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Waveform characteristics and losses of a new double sided axial and radial flux generator

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ABSTRACT

In this paper, the waveform characteristics and the losses of a new three phase permanent magnet generator, which has a rated power 250 W at 1000 rpm have been explored theoretically and experimentally. The proposed generator has new flux morphology with the axial and radial directions, therefore the waveform characteristics become important for this new machine. The detailed phase voltage measurements prove that the machine generates sinusoidal waveform and the total harmonic distortion (THD) is found to be sufficient for such a new prototype machine. According to the detailed experimental measurements, the machine has THD values of 0.4% and 4.7% for resistive load and no-load cases. In addition, the losses and the efficiency measurements are found to be very promising although the airgap optimization has not been completed. According to the simulation studies, the machine has the core and copper losses of 2.5 W and 23 W for loaded cases, respectively.

Introduction

The motivation on the axial flux permanent magnet generators (AFPMG) enhances due to their compactness, high power densities and natural cooling mechanisms [1]. The invention of the first axial flux generators went to 150 years before [2]. Indeed, the production of the NdFeB magnets has accelerated the motivation for the design and generation of new permanent magnet (PM) machines from 1980s and this trend still continues due to some advantages of the PM usage [3]. Frankly speaking, PM machines have better power density and cogging torque value, cheaper construction and higher moment values [4]. Besides, the phase waveform can be obtained sinusoidal from the output [5–7]. For instance, although the power densities change from one machine to the other, the machines with power densities from 6 kW/m^3 to 710 kW/m^3 can be encountered in literature [8].

In reality, the geometry and flux topology are the key points to increase the power densities in AFPMG. For instance, Vansompel, et al. [9] explored the effects of core shapes, laminations over the efficiency in an AFPMG by using FEA. In addition, the effect of airgap and the core losses were also investigated by the same group by using the same method in terms of efficiency. It has been known that the core mass and volume should be minimized in the designs since it affects the

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weight, efficiency and compactness of the machine [10]. In AFPMGs, the stators and rotors can be designed in many combinations. They can be double sided as in our research, or more stators and rotors can be added [11]. The double sided machines become much energetic than the single sided ones due to the coil numbers [12].

The machines can be designed with different core types. They can be designed as slotted or slotless. In most of the designs, the laminated cores are used. While the slotted cores assist to decrease the cogging torque, slotless designs manage to lower the mutual and loss inductances [13]. However one should keep in mind that the magnetic force between the cores and magnets should be optimized in order to decrease the cogging torque [14]. Indeed, the magnetic force causes extreme mechanical stress and vibrations in the machine, the air gaps in axial machines should be larger than those of radial flux ones [12]. The airgap can be designed from 1 mm to 4 mm with respect to the mechanical processing. It should be noted that the airgap affects the entire output of the machine [15]. Thus, the airgap optimization should be performed in a new design [16]. In the coreless machines, the windings should be put into a non-magnetic and insulating material such as epoxy, polyamide, etc. Due to the lack of the cores, there exists no core loss and cogging torque and the machines becomes lighter. However, there can be eddy losses at higher speeds in the windings [16]. On the other hand, the disadvantage of the machine is the low magnetic fluxes Φ compared to the machines with cores and high copper losses. These are the main factors to decrease the efficiency of AFPMGs [17]. The lower airgap values cause higher power (P_{out}) as a result of inducting higher voltages in the windings [18]. Whereas forming a stable airgap between the rotors and stators is hard in the axial machines.

AFPMGs are especially appropriate for medium speed applications; therefore they can be used in robotics, electrical vehicles, trains, etc [19]. In wind energy applications, they are preferred to neglect the gear systems in the turbine. Comparing the axial flux machines with the radial ones, axial flux machines have lower cogging torques and volume and higher power density and efficiency [20]. In addition, the installation of axial flux machines is easier than the radial ones due to the direct addiction to the blades. Jian and colleagues [21] found that the heating of the AFPM machines could be caused by their higher power densities. Therefore, an efficient geometry for the rotors and stators should be designed and the large rotor and stator surfaces of these machines can also help to solve this problem [19]. The air gap is also vital to overcome from this heating problem [2]. However the key point in the design is to determine the appropriate shape of the permanent magnets, since all shapes of the magnets cannot give perfect sinusoidal output. The use of Nd-based magnets has an advantage on the determination of their shapes. Technically, it is possible to produce different shapes of magnets [22]. There can be different types of combinations for the stator and rotor designs. For instance, rotor can be one sided and stators can be double sided or vice versa [10,11]. However, the important point is that the double sided machines can have double energy generation relative to the one sided ones [23].

In this study, we report the recent analyses on the losses and the harmonic analyses of the new AFPMG. Design of Generator section gives a brief explanation on the design and specifications of new machine. Theoretical background on basic connection of phases and losses are given in Theoretical background Section. Experimental Section represents the experimental details of the generator. The main findings on the experiments and simulations are reported in the next section. Finally, the paper ends with the concluding remarks on the findings of the study.

Design of generator

In this work, the design and implementation of an axial/radial flux PM generator with three phases are reported. Initially the designed machine is depicted in Fig. 1. The machine has double rotors at the upper and lower parts and a stator is situated between these rotors. The stator has three main units in order to provide a stable machine especially at high rotations.

The rotors are connected to each other and rotate at two sides on the same shaft. The design has a specific laminated core structure and it has been proven in Ref. [22] that this structure gives lower cogging torque values. Note that the small laminated cores have certain advantages on the machine weight and eddy currents. Since the cores are slotless, they are easy to produce, technically.

The windings, magnets and cores have circular shapes. Since the machine is a three phase one, the design consists of 16 magnets and 12 windings and cores. Note that two windings sit on each core (Fig. 2). In the design, an air gap of 5 mm is used. Due to many air gaps inside the stator unit and air gaps between the rotor and stator, the design has an efficient natural cooling mechanism on the large rotor and stator surface.

The B–H curve of the core material is presented in Fig. 3. The core material has high flux density value up to 1.5 T, which is already sufficient for our application. In the entire FEA simulations, this curve is used for the core characterization.

Each core has 40 laminated layers with the thickness of 0.5 mm each. Note that 40 layers are combined together in axial direction, thus the flux loss is minimized in the axial direction. The coils are positioned as in Fig. 2. In order to decrease the copper losses, circular shape windings are preferred in the design as mentioned in Ref. [23]. Another design advantage is that the windings on the circular shapes can be produced easily than the trapezoidal or triangular ones. The magnets are located symmetrically near the upper and lower ends of the cores in N–S–N–S orientation with opposite

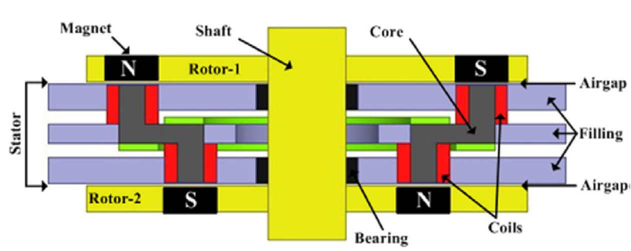

Fig. 1 – A new AFPMG design and units.