Ocean Engineering 161 (2018) 1–19

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Dynamic structural design of offshore direct-drive wind turbine electrical generators

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ARTICLE INFO

Keywords:
Direct-drive wind turbine
Generator structure
Dynamic design
Modal analysis

ABSTRACT

Direct-drive permanent magnet generators for multi-MW wind turbines are low speed high torque electrical machines requiring large, heavy and robust structures to maintain the airgap clearance open and stable. The structural mass of radial-flux generators can be estimated at an early phase of the design process. Using distinct approaches, the integrity of a 3 MW electrical machine structure has been addressed from a dynamic perspective by carrying out modal analyses with a view to minimize its mass. A versatile tool has also been developed to help the engineers with the dynamic design of generator disc structures. Conical structures have been analysed and compared with the baseline disc model obtaining very promising results. Potential improvements have been proposed for more ambitious structural designs.

1. Introduction

The recent concerns on global warming and the rapid increase in energy demand are taking governments and institutions to look at renewable energies as a potential solution. In this context, wind energy industry has a foremost role to play. Considered as the most consolidated among the renewable energy types, wind power has been widely researched and developed. Wind energy gathering devices have been deployed onshore and offshore. Due to the larger wind resources and steadier conditions taking place in deep waters as well as the fast development of the technology, offshore wind energy has recently drawn more attention.

However, significant challenges have to be considered when planning and installing offshore wind farms. The sea is a harsh environment which does not always allow an easy access to the turbines for installation or maintenance, where the air has a high salt content and humidity. In the installation case, both the wind speed and wave height must be below certain levels so that cranes and vessels can work safely. In addition, if a scheduled maintenance cannot be carried out because of extreme conditions, a very high cost produced by the downturn in the turbine availability will be paid by the owner. This is why manufacturing reliable elements at a minimum cost is of high importance. Lightweight and easy to install structures are of interest although not always possible since generators and other components such as gearboxes can be very complex and heavy.

Over the past years, the use of non-conventional drivetrain configurations for offshore purposes has arisen. With a view to increase the reliability and availability of the turbine, the direct-drive concept has been introduced. Directly driven wind turbines present a number of advantages, among which the removal of the gearbox stands out. With it expensive gearbox matters can be avoided. Moreover, the decrease in the number of moving parts represents a significant reduction in downtime periods. On the other hand, the rotational speed of large multi-MW wind turbines is very low (in the order of 10 rpm) and knowing that the power of a generator is equal to the product of the machine's torque 'T' and the angular velocity 'P', ($P = T$P), very large torques must be developed by direct-drive machines. Practical limits to electrical and magnetic loading exist, thus there is an upper threshold to the shear stress that can be produced. A typical range for the shear stress, 'σ', goes from 25 to 50 kN/m^2 (Polinder et al., 2005). Since the torque for an electrical generator can be calculated as

$$T = 2\pi\sigma R^2 l \quad (1)$$

Where R corresponds to the radius of the machine's airgap and l is the axial length, a very large device of considerable mass should be considered.

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https://doi.org/10.1016/j.oceaneng.2018.04.074
Received 11 December 2017; Received in revised form 17 April 2018; Accepted 19 April 2018

Minimising the structural mass of low speed multi-MW electrical machines for renewable energy purposes have become an important object of study as with the reduction in mass a substantial decrease in the machine capital cost can be achieved (Jaen-Sola and McDonald, 2014). Generators utilised in direct-drive wind turbines are all synchronous. One way of reducing its weight is moving from electrical excitation to permanent magnet excitation. Going a step beyond, permanent magnet machine's topology is also a variable that can be taken into account. There are three different types: radial-flux, axial-flux and transverse-flux and can be contrasted by looking at either their cost per torque or their torque density. Although axial-flux and transverse-flux machines are of substantial interest, this paper concentrates on radial-flux generators.

The vast majority of the research in the field focuses all the attention on the mass decrease of 'active material', which includes permanent magnets, copper and back iron. Nevertheless, it is the supporting structure, also known as 'inactive material', which accounts for the highest percentage of mass. The excessive weight of the generator structure was highlighted by Hartkopf et al.. who claimed that 2/3 of a direct-drive radial-flux electrical machine mass corresponded to the inactive material (Hartkopf et al., 1997). Mueller, McDonald and MacPherson claimed in (Mueller et al., 2005) that at multi-MW ratings the inactive mass of a direct-drive axial flux machine is almost 90% of the total mass. A series of studies have been available on this regard presenting different approaches that can be utilised when designing these machines in order to minimize their structural mass (McDonald, 2008) (Jaen-Sola and McDonald, 2016). In these investigations, analytical and numerical analysis techniques were used with the objective of finding the minimum required stiffness so that the machine can withstand the loads. As known, the structural stiffness, 'k', is the ratio between the force applied on a body, 'F', and the deflection produced by the force along the same degree of freedom, 'δ', ($k = F/\delta$). By having the minimum stiffness, the designers are able to estimate the minimum structural mass in a low cost and fast manner.

