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Design, modeling and simulation of variable speed Axial Flux Permanent Magnet Wind Generator

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ABSTRACT

Variable speed wind energy systems using permanent magnet generators are increasingly becoming popular for both standalone and grid connected applications. Axial Flux Permanent Magnet Generators (AFPMG) are a relatively new class of generators which are being considered as effective alternative to conventional Radial Flux generators, especially in wind applications, owing to their special features and attractive benefits. This paper presents the design of an Axial Flux Permanent Magnet Generator well suited for variable speed wind applications. A 2000 VA, 240 V, 3 phase, 10 pole, 5 rps AFPMG with Single Stator Double Rotor configuration has been considered for the design and analysis. The behaviour of the AFPM wind generator is investigated for different wind conditions, through dynamic modeling and simulation. The comprehensive modeling of AFPMG along with the details of the models for the Horizontal Axis Wind Turbine (HAWT), drive train, speed controller and pitch controller have been presented. The complete system model is implemented on MATLAB/Simulink platform and simulations are carried out for various wind conditions. The response of the generator for both constant wind input and variable wind pattern have been presented and discussed. The functioning of pitch controller is also verified for high wind speed conditions.

Introduction

In the prevailing global energy deficit scenario, generating energy from renewable energy sources has emerged as the most viable and sustainable solution. Although the presence of renewable energy systems is ubiquitous in the present landscape of energy, the renewable energy sector is still beset with many technical issues. However, a strong commitment exists to address such issues and make the renewable energy option attractive and competitive compared to the conventional energy systems. In line with this, significant efforts are being made to maximise the production of energy from renewable energy sources while keeping the prime focus on improving their associated economic aspects.

Among the renewables, wind energy has historically been a front runner for both large scale and small scale applications, still holding huge scope for exploitation in many parts of the world. Wind energy conversion systems have undergone vast transformations over the years, achieving remarkable technical progress and is presently considered a matured technology [1]. Traditional wind energy systems have been constant speed systems which were designed to give their optimal performance at certain wind speeds. They use gear boxes to couple the wind turbine with the generator and hence suffer a lot of related problems such as complexity in their control, high fatigue, noise and maintenance requirements. The newer wind energy systems have therefore moved on to gearless direct drive concept in which the turbine and generator are coupled directly without a gear box. Such systems, known as variable speed systems, have superior low speed performance and improved energy capture capability [2]. However, variable speed systems require a generator with a large number of poles since the speed of operation would be lower, limited by the directly coupled wind turbine.

With the advent of high strength permanent magnets and the remarkable advancements that occurred in their field lately, electrical machines using permanent magnets have been increasingly sought after owing to their relatively simple design, compact structure and robustness. Permanent magnet generators have been found most suitable for variable speed systems wind systems since their construction allows the inclusion of a large number of poles easily which would have been difficult in the case of conventional field excited generators [3,4].

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Axial Flux machines with conventional field poles machines were developed almost a century ago, though their successful foray into the field of electric machines was hindered owing to certain complexities involved in their construction and difficulties encountered in providing ventilation. Hence, traditionally electric machines have been commonly of radial flux type. However, the huge popularity of permanent magnet generators has kindled an immense interest in Axial Flux Permanent Magnet Generators (AFPMG) recently, since the use of permanent magnets enables easier design and construction. These machines hold a promising future, offering many exciting features and advantages over radial flux machines. They have been brought into the limelight of active research ever since, with commendable studies already been conducted on its performance and applications, especially as generators in wind energy conversion systems [5,6].

From the comprehensive literature survey conducted on the subject it is seen that abundant work has been carried out in terms of designing and modeling of permanent magnet machines, albeit majority of them consider radial flux machines. The relatively lesser research efforts intended towards axial flux machines seem to focus on the physical design, design optimization, thermal analysis etc. using various tools and techniques. Various electromagnetic and mechanical design procedures for Axial Flux Permanent Magnet Generators of different topologies have been discussed in [6–10]. The studies presented in [11–13] deal with the modeling analysis of permanent magnet generators of radial flux type in variable speed wind systems while those presented in [14–16] deal with analytical modeling of Axial Flux Permanent Magnet machines. It can be seen that comprehensive studies comprising design of an AFPMG for wind systems, both the mathematical and tool based dynamic modeling of the entire system and subsequent simulation studies to understand the generator characteristics, is fairly limited. In this paper, an Axial Flux Permanent Magnet Generator (AFPMG) has been designed, which is most suited to be used as a wind generator in variable speed systems. Then, the mathematical model of the system consisting of the AFPMG directly coupled to a pitch controlled Horizontal Axis Wind Turbine (HAWT) is obtained and is implemented in MATLAB/Simulink platform. Simulations have been carried out to examine the behaviour of the wind generator under different wind speed conditions and the results have been discussed.

