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Probabilistic capacity assessment of single circuit transmission tower-line system subjected to strong winds☆

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ABSTRACT

The safety and resilience of physical infrastructure of the power systems, including the transmission towers and lines for high-voltage transmission as well as the poles and wires for power distribution at a lower voltage level, is critical to avoid and recover from power outages under the extreme weather related loads such as strong winds from hurricanes, tornados, downbursts or isolated thunderstorms. In the current engineering practices, single circuit lattice steel towers linked by transmission lines are widely used to form power transmission systems. Failure of either a structural component (local failures, such as buckling of a local member or breakage of a single wire) or the entire structure (global failures, such as instability of the entire tower) could propagate to their adjacent structural members or systems (such as neighboring towers or lines). Therefore, there is a strong need to identify the root cause of the failure of the transmission tower-line system and identify the weakest link under various extreme weather scenarios. This study is to develop a probabilistic assessment approach for a typical transmission tower-line system subjected to strong wind loadings under synoptic winds (atmospheric boundary layer wind). Due to the complicated structural details and complex wind-structure interactions, wind tunnel experiments were carried out to obtain the static wind load coefficients for different panels of the transmission towers as well as for the transmission lines. Incremental dynamic analysis (IDA) is carried out to obtain the capacity curve for the transmission tower-line system. Uncertainties from the meteorological parameters are also considered in the analysis. The probabilities of failure for the two predefined limit state functions are obtained considering the meteorological uncertainties. Meanwhile, the probabilities of failure at different return periods are presented for a transmission tower-line system subjected to strong winds in a coastal region. Finally, the effects of the aerodynamic damping for the transmission lines on the dynamic responses of the tower-line system are discussed, as well.

1. Introduction

The transmission tower-line system, consisting of lattice steel towers and conductors, plays an important role in the power transmission and distribution network. Under a complex of threats from natural hazards and man-made disasters, the failure of individual structural components and/or system and the possible cascading failures could cause large area blackouts with a huge economic loss, which are of great concern to the stakeholders, decision makers and the community residents. Under a continuous effort, taller high-voltage transmission towers connected by longer span conductors have been built to meet the economic development and the power needs in the communities. Even carefully following the design codes and specifications, many transmission towers and/or lines could still collapse and/or break under strong winds, such as those from hurricanes, tornados, or isolated thunderstorms, due to the lack of the understanding of the structural performance and failure modes of the transmission tower-line system as well as the surrounding complex wind environment. For example, in the Americas, Australia and South Africa, about 80% of the transmission tower failures are due to the strong wind loadings from the extreme weather events and such failures could lead to large area power outages [12,20,29]. Therefore, understanding the structural capacity of the transmission tower-line system and the characteristics of the interactions between structures and strong winds are essential to avoid future failure of the transmission tower-line system and achieve a quick recovery of regional areas from future extreme natural hazards.

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As discussed earlier, many design codes, specifications or manuals are available for the transmission tower-line system design, such as the CSA C22.3 No. 60826-10 [9], the International Electrotechnical Commission (IEC) Standard 60826:2003 [19], and the ASCE Manual 74 [3], etc. In these codes or design manuals, only linear elastic behavior is considered. However, under the strong winds, the nonlinear inelastic behavior could become dominated, which could be crucial for evaluating the structural safety and reliability. Also in these codes, the wind loads, defined in an orthogonal approach, are only modeled in the transverse and longitudinal directions, which could lead to a significant deviation for modeling wind drag forces in other wind directions [26]. In addition, the design procedures only include the wind loads on the conductors as quasi-steady dynamic loads at the wire attachment points. Full dynamic interactions between the transmission towers and conductors are not considered. Meanwhile, the drag coefficient of the lattice frames is based on the solidity ratio in the design codes, which could not effectively represent the load distributions of the wind drag forces on the transmission towers with different structural geometries. To better understand wind-structure interactions, wind tunnel experiments are usually carried out to obtain the drag coefficients of the towers and conductors in different wind directions considering their real geometry [24,25,27].

Due to the localized and unpredictable characteristics of the wind environment at different sites, the wind time histories and the drag forces acting on the transmission tower-line system could be site specific and result in different performance of the transmission tower-line system comparing with those defined in the codes or specifications. Meanwhile, the non-stationary wind gusts caused by extreme storm events could also lead to significant differences in structural responses [23,29,30]. In addition, with a more dynamic climate environment, more extreme weather events are expected leading to a more adverse service condition with a potential increase in the failure probability of structures [28]. Therefore, it is essential to evaluate structural performance systematically in different limit states for various failure modes to meet the arising challenges of infrastructure management and the associated cost-benefit optimization demand [37]. In addition, the associated uncertainties from the structures as well as the built environments should also be integrated with other related heterogeneous data in a probabilistic framework to understand the relationship between the extreme meteorological events and structural failures.

