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Development of rare earth free permanent magnet generator using Halbach cylinder rotor design

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ABSTRACT

Direct-drive permanent magnet generators (DDPMGs) offer increased reliability and efficiency for wind turbine application over the more commonly used geared doubly-fed induction generators. However, deployment of DDPMGs is limited in the U.S. wind industry due to reliance on NdFeB permanent magnets, which contain critical rare earth elements Nd and Dy. To allow for the use of lower energy density, rare earth free permanent magnets, Halbach cylinders are employed as the rotor in a 3.5 kW PMG to concentrate magnetic flux over the rotor surface and increase magnetic loading. By varying the slot-to-pole ratio in Halbach PMGs (HPMGs), designs are developed, which allow for the use of ceramic, or hard ferrite, strontium iron oxide permanent magnets. At the 3.5 kW scale, the ceramic HPMGs are able to achieve rated performance at reduced average efficiency of between 82 and 87%, which is due to the difference in permanent magnet material properties. For scaling of the ceramic HPMGs to 3 MW, rated performance and high efficiency were achieved on average at rated speed, demonstrating the potential for a rare earth free PMG in commercial scale wind turbines.

1. Introduction

The U.S. Department of Energy (DOE) has recommended the advancement of wind turbine drive train technology, including direct-drive permanent magnet generators (DDPMGs), to achieve the long-term goal of 35% wind electricity generation in the U.S. by 2050 [1,2]. Currently, the majority of wind turbines in the U.S. employ geared doubly-fed induction generators (DFIGs) for conversion of mechanical to electrical energy [1]. However, gearboxes account for the most downtime per failure in wind turbines, significantly increasing operation and maintenance costs [3]. By eliminating the gearbox, DDPMGs increase reliability and decrease operation and maintenance costs [4,5]. DDPMGs also have higher efficiency at both full and partial load than geared DFIGs [4,5]. Yet, as of September 2015 DDPMGs were only employed in less than 1% of utility scale (>100 kW) wind turbines in the U.S. wind industry [6].

NdFeB permanent magnets, used as the magnetic flux source in PMGs for wind turbines, contain rare earth elements Nd and Dy. Partial substitution of Dy for Nd in the NdFeB alloy is performed to increase anisotropy, which increases coercivity and temperature coefficient, allowing for high-temperature application without risk of demagnetization [7]. Nd and Dy are considered “critical materials” by the DOE due to their supply risk and importance to renewable energy technologies [8]. This presents a major barrier to their increased deployment in the U.S. as an estimated 250–600 kg of permanent magnet material per MW is required [8,9]. Elimination of rare earth NdFeB permanent magnets in DDPMGs is desirable to allow for their increased use in the U.S. wind industry.

1.1. Background

To generate rated power, DDPMGs must generate high torque at low speeds as described by Equation (1).

$$P = T\omega \tag{1}$$

$$T = KBAV_r \tag{2}$$

where P is power, ω is rated speed, T is torque, K is the output coefficient, B is the magnetic loading, A is the electric loading and V_r is

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Table 1
Typical properties of commercial permanent magnets [12].

	B_r (kG)	H_c (kOe)	BH_{max} (MGOe)	T_m (°C)
NdFeB	10.8–14.9	11.0–34.0	28–54	220
SmCo	8.7–11.6	8.2–10.9	18–31.5	350
Hard Ferrites	2.0–4.1	1.57–4.0	0.8–4.32	300
Alnico	6.6–13.2	0.475–1.475	1.35–10.5	538

rotor diameter [10,11]. To generate high levels of torque at low speeds, large rotor volumes and high energy density NdFeB permanent magnets, which increase the magnetic loading *B*, are used. The magnetic loading *B* is defined as the average magnetic flux density over the rotor surface [10,11].

Permanent magnets have four figures of merit including the remanence B_r, coercivity H_c, energy product *BH*, and maximum working temperature T_w. The remanence B_r is the residual magnetic flux density remaining after an applied magnetic field is removed. The coercivity H_c is the magnetic field strength required to demagnetize the permanent magnet. The energy product *BH* is the energy density and the maximum working temperature T_m is the maximum temperature the permanent magnet can operate at without becoming demagnetized. Rare earth permanent magnets such as NdFeB and SmCo have the highest energy product, or energy density, of all commercial permanent magnets (Table 1). Rare earth free permanent magnets, such as hard ferrite (ceramic) permanent magnets require much more volume to produce the same magnetic flux. Thus, for the same volume, magnetic loading will be significantly reduced for the use of ceramic permanent magnets.

