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Structural integrity of a direct-drive generator for a floating wind turbine

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ABSTRACT

In this work, the suitability of a direct-drive radial flux permanent magnet generator is examined as a probable drive-train candidate for a stepped-spar floating wind turbine system that supports a 2 MW downwind turbine. The suitability of the generator is assessed based on the structural integrity of its design (i.e., the stability of the air-gap between the rotor and stator) in response to the nacelle motions and its possible design implications on the overall system. Air gap deflections due to structural deflection and bearing tolerances were examined independently. The nacelle motions are obtained from experimental and numerical investigations on a 1:100 scale model. ANSYS suite is used to estimate the structural deformations of the generator and the changes in the air-gap distribution. Also, a simplified analytical model is used to compute the resulting changes in flux density and force distribution along the rotor periphery. The analytical model is also validated by 2D magneto-static simulations by utilising Finite Element Methods Magnetics software (FEMM).

Preliminary results suggest that, if the nacelle accelerations are limited to 0.3 times the acceleration due to gravity (g) and the motion response cycles are below the fatigue limit, the air-gap stability of the generator is more sensitive to magnetic forces. Contributions to air-gap eccentricity from shaft displacements can be limited if the bearing supports can be designed for high stiffness. This also confirmed the adequacy of the platform design. The results also emphasise the need for air-gap management when designing direct-drive generators for floating wind turbines. Two methods are investigated as potential solutions to limit the maximum air-gap deflection to 10% level. The method of increasing structural stiffness led to a structurally unfavourable design that could potentially affect the stability and resonance properties of the system. The method of increasing the design air-gap led to a structurally more favourable design, although this meant an increase in magnetic material and hence the costs. Thus, implementing direct-drive radial flux permanent magnet generators for floating wind turbines is challenged by the difficulty in achieving optimal weight and costs at acceptable performance without compromising the air-gap tolerances. There is a need for an amendment to design standards to recognise the design challenges of Floating wind turbines.

1. Introduction

Floating wind turbines (FWTs) are proposed as the next big step in making energy from offshore wind competitive. Operating a wind turbine at greater distance from the shore in deeper waters offers new opportunities. As wind is stronger and more consistent in deeper waters, a higher and reliable energy output over time can outweigh the additional costs, resulting in lower costs of energy. The techno-economic feasibility of such a system lies in its capacity to ensure high reliability and efficiency without compromising the structural integrity of the system. The design space at the nacelle for a floating wind turbine is very limited because of the dynamic nature of loads that places huge mechanical restrictions on size, mass and strength of the components that can be supported. The dynamic action of the floater, wind turbine and control system can result in excessive torque pulsations, shaft misalignments, mass imbalance, vibrations and a high degree of mechanical wear on the drive-train. Therefore, proper choice of the drive-train technology, the components as well as their performance considering the overall dynamics of the floating wind turbine will have a major role to play in the success of such a system.

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Nomenclature

g	acceleration due to gravity, 9.81 m/s^2
λ	model scale factor
g_a	measured air-gap length (m)
g_{nom}	nominal air-gap length (m)
g_{ash}	measured air gap length due to shaft displacements (m)
h_m	magnet height (m)
R_o	stator inner radius (m)
r	rotor outer radius (m)
dA	segmental area of stator/rotor surface
θ	angular position along the rotor/stator periphery (deg)
$\ddot{a}_i$	nacelle linear acceleration component (m/s^2)
$\dot{a}_i$	nacelle angular velocity component (rad/s)

1.1. Direct-drive generator for floating wind turbine

Presently a wide range of drive-train architecture options is available for designers to choose from Refs. [1,2]. The conventional drive-train with gear box has been the standard design choice for FWT concepts that are currently under development. A recent survey on the current state of art of drive-train technology showed good potential for direct-drive generators [3]. The simple configuration, low probability of failure, increased reliability with great potential for weight reduction make the direct-drive technology a prospective design choice for floating wind turbine. Yet, for direct-drive technology to be implemented for the FWT, the structural integrity of the components must be demonstrated to be at an acceptable level in response to the various loads endured during their operation.

