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Behaviour of guyed transmission line structures under tornado wind loading

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ABSTRACT

Localized severe wind events, in the form of downbursts and tornadoes, are responsible of the majority of transmission line structures failures in many regions around the globe. The wind profiles associated with these events are different than the conventional boundary layer wind profile that is typically used to design the supporting towers. A comprehensive study is presented in this paper to assess and understand the performance of transmission line structures under tornado loading. The study is conducted numerically using a three-dimensional finite-element model and incorporates velocity fields for various tornado scales, which are based on a computational fluid dynamics analysis. The numerical model accounts for the nonlinear behaviour of the conductors, ground-wires, and supporting guys. An extensive parametric study is conducted by varying the location of F4 and F2 tornadoes relative to the transmission line system. The study investigates the variation of the tower members' internal forces with the tornado locations. It also provides an insight about the structural response of the towers under tornado wind loads. The dynamic effect associated with the translation motion of the tornado is assessed. Finally, the results of the parametric study are used to assess the sensitivity of the members' peak forces with the parameters defining the location of the tornado relative to the line.

1. Introduction

Localized severe wind events, in the form of downbursts and tornadoes, are referred to as "High Intensity Winds (HIW)". Weather-related events are responsible for most of transmission line failures worldwide [1,2]. The wind loads specified in the design codes for transmission line structures are based on large-scale wind storms with conventional boundary layer wind profile. The wind fields associated with HIW have different profiles and unique characteristics compared to the boundary layer wind fields of large-scale events. Accordingly, wind loads due to HIW are different than those associated with the large-scale events. The research presented in this study is part of an extensive research program conducted at The University of Western Ontario, Canada, in order to understand the behaviour of transmission line structures under HIW. The current study focuses on assessing the behaviour of guyed transmission towers under tornado wind loading.

The development process of HIW, which usually occur during thunderstorms, was described by [3]. A tornado was defined by Fujita [4] as a rotating wind vortex moving at high speeds, affecting a relatively narrow path. Despite the many failures of transmission towers resulting from HIW events, research studies related to this subject have been limited. Previous studies can be classified into two categories: (a) studies conducted to identify the wind field associated with HIW, and (b) studies conducted to assess the structural response of transmission lines during HIW. Fujita and Pearson [5] classified tornadoes based on their intensity and size. The intensities are defined by the gust wind speed, and the sizes are defined by the path length and width. The rating ranges from the smallest damage, "F0", to the largest, "F5". Field measurements for tornadoes were conducted by [6,7] for two different F4 tornadoes. Due to the difficulty of obtaining full-scale data, especially for the near ground region, laboratory simulations are used. These include Tornado Vortex Chambers (TVC), in which tornadoes are represented as vortices. The TVC's provide a good simulation of the characteristics inside a tornado, but the results have been found to be sensitive and easily affected by the applied boundary conditions. For the near ground region, numerical simulations can provide a good assessment for the flow field. A computational fluid dynamics (CFD) simulation for a small-scale tornado model was conducted by [8] using the commercial program FLUENT. The obtained wind field was validated in view of the experimental program conducted by [9] using a Ward-type vortex chamber. The CFD data for tornadoes conducted by [8] is given in a steady-state manner, i.e. has no variation with time. It was shown to match reasonably well with full-scale tornado measurements [8]. To the best of the authors' knowledge, it represents the only CFD data for tornadoes available in the literature. This CFD velocity field for tornadoes were developed assuming smooth ground surface, and

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without considering both the topographical effect and the wind–structure interaction that might occur with the transmission line components. In addition, This CFD model does not include a turbulence component.

The failure of a self-supported lattice tower under tornadoes and downburst wind profiles was investigated by [10]. The tornado wind profile used in this study is based on the model developed by [11]. The chosen tornado corresponded to F3 on the Fujita scale. Dynamic analysis was conducted for the tower alone, without modelling the transmission lines, and without considering the vertical velocity component of the tornado field. Shehata et al. [12] evaluated the natural periods of the same transmission line considered in the current study, and recommended to proceed with static analysis, due to the significant difference between the period of loading and the natural periods of the structure. Chay et al. [13], and Darwish et al. [14] investigated the dynamic behaviour of the transmission line system, taking into account the turbulent component of downbursts. It can be concluded from previous studies that no significant dynamic effect occurs when turbulence is not included in the analysis of transmission lines under high intensity wind loading. Hamada et al. [15] developed a numerical model for the analysis of transmission lines under tornadoes. The model included a simulation for the towers and the conductors. The wind field resulting from Hangan and Kim [8] simulation was included in this numerical model. Due to the localized nature of HIW, the corresponding wind loads acting on the tower and the conductors vary significantly with the location of the HIW event relative to the tower. Various tower members can have different critical HIW locations that lead to maximum forces in these members. This was also shown in the studies conducted by [16–18] to assess the behaviour of guyed transmission lines under downburst loading.

