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Analysis of brushless DC generator incorporating an axial field coil

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A B S T R A C T

This paper describes the magnetic analysis and experiment of a three-phase field assisted brushless DC (BLDC) generator. Unlike conventional BLDC generators, the permanent magnet is replaced with an assisted field winding. The stator and rotor are constructed with two dependent magnetically sets, in which each stator set includes nine salient poles with coil windings, and the rotor comprises of six salient poles. Other pole combinations also are possible. This construction is similar to a homopolar inductor alternator. The DC current in the assisted field winding produces axial flux which makes the rotor magnetically polarized at its ends. The magnetic field flows axially through the rotor shaft and closes through the stator teeth and the machine housing. To evaluate the generator performance, two types of analysis, namely the numerical technique and the experimental study have been utilized. In the numerical analysis, 2-D finite element (FE) analysis has been carried out using a MagNet CAD package (Infolytica Corporation Ltd.), to confirm the accuracy of the predicted flux-linkage characteristics, whereas in the experimental study, a prototype BLDC generator was constructed for verifying the actual performance. Furthermore, the evaluation method based on a hybrid numerical method coupling the finite element (FE) analysis and boundary element (BE) method, has been carried out to confirm the accuracy of the 2-D FE analysis simulation results. It provides not only confirmations of the investigation in results but also exact illustration for magnetic field distribution for this complex generator geometry.

1. Introduction

Variable speed permanent magnet brushless DC (BLDC) machines offer many advantages including compact form, high efficiency, robustness to harsh environment, low maintenance and easy manufacturability [1,2]. BLDC machines are used in industries for different applications such as, wind energy, automotive, aerospace, home appliances and many industrial equipment and instrumentation [3,4].

Fundamentally, a BLDC generator produces out-put power characteristics very similar to the classical separately excited DC generator. The stator of a BLDC generator consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery or around stator salient poles. In the conventional BLDC generator, excitation is provided by permanent magnets mounted on a solid iron rotor [5]. This structure has some inherent disadvantages such as: loss of flexibility of field flux control, changing the magnetic properties of permanent magnets when subjected to external magnetic fields and/or temperature changes, limited operating-speed range and high cost of the high flux density permanent magnets. These problems have been addressed by many researchers [6,7].

In the case of variable speed application likes to wind energy and automotive applications [8], when conventional permanent magnet BLDC machine are used as generators, the output voltage will be of variable magnitude and frequency. Electronic converters are then necessary to obtain a regulated output voltage. The initial and maintenance costs of these converters are high [9]. Furthermore, wind energy systems based on synchronous generators [10,11], and also induction machines, especially the cage type [12,13] are widely used. For these kinds of electrical machines for a wide range of speed variation, an electronic converter as an interface between the generator and the grid, and also a voltage regulator to control the magnitude of the output voltage are needed. This is because of their structure with inherent inflexibility of field flux control. For such applications a machine with capability of field flux control to hold the output voltage at a desirable level for different speeds are suggested.

This paper presents characteristic analysis of a field assisted Salient-Pole BLDC generator, which does not use a permanent magnet in the rotor. The generator configuration is modified and designed based on having double layers of the stator/rotor and a stationary field assisted coil placed between them for achieving maximum output voltage as well as power for a certain machine volume. The electric machine is operated as an electrical generator by rotating the shaft, varying the amplitude and direction of current in the assisted coil, and extracting electrical energy from the stator winding. Unlike a permanent magnet generator, the field

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assisted coil brushless DC generator does not require complex circuitry for regulation output voltage, and it does not require a parasitic load for damping excess energy. For the two layers field assisted machine, the absence of windings and permanent magnets on the rotor support both high rotational speeds and high-temperature operation. Furthermore, the absence of permanent magnets on the machine structure reduces the machine cost. Varying the amplitude and direction of the current in the field coil can control the output voltage to a level between zero volts and the maximum voltage. Unlike a permanent magnet generator, the field assisted coil brushless DC generator does not require complex circuitry for regulation output voltage. The nature of this configuration makes it compatible with any application that requires variable-speed operation.

Complex geometry and non-linear properties of the proposed Salient-Pole structure is the main reason for calculation and analysis of the flux distribution inside the machine for different excitation currents and rotor positions. So, an accurate knowledge of the magnetization characteristics is essential for the prediction and evaluation of machine performance. In the numerical analysis, 2-D FE analysis has been carried out to confirm the accuracy of the predicted flux-linkage characteristics. Furthermore, the evaluation method based on a hybrid numerical method coupling the FE analysis and boundary equation (BE) method, has been carried out to confirm the accuracy of the 2-D FE analysis simulation results. For the experimental determination of the magnetic characteristics of BLDC machine, the flux density are measured in the teeth, furthermore the Output parameters of generator are measured for No-Load and under-load by different speed. This paper is managed the following manner.

