direct drive technology, high efficiency and high torque with less volume. It also have low synchronous inductance [9–11].

Cogging torque is the torque due to the interaction between the permanent magnets of the rotor and the stator slots of a PM machine when the phase currents are zero. It is also known as detent or 'no-current' torque. Cogging torque is an undesirable component in electrical machinery and it gives rise to vibration and acoustic noise [12]. Lots of methods are presented to reduce cogging torque in the related literature. Potgieter and Kamper showed the effect of yoke heights and material type over the cogging torque [13]. Hemmati and et al. optimized the value of cogging torque using non-dominated sorting genetic algorithm by selecting the values of pole embrace, pole thickness and pole offset as the optimization parameters, where finite element method (FEM) was used for the calculation of cogging torque and air-gap flux density. By the optimization, the amount of magnet used was also diminished [14]. Zheng and et al. reduced the torque ripples by 8.7% and increased the output torque by 3.2% of a PM synchronous motor used in air conditioning compressors by optimizing the components of magnetic pole embrace, magnetic bridge and magnetic pole eccentricity using the FEM [15]. By examining the effects of permanent magnets with three different geometries over the cogging torque, Lin and et al. stated that two-step magnet skew reduced the cogging torque component [16]. They also found that magnets with sine-shaped structure contained low cogging torque effect and low back-emf harmonics, though these types of magnets decreased the average output torque level. For a four-pole permanent magnet synchronous machine, Trifu and et al. managed to reduce the cogging torque below 1% of the rated torque by optimizing the cogging torque by keeping the magnet and stator geometry constant. At the end of their study, they pointed out that among the methods used in the study, the most effective one was to adjust the outer radius of curvature of the magnet [17]. Yan and et al. remarked that the cogging torque is greatly influenced by the ratios of stator and rotor circumferential widths to pole pitch [18]. Other methods related to the reduction of cogging torque is to use surface-mounted permanent magnets with discrete skew angle, slot and pole number combination and magnetic pole shifting [19,20].

In this study, using FEA, a PMSG with a rated power of 2.5 kW has been designed for efficient use in wind turbines. In the study, it is preferred to design a generator with low power and high pole number especially suitable for small-scale applications, e.g. for use on private fields and farms where electrical energy is required. As the optimization method, parametric approach method is used, in which a starting point and an end point are determined for the variable to be optimized and then a step-by-step solution is performed within the specified precision. After the initial design stage, using the parametric solution method, design parameters of skew, pole embrace, and pole arc offset that have a crucial impact on the generator performance have been optimized to obtain a generator with reduced-cogging torque component.

The organization of the paper is given as follows: Section Output equations of PMSG shows the design of PMSG with given equations. Section FEM analysis and optimization of generator provides the FEM analysis and optimization of PMSG, and Section Conclusion concludes the paper.

Output equations of PMSG

Design of electric machines generally begins with the sizing equation as in Eq. (1) [21]. In machine design, specifically, selection of specific electrical and magnetic loading directly affects the machine performance. Nonetheless, there is no direct restriction in the selection of these parameters. It is the common and general way to consult the designer's experience and knowledge.

$$S = 11 \cdot K_{w1} \cdot \overline{B} \cdot ac \cdot \left(\frac{D}{1000}\right)^2 \cdot \frac{L}{1000} \cdot N \qquad (1)$$

where,

S: power (VA)
$\overline{B}$: specific magnetic loading (T)
ac: specific electrical loading (A/m)
D: stator outer diameter (mm)
L: generator stack length (mm)
N: generator rated speed (rpm)
K_{w1}: winding factor

The equivalent circuit of the three-phase star-connected PMSG is given in Fig. 1.