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Site-specific controller design for monopile offshore wind turbines

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A B S T R A C T

The fatigue life of offshore wind turbine (OWT) support structures is sensitive to variations in site-specific conditions such as the water depth and soil properties. Site condtions may vary significantly within a wind farm, and they may change throughout the lifetime of the OWT. This paper analyses how control strategies for fatigue life extension can compensate for differing fatigue loads due to varying site conditions. Control strategies applicable for both power production and idling situations are analysed, and methodology to reduce undesirable side-effects is proposed. The design case is a 10 MW monopile OWT located in 30 m water depth at the Dogger Bank in the North Sea, and results are based on time-domain simulations performed using an aero-hydro-servo-elastic simulation tool. The results show that, when all the investigated control strategies are utilized, a fatigue damage reduction over the 20-year lifetime of approximately 50% is possible. Furthermore, it is shown that adverse side-effects such as wear of pitch actuators and fluctuations in the power output can be significantly reduced by limiting the use of control strategies to some predefined situations. With only moderate cost to other system components, the control system is able to compensate for 20% variation in soil stiffness, and 5% (1.5 m) variation in water depth.

1. Introduction

The offshore wind industry is continuously progressing towards larger wind turbines, with the first 8 MW wind turbines grid-connected in 2016 [1]. Larger wind turbines require larger support structures, which without considering the cost of installation, is a component that represents close to 20% of the total cost of offshore wind farms [2,3]. Monopiles remain the favoured choice of foundation with a market share of 88% in Europe [1], and this trend is expected to persist for wind turbines installed in shallow and intermediate water depths (<40 meters) [4]. Monopile dimensions are mainly driven by fatigue considerations, and the increase in fatigue loads resuting from the upscaling of turbines in combination with deeper water, is a challenge for the economical feasibility of monopile foundations [5]. In particular, large monopiles are more susceptible to fatigue damage from first order wave loads. The magnitude of the hydrodynamic loads increases due to the larger diameter of the monopile. Furthermore, the increased mass of the rotor-nacelle assembly (RNA) and height of the wind turbine, together with a reduction of the rotor speed and the corresponding frequency constraint imposed by the blade passing frequency (3P), pushes the first modal frequencies of the support structure closer to typical wave frequencies [6,7].

The wind turbine's blade pitch and generator torque control system influences the dynamic response of the structure. The design

Abbreviations: AAD, Active aerodynamic damping; AGT, Active generator torque control; AIC, Active idling control; DEL, Damage equivalent load; DLC, Design load case; ELC, Environmental load case; FLS, Fatigue limit state; OWT, Offshore wind turbine; RNA, Rotor-nacelle assembly; SCO, Soft cut-out; TMD, Tuned mass damper; ULS, Ultimate limit state

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process for offshore wind turbines (OWTs) should therefore be carried out in an integrated manner, including the design of control strategies that aim to reduce fatigue loads in the support structure [5]. Monopile OWTs are lightly damped, with typical damping ratios in the range 1% - 2.5% of critical for the first fore-aft and side-side vibration modes [8–10]. Aerodynamic damping from the rotor is an important contribution to the overall damping of the fore-aft vibration modes, and several control strategies that are based on enhancing the aerodynamic damping to reduce fatigue loads have been studied [7,11–15]. Because the rotor mainly contributes with damping in the fore-aft direction, the support structure is particularly prone to excitation by waves coming from a different direction than the wind. The incidence of environmental conditions with wind/wave misalignment is site-specific, but it can be significant for exposed wind farm locations [16,17]. Several control strategies that aim to increase the damping of the side-side vibration modes of the support structure have been proposed [7,11,13,14,18,19]. The various control strategies for fatigue load reduction are presented in more detail in Section 2.