Section 2 describes the principle of operation of the presented BLDC generator. Section 3 describes numerical analysis of magnetic field for BLDC generator. Next section describes methodology evaluation for flux density distribution. Section 6 puts forward an algorithm for design procedure of presented machine. Detailed experimental results on the prototype are presented in Section 7. Finally, conclusion is presented.

2. Two layer BLDC generator discription

The proposed Field assisted generator can be considered the dual of the BLDC motor that is presented in [14,15], although there are some important differences in control objectives and control implementation also in the field and phases winding. The BLDC generator of Fig. 1 has steel laminations on the rotor and stator. Fig. 1 shows a structure and a field flux path of proposed configuration ((a) 3-D field flux path, (b) 3-D cut view and (c) 2-D front view of proposed configuration by magnetic flux path). The stator and rotor are constructed with two dependent magnetically sets, in which the two sets are exactly symmetrical with respect to a plane perpendicular to the middle of the machine shaft. Each layer consists of nine stator poles and six rotor poles, respectively. Every stator and rotor pole arcs are 30°. This is a three-phase machine, therefore, three coil windings from one layer is connected in series with the other three coil windings in the other layer. There are concentrated windings placed around each salient pole on the stator. The coils around the individual poles are connected to form the phase windings. Number of turns for each phase winding is calculated and optimized for generator mode and a wire with suitable diameter for up to 10 A load current is utilized.

There is a stationary reel by a rotating cylindrical core, which has the field coils wrapped around it and is placed between the two-stator sets. The DC current in the assisted field coil produces an axial field which makes the ends of the rotor a north and south magnetically (Fig. 1c). The magnetic flux produced by the coils travels through the guide and shaft to the rotor and then to the stator poles, and finally closes itself through the machine housing (Fig. 1c). It is worth mentioning that, the number of stator poles and their configuration is completely different than that of the switched reluctance generator. A cut view and 3-D view of the machine are shown in Fig. 1a and b respectively.

The basic dimensions are: a rotor pole arc of 30°, a stator pole arc of 30° (rotor and stator pole arc are like to BLDC motor presented in [14,15]), and an air-gap length of 0.6 mm. For ease of manufacture, the diameter of the shaft is chosen to be 9 mm, the outer diameter of the rotor is 59.4 mm, and the length of the stator pole is 15 mm. To sum up the above design, the geometric parameters, which are summarized as in Table 1, appear to be reasonable for the constraints previously described.

The suggested configuration is to some extent similar to the switched reluctance (SR) machine, but it is worth mentioning that, the number of stator and rotor poles and their configuration, phases overlapping region, number of phases that can be excited simultaneously and commutator to excite the phases is completely different than that of the SR machine [16,17].

As mentioned before, for the proposed machine, the absence of windings and permanent magnets on the rotor support both high rotational speeds and high-temperature operation. Furthermore, the absence of permanent magnets on the machine structure reduces the machine cost. Varying the amplitude and direction of the current in the field coil can control the output voltage to a level between zero volts and the maximum voltage. Unlike a permanent magnet generator, the field assisted coil brushless DC generator does not require complex circuitry for regulation output voltage. The nature of this configuration makes it compatible with any application that requires variable-speed operation.

3. Numerical analysis of magnetic field for BLDC generator

Because of inherent non-linear magnetic characteristics and the doubly Salient-Pole structure of presented two layers BLDC machine, numerical methods must be used for the calculation of the magnetic field distribution and the prediction of the machine magnetization characteristics. So it's an essential part of design procedure [18]. The FE method, which has its root in variational calculus, and is a very useful engineering numerical method for the solution of boundary value problems defined over irregular boundaries. The method can be applied to solve both linear and non-linear problems, but is particularly powerful for non-linear problems that involve the field variables defined within a computational domain [19]. Due to FEM being a well known numerical method for field solution and design validation of Salient-Pole machine by complex geometry and non-linear properties [20]; it is used as efficient tools for accurate evaluation of the machine performance in the proposed configuration.

3.1. Field distribution background

Complex geometry and non-linear properties of the Salient-Pole field assisted structure is main reason for calculation and analysis of the flux distribution inside the machine for different excitation currents and rotor positions. So, an accurate knowledge of the magnetization characteristics is essential for the prediction and evaluation of Machine performance. In this section, field distribution analysis background for the proposed BLDC machine is presented.

3.2. Magnetic field theory

There are two common methods for solving magnetic field problems. One utilizes magnetic vector potential A, and the other