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A compact, high efficiency contra-rotating generator suitable for wind turbines in the urban environment

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ABSTRACT

This paper is concerned with the design, development and performance testing of a permanent magnet (PM) generator for wind turbine applications in urban areas. The radially interacting armature windings and magnet array are carried on direct drive, contra-rotating rotors, resulting in a high torque density and efficiency. This topology also provides improved physical and mechanical characteristics such as compactness, low starting torque, elimination of gearboxes, low maintenance, low noise and vibration, and the potential for modular construction. The design brief required a 50 kW continuous rated prototype generator, with a relative speed at the air-gap of 500 rpm. A test rig has been instrumented to give measurements of the mechanical input (torque and speed) and electrical output (voltage, current and power) of the generator, as well as temperature readings from inside the generator using a wireless telemetry device. Peak power output was found to be 48 kW at a contra-rotating speed of 500 rpm, close to the design target, with an efficiency of 94%. It is anticipated that the generator will find application in a wide range of wind turbine designs suited to the urban environment, e.g. types sited on the top of buildings, as there is growing interest in providing quiet, low cost, clean electricity at point of use.

1. Introduction

By 2050, the UK aims to achieve an 80% reduction in CO_2 from current levels [1]. Renewable energy provided by wind turbines, photovoltaic cells and tidal schemes, can all contribute towards achieving this target. The UK has some of the best wind resources in the world, and so targets for electricity generation from renewable sources (15% by 2015 compared to 3% actual currently) could be attained by wind energy alone. From an engineering perspective, there does not appear to be any major barriers in achieving this, and in theory over 30% of the UK's electricity supply could be provided by wind by the year 2050 [2,3]. For large scale wind energy projects, potential obstacles include the rural location of wind turbines, high level of investment,[1] escalating costs and stakeholder collaboration difficulties between commercial, governmental and environmental organisations. There is growing interest in smaller wind turbines located in areas previously considered unsuitable, such as in urban or built environments, harnessing low to moderate amounts of energy to supplement the large demands of offices, factories and public buildings at point of use for heat and power [4,5]. The UK Government's energy strategy includes local and micro-generation renewable energy schemes, and so the development of these technologies is important in the future attainment of the targets.

To date, the success of wind turbine installations in the urban or built environment has been variable [6]. Energy production in urban areas is generally significantly lower than in open rural areas. Subsequently, the direct transfer of the more familiar existing technologies to urban areas may not be straightforward or even applicable. What is required is a system that has the ability to extract maximum power from complex winds flows with variable direction. Novel means of achieving this are being continuously researched and developed e.g. new topologies for vertical-axis, horizontal-axis and hybrid wind turbine designs [7], ducting of air flows [8] and new more efficient generators [9]. A great deal of emphasis is being placed on direct-drive permanent magnet (PM) generators that are compact, light weight, quiet, exhibit low vibration and are suitable for mounting on buildings, with minimum additional infrastructure. Higher efficiency PM generators alone may not make the difference to a viable electricity generating system. One method for reducing the size of the generator is to employ a pair of contra-rotating wind turbines that are configured to rotate the PM array and the windings in opposite directions, thereby effectively doubling the air-gap speed for

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[1] In 2008, both BP and Shell have announced their withdrawal from wind turbine projects in the UK.

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a given turbine speed and hence removing the need for a gearbox for a given turbine speed.

In this paper, the design, development and construction of a contra-rotating, radial-flux, PM generator is presented together with the rationale for selection of the system features. Its main performance measures are evaluated using simulated contra-rotating inputs at this stage of development. Important performance results and measurements include the power output, current, efficiency (at full and part-load) and torque relative to the contra-rotating speed, as well as mechanical and electromagnetic losses, thermal characteristics, and mass specific performance measures for generator comparison purposes.

2. Design and manufacture considerations

There are a number of technical issues which need to be addressed when developing wind turbine systems for urban areas or the built environment [4,7]:

- System type: static, integrated with building/structure, yawing system, with/without collector and/or diffuser;
- System attributes: self-starting, safe, low noise, low vibration, robust design to the service conditions, minimal maintenance, low installation weight, high power per active volume of material;
- Location: aesthetics, building/infrastructure strength, electromagnetic interference with existing electrical installations, space for other equipment e.g. inverters, monitoring devices etc.