In the current study, the numerical model developed by [15] is used to conduct an extensive parametric study to assess the behaviour of a guyed transmission tower under tornado loading. The model includes a simulation for the tower of interest in addition to a number of adjacent towers and the in-between conductors and ground-wires. The dynamic effect resulting from the translation motion of the tornado is first assessed through time history analysis. An extensive parametric study, involving a large number of quasi-static analyses, is conducted by varying the location of the tornado relative to the tower of interest. A nonlinear finite-element analysis is conducted under the tornado loads associated with each tornado location. The maximum and minimum internal forces obtained from the entire analyses are determined for all the tower members. The parametric study is conducted using both the F2 and the F4 tornado wind fields. The paper starts by briefly describing the applied tornado wind fields. This is followed by a brief description of the finite-element model. Results of the dynamic analysis and the quasi-static parametric study are presented, and then used to describe the structural behaviour of the tower under tornado loading. The results of the parametric study are then used to assess the sensitivity of the members' peak forces with the parameters defining the location of the tornado. Finally, the main conclusions obtained from the study are presented.

2. F4 and F2 tornado wind field

A computational fluid dynamics (CFD) simulation for a small-scale tornado model was conducted by [8] using the commercial program FLUENT. The simulation was first conducted using a swirl ratio S of 0.28, where S is the ratio between the tangential and radial velocity at the inlet boundary. This value of 0.28 represents the swirl ratio applied in the experimental program conducted by [9] using a Ward-type vortex chamber. The experimental results were used to validate the CFD model. The numerical analysis was then extended by [8] by considering values for $S = 0.10$, 0.4, 0.7, 0.8, 1.0 and 2.0, respectively.

By comparing the numerical results to the field measurements, [8] estimated that the F4 tornado corresponds to a CFD model with swirl ratio $S = 2$. The proper length "$L_s = 4000$" and velocity scale "$V_s = 13$" factors between the numerical and the full-scale data were also established in the same study. In the study conducted by [15], it was established that a swirl ratio $S = 1$ provides a good simulation for the F2 scale tornadoes. As such, the wind fields of fully developed F4 and F2 tornadoes can be estimated from the CFD data corresponding to $S = 2$ and 1, respectively, after scaling the data using the length "$L_s = 4000$" and velocity scale "$V_s = 13$" factors. The velocity profiles vary in space in a three dimensional manner, and are presented as functions of the cylindrical coordinates r, θ and z, measured relative to the tornado centres. The tornado wind fields have three velocity components; the axial component $V_{ma}(r, \theta, z)$, the radial component $V_{mr}(r, \theta, z)$, and the tangential component $V_{mt}(r, \theta, z)$. In addition to the three-dimensional wind field, an axisymmetric wind field for a F4 tornado is generated by averaging the three velocity components along the circumferential direction, eliminating the variation of the velocities with θ. More details regarding the F4 and F2 tornado wind fields are provided by [15].

3. Finite-element modelling of transmission line system

The transmission line system simulated in the current study is a generic guyed tower used in Manitoba Hydro transmission line systems. The chosen guyed tower is labelled as Type A-402-0. The tower height is 44.39 (m) and is supported by four guys attached to the tower, with two cross-arms at an elevation 35.18 (m) relative to the ground. Two conductors are connected to the towers cross-arms using a 4.27 (m) insulator at a height of 38.23 (m). One ground-wire is connected to the top of the tower. The conductors and ground-wire span is 480 (m). The conductors and ground-wire sags are 20 (m) and 13 (m), respectively. Fig. 1 shows a schematic of the transmission line system. The geometric and material properties of the conductors, ground-wire, and guys are provided by [12].

The simulated transmission line system consists of the tower of interest and two towers from each side, which are included in order to properly simulate the rigidity of the system. As shown in Fig. 1, the model includes five towers with six bays for conductors and ground-wire. Such a number of bays was recommended by [12], in order to accurately account for the forces transferred from the conductors to the tower of interest. The transmission line system is modelled using the numerical finite-element commercial program SAP 2000. As shown in Fig. 2, the tower is divided into seven zones. Zones 1–5 are located below the supporting guys. Zone 6 represents the cross-arm area of the conductors and the guys. Zone 7 is the upper part of the tower, which supports the ground-wire.

The tower members are modelled using two nodded three-dimensional frame elements. Each member is modelled using one element, with three translation and three rotational degrees of freedom per node. Rigid connections are assumed between the tower members in order to simulate the multi bolted connections used in the construction of the tower.

Three-dimensional nonlinear cable elements are used to model the conductors, the ground-wire and the guys. The element has three translational degrees of freedom at each end node. Conductors and ground-wires exhibit highly nonlinear behaviour, due to their elastic catenary behaviour, large spans and slender cross