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Fragility analysis of a 5-MW NREL wind turbine considering aero-elastic and seismic interaction using finite element method

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ABSTRACT

With the improvements and advances made in the field of renewable energy, this alternative method has become competitive with more traditional sources of energy generation techniques, including hydro power or fossil fuels. This has led to construction of wind turbines in areas prone to seismic activity. To increase the power production from wind energy, wind turbines have increased in size and mass, which makes them more vulnerable to lateral loads such as seismic induced forces, wind loads, and in the case of offshore wind turbines, wave loads. For this reason, computational analysis in the field are recently focusing on considering the interaction between lateral loads to present more realistic and cost effective designs. In this paper, the nonlinear dynamic behavior of a 5-MW NREL wind turbine is evaluated considering different earthquake and wind intensities using a newly developed finite element model. The model is first calibrated and verified with simplified models using modal and static pushover analysis. Engineering demand parameters (EDP) and intensity measures (IM) are then obtained from nonlinear incremental dynamic analysis (IDA) and used to assess the probability of exceeding different damage states (DS) using fragility curves. From the findings in this research, it is shown that earthquake loads have considerable effects on the design and analysis of wind turbines.

1. Introduction

For an efficient large scale application of wind energy, the cost of construction of wind turbines must be relatively near or less than the traditional methods of energy production, such as hydro power or fossil fuels. Using traditional methods for power production can lead to some drawbacks that include carbon emissions, hazardous waste disposal, high construction and maintenance costs, and potential for damaging ecosystems. With the rapid advancements in the recent decade in the wind energy industry, several countries in the world have focused their resources to take advantage of the power that can be generated from wind. According to recently published DOE report [1], by taking advantage of the growth in the wind technology industry and also by using the complete potential of the offshore wind from the east and west coasts of the US, the goal is to reach 20% of the total energy production in the US (300 GW) using wind energy by the end of 2030. In the year 2013 this value is estimated to be 61 GW and rapidly increasing.

The power that is generated from wind is proportional to the wind speed, and rotor diameter [2]. For this reason, to achieve the optimum power from the wind, rotor diameter has to increase in size. A larger rotor results in a higher mass at the top of the tower which will require a steel tower with higher load demands as discussed in [3,4]. Modern wind turbines are utilized with advanced control systems to enhance power production and to meet safety requirements in case of harsh environmental conditions. The blade pitch control system is responsible for controlling the aerodynamic load applied to the turbine. In case of a severe wind condition, the blade pitch control system will feather (rotate) the blades to decrease the lift forces produced on the blades and prevent the system from sustaining damage [5,6].

Recently, with the growth in the wind energy industry, various wind farms have been constructed in regions prone to high seismic activities. It is important to note that, as a coincidence, most of the regions in the world with high potential in wind resources also have a high seismic hazard [3,7]. These regions include, the Pacific Rim which contains the west coast of the United States, Japan, and the east coast of Asia. Modern turbines have increased in size and mass which leads to a decrease in natural frequency and for this

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reason they become more vulnerable to earthquake motions. Therefore, the interaction between earthquake, aerodynamic, and operational loading conditions is important in accurately determining ultimate demand for wind turbine tower structures.

The interaction between wind and earthquake and their effects on wind turbines is not yet well understood. Most of the research in this field considers multibody dynamic linear models with limited degrees of freedom [8,9] without considering earthquake excitation. There are three documents that provide direct guidelines for seismic design of wind turbines [10–12]. In these guidelines, wind turbines are represented in frequency domain and treated as a SDOF system. The structure is assumed to be linear, even in extreme load cases. IEC [10] and GL [11] rely on local building codes in the absence of specific provisions. The most recent publication is the ASCE/AWEA guideline for the design and permitting of large wind turbine support structures [13] which begins to address nonlinear response for large wind turbines. For buckling analysis, it is mentioned that a procedure that considers material and geometrical nonlinearity would be acceptable to obtain the design loads of the support structure.