It is important to highlight the fact that all of the mentioned studies have adopted a static approach when analysing the machine. In this paper, the machine's structure has been studied from a dynamic point of view, where much deeper understanding is necessary. Only a few papers have looked in detail at this topic and most of them are centred on a particular machine. For instance, in (Sethuraman, 2014), Sethuraman successfully characterised the dynamic behaviour of the direct drive power train of a spar-buoy floating wind turbine following the well-known two step de-coupled approach proposed by Xing et al. (2012a) (Xing et al., 2012b). This method, originally created for analysing conventional geared wind turbines, utilises the data obtained from an aero-elastic simulation code, on global motion response and loads as inputs for a detailed drivetrain model created in a Multi-Body Simulation piece of software which enables kinematic and dynamic analyses of mechanical systems. However, as the main purpose of this research was to optimise a direct drive machine, the author also needed to address how significant the dynamic effects and feedback forces from the drivetrain were. In (Kirschneck, 2016), Kirschneck employed density based topology optimisation to investigate the potential weight reduction of the XD-115 offshore direct-drive wind turbine generator rotor taking into consideration its dynamic behaviour. Here, the authors have developed a more generic approach that can be used for the excitation frequencies evaluation and alteration of any radial-flux electrical machine. As a rotating piece of machinery, the generator vibrates when its natural frequencies are excited introducing potentially large amplitude oscillations into the forces acting on it that could cause structural fatigue, noise and, in the worst case scenario, the sudden collapse of the structure.

Due to the special nature of its construction and operation, the way of evaluating the vibration of a wind turbine differs from that of any other industrial rotating machine. Vibrations of the tower and nacelle caused by the effect of wind, flow disturbances due to the tower, the natural vibration of the rotor blades and structure itself, and additionally sea swell, in the offshore case, are the sources of excitation to be considered (O 10816–10821:2015(en), 1081). Regarding the wind turbine components dynamics, few studies have been published on the design of large diameter direct-drive generator structures. Typical generator supporting structures are formed by disc, arm or conical sub-structures, which not only connect the shaft with the cylindrical sub-structure but also provide the necessary stiffness in the radial and axial directions. See Fig. 1. Depending on the rated power and the requirements to comply with, the structure shape and dimensions will vary, as well as its natural frequencies and mode shapes. In this investigation, disc and conical structures have been studied. It was assumed that an elastic coupling, similar to Alstom's Pure Torque (https://www.gerenewableen), has been placed between the wind turbine rotor and the electrical generator so that all the non-torque loads are directly diverted to the tower. With this and the appropriate bearing configuration, the electrical generator is virtually isolated from the rest of the turbine. In addition, an elastomeric-hydraulic coupling system has been assumed between the generator and the turbine turret that helps dissipate the vibrations induced by the sea swell. Taking all of these facts into account, the potential excitation frequencies that could activate the structure natural frequencies are as follows (Zavvos, 2013),

The frequency of the wind turbine rotational speed (1P).

The fundamental electrical frequencies (pP, with p being the number of pole pairs).

The frequency of the rotor blades passing in front of the tower (3P and 6P).

Any mode shape, if sufficiently excited can lead to noise and fatigue damage. In order to explore the sufficient number of natural frequencies you may want to check as many modes as it takes to fully analyse the frequency excitation range you are expecting. This usually means that you need to look at 6 modes minimum and do not evaluate more than 10 modes or two hundred Hz. Nonetheless, one can adopt a more precise approach, where the energy contained within each resonant mode is measured so that the amount of system mass participating in each mode and for a particular direction can be estimated. The amount of mass is normalized and the retrieved value is known as the effective mass participation factor or EMPF (Priestley et al., 1996) (SolidWorks help file and Fre, 2015). A mode with large effective mass is typically a substantial contributor to the dynamic system response and must be avoided or passed as quickly as possible. If the sum of all EMPF corresponds to at least 80% in any response direction (X, Y, Z), it can be assumed that the number of modes studied is sufficient to capture the dominant response of the structure. Another important point that this procedure takes into account is that if one mode contributes more than 1% of the total mass it must be considered to avoid resonant issues (Priestley et al., 1996) (SolidWorks help file and Fre, 2015) (James et al., 1992).

The main aim of this investigation is to develop suitable methods and investigate a set of possible designs that would ensure the dynamic integrity of the machine without significantly increasing its weight by following the effective mass participation factor procedure described above.

2. Methodology

This study concentrates on electrical generator supporting structures formed by disc or conical sub-structures and the different methods that can be followed when approaching their dynamic design.

First, the potential excitation frequencies that can trigger the structure's natural frequencies are identified and assessed. Second, the natural frequencies of a statically optimised structure made with discs are estimated by using finite element techniques and plotted with the excitation frequencies on an interference diagram, also known as Campbell diagram, for comparison. This structure was considered the baseline model. The main objective of the static structural optimisation was to minimize the structural mass while keeping the deflection within a certain specified limit corresponding to 0.5 mm in any direction (Jaen-Sola and McDonald, 2014). For this analysis, the author constrained the structure