The spar-buoy based wind turbine is an extensively researched concept. Several studies have examined the coupled interactions between the wind turbine motions, floater motions and the control system for this concept (for e.g., Refs. [4,5]). These studies have assumed a conventional high speed drive-train with high intrinsic structural damping. Recent studies that examined the dynamics of geared drive-train for floating wind turbines have identified greater loading and internal drive-train responses as compared to fixed offshore wind turbines [6,7]. Also studies are yet to determine the structural adequacy of the drive-train in response to the loads acting at the nacelle. This emphasises the need for a better understanding on the influence of nacelle motions on the dynamics of the drive-train. This will also be helpful in deciding the strength requirements of drive-train systems that are better suited for offshore wind turbines with floating supports.

The most critical component of the gearless drive-train is the generator. As these generators are generally very large and heavy, limiting their weight and size to avoid tower/foundation upgrades without compromising on the material strength and air-gap tolerances will be the biggest challenge. Direct-drive generators have already been considered for a few vertical axis floating wind turbines [8–11], however details on their performance are not available for review. In Ref. [10], first attempts were made to design and optimise a 5 MW direct-drive generator for a spar-type floating vertical axis wind turbine. However, with the vertical axis FWT systems, the generators have lesser mechanical restrictions on size, mass and strength as they can be located closer to the centre of gravity of the system where the motion induced loads are substantially reduced.

1.2. Structural design adequacy of a floating wind turbine system

The nacelle of a floating wind turbine is highly constrained mechanically and structurally [3]. The tower top mass must not exceed the minimum value stipulated by hydrostatic stability. This means that the nacelle and its components must be as lightweight as practically possible. Due to the presence of strong coupling, the motions of the floater affect the performance of the wind turbine and vice versa (while floater motion reduces the effective area of wind inflow thus affecting power conversion, rotor rotation can introduce negative damping). Because the loads at the nacelle are stochastic and cyclic, they subject the nacelle to repeated transverse and rotational motions resulting in several undesirable effects such as local component structural deflections, vibrations, shaft misalignments and fatigue. As the size of wind turbines (hub height) increases, even small pitch or roll rotations result in large motions at the nacelle.

1.2.1. Air-gap dynamics of a direct-drive generator

The most critical component of the direct-drive technology is the generator. These generators operate at low speeds and are therefore very large and require massive support structures. The electromagnetic and structural models of the generator are tightly integrated and highly sensitive to external loads [12]. The quality of power conversion for these generators depends on the relative stability of the air-gap that separates the rotor from the stator. A large air-gap results in poor torque output while a small air-gap magnifies the output voltage, and non-uniform air-gap can cause fatigue loads on the generator. The stability of this air-gap qualifies the structural integrity of the generator which is related to the stiffness of the rotor and stator support structures as well as bearing tolerances in effectively countering the loads that act to close the gap. Direct-drive generators for wind turbines can successfully operate as long as eccentricity (i.e. air-gap deflection) is limited to $\pm$10% of the air-gap length [13,14].

Under steady-state, when the rotor is not in operation, the normal gap closing loads include the radial attraction forces of magnets, the self weight/gravitational force and thermal expansion due to heat. An external load such as wind or wave in addition to the normal gap closing forces complicates the air-gap problem. The rotor may be further pulled towards the stator, thereby creating an imbalance in magnetic forces (Unbalanced magnetic pull) and destabilising the air-gap. Therefore, in the presence of external load (such as waves/wind), eccentricity may be induced by support structure deflection of the generator (δ_{stru}) or/as well as shaft displacement/deflection caused by bearing compliances ($\delta_{bearingtol}$).

In order to evaluate the overall integrity of direct-drive generator, it is necessary to examine both these effects. In this study, we examine these effects independently. As a first step, the air-gap behaviour due to structural deflection is examined in response to the external loads such as waves. Firstly, the various loads that appear at the nacelle as a result of wave action must be computed. Then, the structural strength of the generator in response to these loads is verified. As a subsequent step, contributions from shaft displacements/bearing tolerances are examined. Consequently, this can help verify the overall adequacy of the design and help identify the best control measures.

The nacelle acceleration is a key performance index for the wind turbine, so the objective of any design is to minimize that value for all sea states. Previous research suggests that a value $<0.3g$ (2.94 m/s^2) can guarantee satisfactory performance [15]. Since larger nacelle motions can damage equipment or degrade turbine performance, it is important to verify the equipment performance in relation to nacelle motions.

Hence, in this study, an attempt was made to understand the effect of the nacelle motions on the structural strength of a direct-