As demonstrated in Refs. [5,7], control strategies for fatigue load reduction can be integrated in the design process for the support structure, leading to a 9.2% reduction in the weight. A control system that can extend the fatigue life of the OWT can also be used to compensate for uncertainties or simplifications in the design process. The fatigue loading of monopile OWTs is sensitive to variations in site specific conditions such as the water depth and soil properties [20–22]. Because the water depth and soil properties may vary significantly within a wind farm, it is common industry practice to group the OWTs into clusters, and design the support structures according to the most loaded location in the cluster [23]. The conservatism of this approach may be reduced by introducing control strategies that can compensate for differing fatigue loads due to varying site conditions. Moreover, such control strategies may be applied to increase the size of the design clusters, thereby reducing the number of customized foundation designs. Because the soil properties are associated with large uncertainties [24,25], the true modal properties of the support structure, particularly the natural frequencies and damping ratios, are often not known before the wind turbine is installed [9]. Furthermore, long-term cyclic loading may cause accumulated pile displacements and changes in the soil properties, thereby changing the modal properties over the lifetime of the OWT [22]. Control strategies that extend the fatigue life of the OWT, may reduce the design conservatism resulting from uncertainty in the modal parameters. Moreover, one could equalize the fatigue utilization for the foundations across the wind farm such that the turbines can be decommissioned at the same time without wasting structural reserves.

Control strategies which mitigate fatigue loads in the support structure, can lead to undesirable side-effects in other wind turbine components. The reliability of the pitch system is a concern with control strategies that require additional pitch activity. A survey consisting of 1400 turbine years of operational data for onshore variable speed turbines found the pitch system to be the sub-assembly with the highest failure rate [26,27]. Moreover, because the pitch system reliability is difficult to predict, it is desirable to limit the use of pitch actuators. Other critical components that may be negatively affected by the control system are the blades, main shaft, gearbox, and generator. These components have lower failure rates, but they cause higher downtimes when they fail [26]. Furthermore, it is essential to maintain power production, with power quality that complies with grid requirements [28]. A compromise between fatigue load reduction and collateral effects can be achieved by limiting the use of control strategies to certain predefined situations. Enabling control strategies in situations where the tower-top vibration frequency is within a frequency band containing the first modal frequency of the support structure was proposed by Refs. [29,30]. Further [3,31], proposed enabling control strategies based on information about environmental conditions, and a multi-objective optimization method was developed to establish the trigger criteria.

The main contribution of the present work is the analysis of the applicability of control strategies for fatigue load reduction to compensate for differing fatigue loads due to varying site conditions. As such, only the fatigue limit state (FLS) is considered, not the ultimate limit state (ULS) and serviceability limit state (SLS). This paper also demonstrates the long-term effects of control strategies for fatigue load reduction. A similar study was performed by Ref. [7] for a 5 MW OWT. In this paper, a 10 MW OWT is considered, and by comparing the results, the present work serves as a verification and extension of previous research. Furthermore, this paper analyses the trade-offs between fatigue load reduction and undesirable side-effects, and proposes a methodology to improve the overall trade-offs associated with the control strategies. The simulation model is based on the 10 MW reference wind turbine of DTU Wind Energy [32], and long-term variations in environmental conditions are based on 60 years of hindcast data for a wind farm site at the Dogger Bank in the North Sea [33]. Simulations are performed using the software tool SIMA by SINTEF Ocean with post-processing in MATLAB by aid of the WAFO toolbox [34].

The paper is organized as follows: In Sec. 2, an overview of control strategies for fatigue load reduction is given, and the studied control strategies are presented in detail. In Sec. 3, the simulation setup is described, and controller performance parameters are established. In Sec. 4, the simulation results are presented and discussed. First, the baseline design case is evaluated, and the long-term effects of control strategies are assessed. Next, the trade-offs between fatigue load reduction and undesirable side-effects are investigated, and methodology to improve the overall performance is developed. Finally, applicability of control system design to compensate for differing fatigue loads due to varying site condtions, is assessed. The paper is concluded in Sec. 5.

2. Control concepts for fatigue load reduction

2.1. Overview of control strategies

Wind turbines harvest energy between a cut-in wind speed (typical $V_{In} = 4$ [m/s]) and a cut-out wind speed ($V_{Out} = 25$ [m/s]) [35]. Depending on the wind speed, the wind turbine control system operates in one of two modes. For wind speeds below the rated