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Electromagnetic design of a new axial and radial flux generator with the rotor back-irons

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ABSTRACT

The design and simulation of a new three-phase axial flux generator have been performed. The generator is a permanent magnet machine (PMG) and consists of two rotors at two sides and a stator at the middle. In the machine, each rotor has 16 rare earth disc-type magnets and back-iron units and the stator at the middle has 24 coils. It has been understood that the generator produces directly sinusoidal output and requires no conversion in the wave shape. The 3D simulations have been performed via the finite element analysis (FEA) method by the magnetostatic and magnetodynamic tools. It has been found that the machine generates 3.4 kW at 1000 rpm for the air gap of 1.5 mm. This gives the power density of 336 kW/m^3 for the rated value of the generator and it is higher than the power densities of many axial flux generators in the literature. The maximal cogging torque value has been estimated as 3.6 Nm, which is a good value for a back-iron machine. It has been also proven that the waveform harmonics become lower at higher rotor speeds.

Introduction

The use of rare earth elements in the production of permanent magnets (PMs) has accelerated the permanent generator production. That has enhanced the importance of permanent magnet synchronous machines (PMSM) in the wind energy market. PM generators became popular in 1980's, after NdFeB magnets were invented [1,2]. Since higher energy densities, low cogging torque value, low cost and high mechanical torque can be available with these machines, the PM generators have been used in many applications [3,4].

According to the literature [5], PM generators have some superiorities over the asynchronous or current excited synchronous generators. Efficiency, stability and reliability comes in the first order to study on these generators [5]. They even can produce direct sinusoidal current and that is counted among the other advantages [6]. Strictly speaking, two distinct PMG structures are found in the literature: Axial flux and radial flux PMGs. If the flux goes through the coils in the radial direction, that is a radial flux generator, however if the flux

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passes perpendicular to the radial direction, it is an axial flux machine [7]. Indeed, the flux direction becomes parallel to the moving axis in the latter structure.

The axial flux machines become appropriate for especially medium speed applications. This reality makes them useful in moment control, machine units, robotics, electrical vehicles as well as wind energy [8]. According to the researches, they have another advantage on wind energy applications since these generators do not require an additional gear system inside the wind turbine [1,9,10]. It means that the rotation effect can be directly applied on the generator via the turbine blades. In addition, the rotor speed and power densities do not exhibit a basic correlation. There exist many studies on different types of axial generators with various power densities. Basically the power densities can have values from 6 kW/m^3 to 700 kW/m^3 [11].

In a previous design [6], Kurt et al. studied a radial/axial flux generator having one phase and 12 poles. In this generator, they have observed a power density of 28.5 kW/m^3. However this machine was not a preliminary design of a new type core and the effect of this new core on the cogging torque has been studied compared to a bar-shaped core. It has been proven that the new core has certain advantages over the bar-shaped one in order to decrease the cogging torque values. This one phase machine has maximal output power for 5 Ω and increasing efficiency for high rotor speeds upto 1000 rpm. According to simulations, the machine has a cogging torque value of 25 mNm which is nearly the half of the bar-shaped core. Besides, the experimental output has proven that the signal type is sinusoidal and has some harmonics for lower rotor speeds as result of mechanical contact [6].

In the electromagnetic designs, the moving units of the machines, especially rotors should be mechanically durable and light. Indeed, these units are the important parts to determine the operational life of the machine, which becomes much vital for medium and high rotation speeds. However, in the case of the stator part, the magnetic flux over the stator coils and the frequency of the stator current are important [12]. All these factors may cause problem in high speeds and they can be solved by good mechanical and electromagnetic designs.

In the case of conventional axial flux PMGs, they have lower cogging torque, higher power density and efficiency, easy maintenance, lower volume and cost [9,13–17]. The machine designs still focus on lowering cogging torque, increasing the electrical power and efficiency, whereas, as an important artifact, AFPMGs have a cooling problem [18]. Indeed the cores, coils and stator units get heat due to the magnetic flux rotation inside the cores and current circulation in the windings. For instance, according to Li and his colleagues [14], high power density causes heating problems in PMGS. Therefore an appropriate mechanical design should be explored to cool down them. One way is the adjustment of air gap distance, since it assists to decrease the cogging torque, acoustic noises and mechanical vibrations [19]. Other way is the shape of the core, since it affects the cogging torque. Another solution is to decrease the losses in the machine. With that regard, Vansompel and his colleagues [10] investigated the efficiency of an axial flux machine in terms of core mass, shape and lamination. They proved that the varying air gap can decrease the core losses within the rate of 8% and assists to improve the efficiency for continuous working conditions [20].

In the present paper, we report the results of a new designed three phase axial/radial flux machine. Mainly the new machine uses a different core shape. The coils have different winding numbers and the diameters of the rotors are certainly different. Section Design properties of new AFPMG introduces the units of the machine. The electromagnetic 3D simulations and transient solutions over flux, flux density, voltage and power are presented in Section Magnetostatic simulations of PMG. Finally, the concluding remarks are given in the conclusions.

Design properties of new AFPMG

In order to produce the design and simulations, a finite element programme has been used. In the simulation environment, the definition of the simulation volume and machine units with the corresponding meshes, the material characteristics are performed to all units. Table 1 presents the design parameters of new generator. The stator unit has two types of windings attached to both tips of the cores.

While one series have larger winding numbers (i.e. 300), other series have lower winding numbers (i.e. 200). However, if the serial connection is provided among the series, there exists no waveform difference between two serial connected coils. Indeed, the coils with larger sectional areas gives larger amplitude compared to the smaller one.

The air gap is adjusted as 1.5 mm for two sides of the stator located at the middle. The cross-section view of the PMG is shown in Fig. 1. Two rotors are positioned on the upper and

Table 1 – Design parameters of the machine.

Components	Features
Inner radius of rotor R_2 (mm)	75
Outer radius of rotor R_2 (mm)	105
Inner radius of rotor R_1 (mm)	120
Outer radius of rotor R_1(mm)	150
Inner radius of stator disc (mm)	70
Outer radius of stator disc (mm)	155
Thickness of *back-irons* (mm)	5
Radial width of *back-irons* (mm)	40
Coil inner diameter (mm)	30
Small coil outer diameter (mm)	46.4
Large coil outer diameter (mm)	69.6
Phase	3
Winding turns for large coil	300
Winding turns for small coil	200
Coil number	24
Wire diameter (mm)	0.75
Magnet type	NdFeB
Magnet shape	Circular
Magnet number	16
Magnet diameter (mm)	30
Magnet thickness (mm)	5
Core material	M19
Core type	Axially/radially laminated
Core number	12
Air gap (mm)	1.5