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Improved reliability of wind turbine towers with active tuned mass dampers (ATMDs)

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ABSTRACT

Modern multi-megawatt wind turbines are composed of slender, flexible, and lightly damped blades and towers. These components exhibit high susceptibility to wind-induced vibrations. As the size, flexibility and cost of the towers have increased in recent years, the need to protect these structures against damage induced by turbulent aerodynamic loading has become apparent. This paper combines structural dynamic models and probabilistic assessment tools to demonstrate improvements in structural reliability when modern wind turbine towers are equipped with active tuned mass dampers (ATMDs). This study proposes a multi-modal wind turbine model for wind turbine control design and analysis. This study incorporates an ATMD into the tower of this model. The model is subjected to stochastically generated wind loads of varying speeds to develop wind-induced probabilistic demand models for towers of modern multi-megawatt wind turbines under structural uncertainty. Numerical simulations have been carried out to ascertain the effectiveness of the active control system to improve the structural performance of the wind turbine and its reliability. The study constructs fragility curves, which illustrate reductions in the vulnerability of towers to wind loading owing to the inclusion of the damper. Results show that the active controller is successful in increasing the reliability of the tower responses. According to the analysis carried out in this paper, a strong reduction of the probability of exceeding a given displacement at the rated wind speed has been observed.

1. Introduction

Developing an economically viable supply of renewable and sustainable energy is one of the biggest challenges facing our society today. To achieve such an energy supply, wind energy will likely provide the main renewable contribution in the coming decades. The move towards wind energy has been driven primarily by cost. Wind turbine prices have fallen by almost a third since 2009. Wind power has become the least cost option when adding new capacity to the power grid in an increasing number of markets, and prices continue to fall. Some onshore wind farms are now delivering electricity for as little as 4 US cents per kWh [1]. Nuclear power costs three times more to produce in the Americas than onshore wind and energy from new coal/gas-fired power plants costs up to 30% more in Europe, the Middle East and Africa [1]. Due to these huge reductions in the cost of wind energy, the past decade has seen rapid growth and expansion of wind turbines and wind farms worldwide. The Global Wind Energy Council (GWEC) calculated the global total installed capacity for wind power at the end of 2015 as 432.9 GW [2], this represents an increase of over 600% compared to the 2005 figure of 59.1 GW [3]. This exponential increase in installed capacity

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in only ten years has been made possible due to developments in wind turbine technology and design.

Wind turbines are now the largest rotating machines on Earth. The past decade has seen the size of wind turbine blades and towers increase dramatically. Current state-of-the-art wind turbines have very large, flexible blades and are supported by very tall, slender towers. These components are manufactured from lightweight high-strength materials and as such they are very flexible and lightly damped. Due to their structural characteristics, wind turbine towers are very susceptible to wind induced vibrations and they may undergo significant vibration during operation under turbulent aerodynamic loads. It has been well known for over a decade that blade and tower vibrations can have a negative impact on power production [4]. Tower vibrations may slow down wind energy conversion to electrical power and reduce the fatigue life of the structure [5]. Dueñas-Osorio and Basu investigated wind turbine unavailability as a function of wind-induced vibration of the tower. Tower vibration can lead to the malfunction of acceleration-sensitive equipment housed in the nacelle of the wind turbine, resulting in reduced annual wind turbine availability [6]. Moreover, a significant number of tower collapses have been attributed to excessive tower vibration during strong wind events [7]. It is clear then, that modern wind turbine towers are susceptible to vibration issues which may have significant negative impacts on downtime, lifetime of the components, and even on the overall integrity of the structural system. These impacts will have associated implications for the cost of wind power. Therefore, there is now increasing interest in reducing the harmful effects of mechanical vibration on wind turbine towers in the wind energy industry.