Axial Flux Permanent Magnet Generator (AFPMG)

In an AFPMG, the stator and rotor are in the shape of discs stacked or mounted on a shaft and the magnetic flux traverses from one disc to the other in a direction parallel to the shaft (i.e. axial direction). When compared to their Radial Flux counterparts, Axial Flux Permanent Magnet Generators possess a multitude of attractive features such as better design flexibility, higher power to weight ratio, negligible cogging torque, lower noise, adjustable planar air gap, higher energy efficiency, possibility of modular construction etc. They can be designed in a wide variety of topologies having multiple stators and rotors in the same machine with different assemblies for stator winding and different configurations for the placement of permanent magnets [17–21]. Axial Flux Permanent Magnet Generators can also be designed with several stages of stator-rotor units mechanically coupled together on the same shaft and electrically connected together in series or parallel as required. By doing so, the electrical output that can be generated from the available wind increases as many folds as generated by a single stage, with minimal increase in overall size.

Among the various configurations, Single Stator Double Rotor (SSDR) configuration is found to have better operational features and in this configuration, the stator carrying three phase winding is sandwiched between two rotors carrying permanent magnet poles [22,23]. The arrangement of permanent magnets is in such a way that the North Pole of one rotor faces the South Pole of the other rotor and vice versa (NS-SN configuration). The unique feature of this particular configuration is that the magnetic flux passes from one rotor to the other crossing the stator axially completing the magnetic circuit, without passing through the stator disc itself in a radial direction, i.e., the stator disc does not necessarily serve any purpose for the path of the magnetic flux, other than supporting the three phase windings. This allows the generator to have a non-magnetic non-conducting material such as plastic or wood for the stator disc, making it lighter in weight. This also eliminates iron losses and makes the machine more efficient.

Design of Axial Flux Permanent Magnet Generator

The AFPMG under consideration has a SSDR structure with NS-SN configuration for permanent magnets as shown in Fig. 1. This configuration of the AFPMG makes it most suitable for wind applications since the short axial length of the machine enables it to be comfortably accommodated in the nacelle of the wind turbine (which usually has space constraints). Since the machine is compact, a nacelle of smaller size could be employed. Also, lesser weight of the generator would mean that the weight of the nacelle is reduced. Moreover, it offers a higher power density and higher efficiency since iron losses are absent.

The AFPMG has been designed following the fundamentals of permanent magnet machine design [24,25] and the basic design equations have been presented below.

The sizing equation of the AFPMG is given by

$$P_{out} = \frac{\pi^2}{8} \times B_{av} \times ac \times \left(1 - \lambda^2\right) \times (1 + \lambda) \times D_{so}^3 \times N_s \quad (1)$$

where P_{out} is the output power B_{av} is the average air gap flux density or specific magnetic loading (chosen as 0.6 Wb/m^2), ac is the specific electric loading, D_{so} is the outer diameter of stator, N_s is the speed of rotation and λ is the diameter ratio, which is the ratio of inner diameter (D_{si}) to outer diameter of stator (D_{so}).

Considering the disc forms of stator and rotor, the specific electric loading is worked out as,

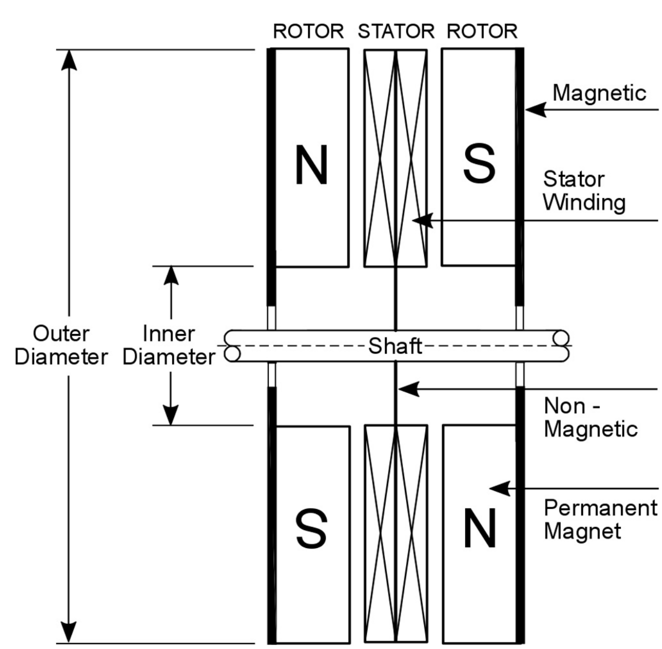

Fig. 1. AFPMG with SSDR (NS-SN) configuration.