Recently, a number of studies were carried out to evaluate the dynamic response of the transmission tower-line system subjected to synoptic winds and non-synoptic winds and the effect of aerodynamic damping on conductors was investigated as well. Zhang et al. [37] carried out the capacity assessment of a single transmission tower without conductors with one defined limit state. To improve the simulation accuracy especially considering the tower and line interactions, an improved probabilistic assessment was carried out to evaluate the system performance of the transmission tower-line system subjected to strong winds. Aboshosha and El Damatty [1] assessed the importance of including the dynamic effect for the response of multiple-spanned and single-spanned conductors under both synoptic winds and down bursts. The total response was separated into the mean, background, and resonant component in their study and the effect of the aerodynamic damping on reducing the resonant component was discussed. A review of the previously conducted works related to the dynamic response of a transmission tower-line system under both synoptic and non-synoptic wind loads was made by Aboshosha et al. [2]. In their studies, discrepancies between different design codes were assessed and limitations and gaps in the current design codes were identified. Meanwhile, several suggestions were made for options on filling the research gaps. Elawady et al. [15]experimentally assessed the dynamic response of a multi-span transmission line subjected to downburst winds in terms of the dynamic magnification factor calculated from their proposed decomposition approach. To further evaluate the aeroelastic characteristics and structural response of a guyed transmission line system subjected to boundary layer winds, boundary layer wind tunnel tests were conducted under different wind speeds and wind directions by Hamada et al. [18]. Their study showed that the transmission line system responded in a quasi-static manner to boundary layer wind loads and the resonant dynamic response component became less significant as the wind speed increased due to the aerodynamic damping effect. The present paper is organized as the following. At first, a numerical model for the transmission tower-line system is built using the commercial software ANSYS. Meanwhile, a randomly generated wind time history is used to model the wind loads considering both the vertical correlation within the tower height and the horizontal correlation along the conductors. Next, wind tunnel experiments are carried out to obtain the varying drag coefficients for different panels of the transmission tower as well as for the conductors in different wind yaw angles. After implementing the incremental dynamic analysis (IDA), capacity curves for different wind yaw angles are obtained followed by a probabilistic assessment approach based on the peak values extraction and fitting method. After defining two limit states for the transmission tower-line system, the probabilities of failure for each failure mode and the entire tower-line system are evaluated for all wind yaw angles based on the meteorological data at a given site. The effects of the aerodynamic damping for each failure mode on the structural responses are discussed, as well. Finally, some brief conclusions are drawn and potential improvements for evaluating the entire transmission tower-line system are proposed.

2. Modeling of the tower-line system and the wind loading

2.1. Finite element modeling of the transmission tower-line system

The transmission tower-line system is modeled in ANSYS including three single circuit lattice steel towers with the same design, which are connected by three four-bundled conductors. Four spans are modeled and the two ends of the conductors are fixed as shown in Fig. 1. The prototype of a single transmission tower is shown in Fig. 2. The 550-kV transmission tower is 68.6 m high and has a square base. The side length of the square base is 14.094 m. The tower is built with the steel angle sections. The elastic modulus of the steel is 210 GPa. Bilinear elastoplastic material property is adopted with a 235 MPa yield strength and after that a 1% stress-strain relationship is adopted. Due to the potential large deformation in the analysis, the geometry nonlinearity is also included.

The distance between the adjacent towers is 450 m and the conductor sag is 18 m as designed based on the catenary equation leading to a sag-to-span ratio of 0.04. Because the two ground lines on the top have very small diameters compared with the conductors, the wind drag forces are neglected and the two ground lines are not modeled in the structural model. Detailed properties of a single cable among the four-bundled conductor are listed in Table 1. The conductors are connected to the transmission towers using the suspension insulator strings. Each string is composed of 34 insulators each with the mass of 13 kg.

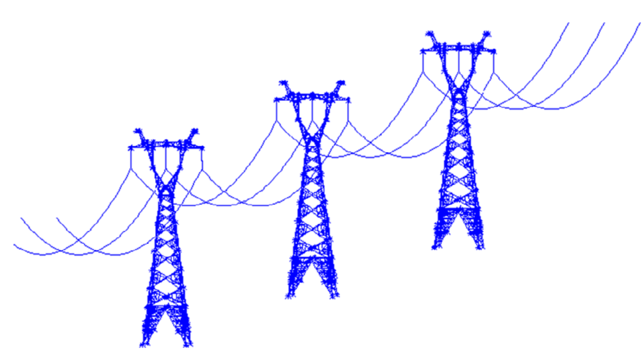

Fig. 1. Model of the transmission tower-line system.

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