Some of these issues presented relate to the generator, some are more aligned to the turbine and its performance, and others are interrelated system or public concern issues. The research and development project reported here is associated with the generator. Limited data was available from the customer associated with wind turbine design, or any dimensional constraints that its choice may have on the generator. However, as far as possible, the main technical issues discussed above were also incorporated in the existing detailed Product Design Specification (PDS) outlining the requirements. This was, in essence, to provide a standalone contra-rotating generator with a maximum rated power of 50 kW (3-phase, 415 V, 90 A) at a combined speed of 500 rpm and 960 Nm of torque. The idea of a contra-rotating wind turbine is not new [10], although there are few successful examples in the literature. The main reason for a contra-rotating system choice is that field tests have demonstrated increased energy conversions of between 25% and 40% compared to more conventional single rotor wind turbines [9,11,12]. It also provides the potential for the generator to be very compact, giving a low installation weight and high power per volume of active material.

In order to take full advantage of a direct-drive generator, the wind turbine blades must be self-starting, a common feature of existing systems for the urban environment [4]. This requirement suggests a low starting torque through a combination of low frictional moment in the bearings and low cogging torque in the PM generator. The choice of wind turbine is also important, however, this issue will be addressed in a subsequent paper. To achieve a low frictional moment and therefore power loss, the correct bearing choice must be made. In the proposed design, high radial loads are set-up through the horizontal over-hanging rotors on both sides, and together with low rotational speeds and with the capability to have integrated shielding for grease, use of double deep groove ball bearings is justified. Modern wind turbines are generally designed to work for some 120,000 h of operation throughout their design lifetime of 20 years [4], and the dynamic loads for the generator are well within specification giving a low frictional moment. In addition, the standalone prototype generator suited a short axial length and larger diameter configuration in order to minimise the cantilevered moment on the bearings supporting the winding armature and rotor assemblies. Given the low-speed and absence of geometry complexities on transmission components, fatigue was not considered a major failure issue and static design principles were applied throughout the structural strength calculations.

The selection and design of electrical machine topology within the generator must be carefully considered for a contra-rotating system. Multi-pole, direct-drive PM machines are already the preferred technology for small gearless, low-speed wind turbines [13]. In the case presented here, a PM machine has also been selected for a number of well documented reasons [14,15]. These include the high specific torque densities (relative to both weight and volume) of PM machines, yielding high power densities even at low, directly driven speeds resulting from the turbine blades of the wind turbine. This benefit allows heavy, noisy and maintenance rich gearbox stages to be omitted from the system with obvious benefits. The use of high-quality bearings with long working lives and low angular velocities further reduces the maintenance burden and hence running costs. Given that the turbine is likely to be sited in a windy area, ducted air cooling will be possible resulting in an operating temperature of the electrical machine being purely a factor of the electrical losses in the machine, increasing output efficiency. With appropriate design considerations, a PM machine will have excellent efficiencies, including operation at part-load. This is particularly significant when considering the variable load conditions for a wind turbine application.

To ensure that the electrical machine used in the generator has a low cogging torque, an optimised, closed-slot topology is selected. This, however, results in a machine that is expensive to manufacture as the copper machine windings have to be formed in-situ on the machine rotor-iron. Given the large radial design envelope of the machine, a carefully selected open-slot machine topology can result in a machine with very low cogging torques and whose windings can be manufactured from coils that are formed before being slotted onto the rotor-iron [16–18]. This results in a modular coil that is more compact, with a smaller end winding which in turn greatly reduces manufacture complexity. Further, due to the more compact end winding, the overhung moment on the bearings is reduced allowing cheaper units with lower ratings to be used.

Fig. 1 shows the progression of the generator design from (a) electrical/mechanical schematic (b) CAD model (shown in section) to (c) physical prototype. The unit comprises two overhung rotors located on rigid hollow shafts that will eventually be coupled to the contra-rotating wind turbines. One of the rotors, shown on the right of Fig. 1(a), is formed as a cup that carries a multi-pole permanent magnet array and back-iron assembly on its inner surface. The second rotor, shown on the left of Fig. 1(b), carries the armature laminations and windings. Since the armature also rotates, it is connected externally via a three-phase slip ring assembly. Fig. 1(b) and (c) shows the bearing housings and the position of the bearings relative to the rotor positions. In order to minimise the bending stresses on the generator housing due to the large over-hanging rotor masses, the bearing houses are a close fit in the end plates, distributing the forces through to the housing itself. All major components were CNC machined providing the necessary accuracy for mating adjacent parts and especially concentricity between contra-rotating rotor assemblies and therefore the air-gap. Stainless steel was used for the hollow shafts and a high strength aluminium alloy used for the generator housing assembly and rotor components providing the required strength, stiffness and corrosion resistance.