The wind energy industry is currently applying technologies and techniques developed in the fields of structural control and health monitoring to reduce vibrations in towers. The application of structural control strategies to wind turbines is now a very active area of research. Murtagh et al. [8] and Lackner and Rotea [9] investigated the use of passive tuned mass dampers (TMDs) to reduce tower vibrations. Si et al. [10] developed a model for a spar-type floating wind turbine with a passive TMD in the platform, the TMD parameters were tuned optimally. Si et al. [11] also developed a model of a spar-type floating wind turbine with a tuned mass damper (TMD) installed in nacelle. Dinh and Basu used passive TMDs to control edgewise vibrations of nacelle/tower and spar of spar-type floating wind turbines [12]. Colwell and Basu [5] used a passive Tuned Liquid Column Damper (TLCD) to reduce vibrations of offshore wind turbine towers. Arrigan et al. [13] and Fitzgerald et al. [14] developed semi-active TMDs to control the vibrations of wind turbine towers and blades. Karimi et al. investigated a semi-active control device to mitigate the vibration of offshore wind turbine tower vibrations [15]. A tuned liquid column damper was used with a controllable valve as an external damping device to mitigate with wind turbine vibrations due to wind and earthquake loads. Caterino [16] has also investigated semi-active control in wind turbines using MR dampers. There has been recent work published on active control of tower vibrations. Lackner and Rotea [17], Fitzgerald and Basu [18], and Fitzgerald et al. [19] have investigated the use of active structural control techniques with mass dampers for mitigating vibrations in wind turbine blades and towers. Innovative hardware configurations adopting active elements mounted in wind turbine towers have also been proposed by Fitzgerald and Basu [20] and Staino et al. [21].

Although much work has been done in recent years on structural control of wind turbines, there is sparse literature available which demonstrates the capability of structural control schemes to improve the reliability of wind turbine components. Quilligan et al. [22] and Kim et al. [23] have recently used reliability methods to assess the performance of wind turbines, however, these studies did not focus on structural control. Improving the structural reliability of wind turbines is a key concern. Avoiding damage and failures in wind energy systems is important because of the impact of downtime on annual energy production and hence the cost of energy. This is especially valid for offshore wind power since the consequences of a failure offshore are more severe in terms of additional downtime due to limited accessibility, the complexity of offshore repairs and hence the overall production costs [24]. Mensah and Dueñas-Osorio [25] recently demonstrated that the use of TLCDs in turbine towers can help achieve long-term reliability and risk targets for utility scale wind turbines.

In this paper, a flexible wind turbine model is proposed in order to study the dynamics of wind turbine vibrations, including the coupling between the in-plane and the out-of-plane modes of the blade due to the structural pre-twist of the blade. A multi-modal representation of the flexible elements (the three blades and the tower) is adopted. The equations of motion are derived by taking into account the blade-tower interaction. Turbulence, vertical wind shear and tower shadow effects are considered in calculating the aerodynamic loads on the structure. An active vibration controller is designed to suppress undesired turbine tower vibrations. The control is implemented by means of an ATMD located at the top of the tower with the aim of reducing the fore-aft vibrations of the tower.

The wind turbine model is used to estimate the displacement of the tower in order to assess the reliability of the system [6]. The dynamic behaviour of the turbine subjected to turbulent aerodynamic loads is investigated in a probabilistic framework. Uncertainty in the dynamic properties of the wind turbine is assumed to obtain a distribution of turbine response for various levels of wind speed. This distribution is then used to develop wind-induced tower fragility curves for the considered wind turbine model. The analysis is carried out on the model with and without the application of the active vibration controller. Results indicate that the proposed controller reduces the probability of exceeding a given displacement limit at various wind speeds and thus it improves the reliability of the tower response.

2. Wind turbine structural model

2.1. Uncontrolled model

A schematic of the uncontrolled model is shown in Fig. 1. The in-plane and out-of-plane vibrations of the ith blade are modelled by two generalized DOFs, $q_{i,in}(t)$ and $q_{i,out}(t)$. The coupled in-plane and out-of-plane mode shapes, $\phi_{in}(x)$ and $\phi_{out}(x)$,