Recently, with the advances in computational tools, researchers have started to consider the importance of seismic load for an operational wind turbine. Early work by Bazeos et al. [14] and Lavassas et al. [15] include consideration of seismic loading of wind turbines by focusing on the loading of the tower. These simplified models assume the tower top components (nacelle and rotor) to be a lumped mass for prototype 450-kW and 1 MW turbines with 38 m and 44 m tall steel towers designed for installation in Greece. The authors speculate that seismic design could become critical in regions with higher seismic hazard and less favorable soil conditions. Witcher [16] presented an overview of the GH Bladed [17] seismic module for a two megawatt upwind turbine with 80 m rotor diameter and 60 m tower height and considers the response of the structure in three different load cases of parked, operational, and earthquake induced emergency shutdown. The significance of time domain analysis and the effects of aerodynamic damping were emphasized in this work. Prowell et al. [18] conducted experimental work on a 65 kW Nordtank wind turbine using the large high performance outdoor shake table available in University of California at San Diego. Earthquake motions were applied in two horizontal directions and the modal characteristics and dynamic behavior of this turbine was obtained. This work also concluded that the importance of considering seismic demand increases as the turbines grow in capacity. Ishihara and Sawar [19] and Haenler [20] also studied the effects of aerodynamic and seismic loads using simplified methods.

More recently, an extensive investigation into the seismic response of a 1.65-MW Vestas turbines was conducted using ANSYS by Nuta et al. [21]. The authors developed fragility curves by performing incremental dynamic analysis and considering different intensity measures, damage measures, and damage states. However, the authors did not consider the effects of aerodynamic loads on the structure. The model included only the tower of the turbine with shell elements and different earthquakes with various intensities were applied to the base of the model. Seismic fragility analyses of the 5-MW offshore platform was also conducted by Kim et al. [22] with the consideration of soil–pile interactions using the properties of the soil layers. Stress at yielding, allowable stress, displacement at yielding, and allowable displacement were the damage criteria used to calculate the probability of failure in fragility analyses. However, in these two studies, aerodynamic loading was not considered in the analysis.

In this paper, fragility analysis of a 5-MW NREL [23] wind turbine considering aerodynamic and seismic load interaction is considered using finite element analysis. The structural and material properties of the studied turbine are described and the FE model is then calibrated and verified with the previous experimental and numerical research done in terms of modal analysis and natural frequencies. A suite of earthquake ground motion is selected and scaled for simulation on the FE model. Different wind intensities are also selected and applied as aerodynamic loads on the blade elements of the model in each time step. Fragility analyses are performed in the last step using different intensity measures (IM), engineering demand parameters (EDP), and damage states (DS) to reflect the nonlinear behavior of the turbine tower in different loading conditions.

2. Properties of 5-MW NREL wind turbine

The 5-MW NREL wind turbine model is intended to serve as a standard model for conceptual studies of modern multi megawatt offshore and onshore wind turbines. The definition of this turbine is described in detail in the report published in the National Wind Technology Center (NWTC) by Jonkman et al. [23]. Some of the properties of this turbine are presented in Table 1. The total mass of different components of the model is approximately 700 metric tons. Tower height and rotor diameter are 87.6 m and 126 m, respectively. From the fore-aft and side-side natural frequencies of the tower, it is concluded that the structure is quite flexible which will result in more sensitivity to lateral loading. Turbine tower material is made from HSS circular section A709 steel with a yield stress of 55 ksi (380 MPa) according to ASCE/AWEA [13] that mentions the consideration of high strength steel material for wind turbine towers. The turbine tower diameter and thickness reduce linearly along the height of the tower.

The finite element model is developed from the 5-MW NREL standard onshore reference turbine model descriptions published by the NWTC for the FAST code [24] using the commercial finite element program ABAQUS [25]. The tower is modeled according to the geometric properties using eight node quadratic shell elements. Material used for the tower has an elastic modulus of 210 GPa, Poisson ratio of 0.3, density of 8500 kg/m^3, and yield stress of 380 MPa. The density is above the typical steel value of 7850 kg/m^3 to account for paint, bolts, welds, and flanges that are not accounted for in the tower thickness data [23].

Table 2 shows the structural properties of the 5-MW NREL wind turbine. According to the recent research done on the effects of aerodynamic damping on the response of wind turbine structures in idle condition (non-operational turbine) the corresponding Rayleigh damping ratio is predicted to be between 0.5% and 1% of the critical damping [4,16,26]. A damping ratio of 5% is also considered to be used to contain the equivalent aerodynamic damping along with structural damping in the operational condition of a turbine. However, the magnitude of equivalent aerodynamic damping of operational turbine varies with the wind speed. In previous work done by authors [4], the equivalent

Table 1
Properties of the 5-MW NREL wind turbine.

Property	Description
Rated power	5-MW
Rated wind speed	11.4 mps
Tower height	87.6 m
Mass of rotor	111,000 kg
Mass of nacelle	240,000 kg
Mass of tower	347,460 kg
1st tower fore-aft freq.	0.32 Hz
1st tower side-side freq.	0.31 Hz
2nd tower fore-aft freq.	2.90 Hz
2nd tower side-side freq.	2.93 Hz