To maintain magnetic loading in a PMG when using lower energy density ceramic permanent magnets, the magnetic flux must be concentrated over the rotor surface. By concentrating magnetic flux over the rotor surface, the magnetic flux density can be increased without the need for a stronger permanent magnet, or increased permanent magnet volume. Halbach arrays can be used to concentrate magnetic flux [13,14]. A Halbach array is an arrangement of permanent magnets that causes magnetic flux to be concentrated to one side of the magnet array (Fig. 1a). Halbach arrays can be arranged in a cylinder, denoted as Halbach cylinder (HC), as shown in Fig. 1b to focus magnetic flux inside or outside of the cylinder. When used in machine application, HCs offer the benefit of sinusoidal airgap flux density and back-EMF, and the possibility of elimination of the rotor back-iron [15,16].

In part due to manufacturing costs, HCs have been limited in application. For a review of these applications, the reader is referred to reviews by Zhu and Howe [15,16]. The potential benefits of HCs in PMGs for wind turbines, especially elimination of rare earth permanent magnets, may make the trade-off for increased manufacturing costs worthwhile. Thus, we have investigated the use of HCs to accomplish this.

In this paper, we found PMG designs that increased magnetic loading, and consequently torque, by employing a HC as the rotor. Ceramic permanent magnets were substituted as the permanent magnet material in these designs and their performance was investigated at the 3.5 kW and 3 MW scale.

2. Methodology

Halbach PMGs (HPMGs) with a rated power of 3.5 kW were designed by employing a HC cylinder as the rotor, eliminating the rotor back-iron (Fig. 2). The number of magnetic poles (1 magnet segment per pole) was varied in allowed multiples of 4 (for a 24 slot machine), giving HPMGs with 4, 8, 16, 20, 28, 32 and 44 poles. The HCs used the magnetization scheme depicted in Fig. 1b (rotation of the magnetization by 90°) for all design variations. NdFeB 32/31 permanent magnets (see Table 3 for properties) were used initially to find designs that increased magnetic loading sufficiently to allow for the use of ceramic permanent magnets by varying the slot-to-pole ratio for each design variation to optimize the efficiency of the magnetic flux path between the rotor and stator. Rotor volume, permanent magnet material volume, outer diameter, stack length, airgap length, and machine ratings were kept constant (Table 2) and were based on a design for a surface mounted PMG [17]. The dimensions of the inner stator were adjusted accordingly for each design to maximize efficiency.

Finite element methods were used to calculate the torque, input and output power, airgap flux density, magnetic loading, and cogging torque as a function of the rotor position, employing 2D steady-state, motion analysis in MotorSolve™ by Infolytica Corporation. The advance angle was set to 180° to allow for simulation of generator operation at rated speed (333 rpm) and rated current (100 A). 24 sampling points per period for the best periodicity, 5 skew samples, and a harmonic amplitude threshold of 1×10^{-6} were used. Efficiency was calculated simply by taking the average output power over the average input power. Finite element methods were also employed to determine the time-averaged hysteresis and eddy-current losses in each conducting component (stator windings and yoke) with 2D steady-state, motion analysis in MagNet by Infolytica Corporation™. Instantaneous windage losses were determined in MotorSolve™. Stray losses and thermal effects are ignored in these calculations.

For NdFeB HPMGs with rated power of 3.5 kW that achieved more than twice the value of rated torque and power, ceramic 11 (C11), a strontium iron oxide grade permanent magnet, was substituted as the permanent magnet material in the HPMGs. No

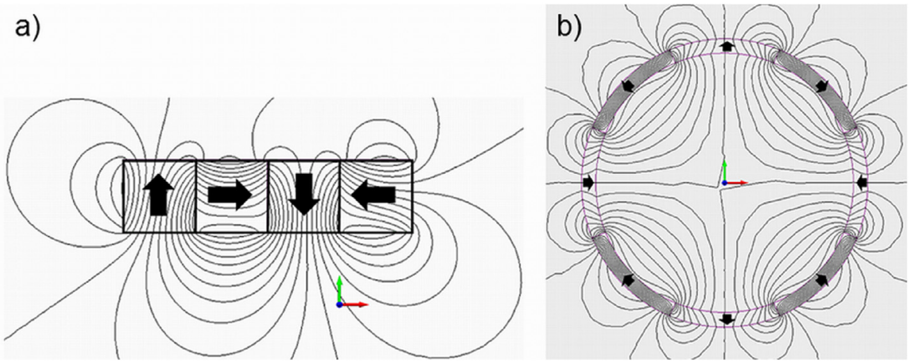

Fig. 1. Magnetic flux profile of a) 4 segment Halbach array and b) 8 segment Halbach cylinder. Arrows indicate magnetization direction.