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Critical load cases for lattice transmission line structures subjected to downbursts: Economic implications for design of transmission lines

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ABSTRACT

An extensive research program was recently conducted at The University of Western Ontario, Canada to investigate the load profiles that can be used in the analysis and the design of transmission towers subjected to downbursts. This research was motivated by many transmission line failures that have occurred in different locations around the globe during downburst events. It was also triggered by the fact that the existing codes of practice and guidelines provide very limited information regarding the critical load profiles associated with downbursts, which act on the towers and conductors of a transmission line system. One of the challenges in predicting the critical forces acting on the towers and conductors is that they are not only dependent on the magnitude of the event but also on its size and location relative to the center of the tower. This complexity results from the localized nature of such events. In the current study, an extensive parametric study is conducted on a number of transmission line systems to evaluate their critical response to downburst loads. The study considers the variations in the downburst location, angle of attack, and size to determine the effect of changing these parameters on the response of the transmission line systems. Based on the results obtained from this parametric study, three critical load cases are identified. The studied towers are then used to assess the economic impact of applying those load cases, expressed by the increase in the weight of the tower.

1. Introduction

A downburst is defined as a mass of cold and moist air that drops suddenly from a thunderstorm cloud base, impinges on the ground surface, and then horizontally diverges from the center of impact [1]. Past reports indicated that about 80% of the weather-related transmission line failures have been attributed to High Intensity Wind (HIW) events in the form of downbursts and tornadoes [2]. In Canada, McCarthy and Melsness [3] reported a series of transmission tower failures under HIW events that belong to the Manitoba Hydro Company. More recently, two 500 kV guyed towers failed during a severe thunderstorm in August 2006 belonging to Hydro One, Ontario, Canada (Hydro One failure report [4]). In the USA, a recent report released by the Executive Office of the President [5] estimated that more than 600 power outages occurred due to severe weather. The report stated that the annual average of financial losses due to the weather-related outages over this period ranged between $18 billion to $33 billion. In China, Zhang [6] reported the failure of 18 (500 kV) and 57 (110 kV) transmission line structures that occurred in 2005 under severe wind events such as typhoons, tornadoes, and downbursts. In addition to the economic losses, the social implications for the affected society due to such outage are tremendous.

Downbursts have unique characteristics compared to synoptic winds such as hurricanes and typhoons. One of those characteristics is the localized nature of downbursts with respect to space and time. The wind field associated with downbursts is quite complicated as it varies from one location to another depending on the distance from the downburst center. The vertical profile of the downburst wind field also varies depending on the location. This profile can differ from the typical boundary layer profile, which is currently used in the design codes. For long span structures such as transmission lines in which towers and conductors extend for many kilometers, the localized nature of the downbursts might result in a non-uniform and unsymmetrical distribution of the wind loads over the line spans. This results in load cases that do not usually exist under uniform and symmetrical large-scale wind events. Despite the large number of failures reported due to downbursts and the unique characteristics of the downburst wind field, the design codes do not provide enough information about critical downburst loads, which should be considered in the design of transmission line structures. The purpose of this research is to fill in this gap.

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A limited of attempts to conduct downburst field measurements are found in the literature. Wolfson et al. [7] reported the field measurements of the FAA/Lincoln Laboratory Operational Weather Studies (FLOWS) where different intensities and durations of downbursts were recorded. Fujita [1] characterized the downburst wind field using the field measurements of Northern Illinois Meteorological Research (NIMROD) and the Joint Airport Weather Studies (JAWS). Hjelmfelt [8] reported a number of individual and line microbursts in Colorado. Recently, a number of downbursts were recorded, classified, and analyzed as a part of the Ports and Winds project in Italy [9–11]. Similarly, Lombardo et al. [12] characterized the downburst wind events recorded in Texas, USA for the period 2003–2010. Despite of the merit provided in the mentioned studies regarding the analysis of the downburst flow field parameters, turbulence characterization, and intensities, available field measurements do not provide data for the spatial variation of downburst which is fundamental for long span structures. Numerical simulations of downbursts have be conducted using one of the following techniques: (a) Ring Vortex Model, (b) Impinging Jet (Impulsive Jet) Model, and (c) Cooling Source (Buoyancy-Driven) Model. The literature related to this subject includes a number of numerical studies conducted to characterize the downburst wind field. Zhu and Etkin [13] used the ring vortex model to simulate the vortex ring formed during the descent of the downburst. Vermeire et al. [14] used the cooling source model to examine the initiation of the event inside a cloud. Kim and Hangan [15] adopted the impinging jet approach using the Reynolds Averaged Navier-Stockes (RANS) equations to simulate the downburst wind field. This yielded a time series of the mean radial and vertical velocity components of the downbursts. Using the impinging jet model, Aboshosha et al. [16] utilized the Large Eddy Simulations (LES) to account for the fluctuating component. In addition, a number of experimental studies explored the downburst flow field using axisymmetric jet impinging on a flat surface [17–20]. Most of the experimental studies utilized small geometries for the jet diameter, which limits the structural applications especially for long span structures such as transmission lines. In order to simulate a relatively large-scale downburst that can be used for structural applications, Lin and Savory [21] simulated downburst-like profile using a slot jet with a controllable gate in boundary layer wind tunnel. Recently, the authors conducted a large-scale experimental simulation of the downburst (diameter considered was 3.2 m) flow at the Wind Engineering, Energy and Environment Research Institute (WindEEE RI) in Canada [22]."

The numerical, experimental and field measurements studies indicated that the mean component of the downburst winds varies with time. As such, the mean component has been referred to as a "varying-mean" or "mobile-mean" [9,15,16,22,23]. Accordingly, a temporal decomposition needs to be applied to separate the mean and fluctuating components. In a number of studies, such as Aboshsosha et al. [16], Elawady et al. [22], the mean component of the wind field was separated from the turbulence component assuming that the cut-off frequency is higher than the shedding frequency of the ring vortices. This approach have shown a good agreement with the averaging periods suggested by Holmes et al. [23] and Solari et al. [9] for particular measured events. More discussion about downburst characteristics is provided in Section 2.1.

Few studies focused on assessing the behaviour of transmission tower systems under downbursts. The first study reported in the literature was conducted by Savory et al. [24] in which they modelled a single self-supported tower with no conductors attached. In their study, the vertical profile of the downburst mean radial velocity was evaluated based on an analytical expression obtained from a wall jet simulation conducted used by Vicroy [25]. Savory et al. [24] reported that the self-supported tower was more vulnerable to tornadoes than to downbursts. Probably this conclusion resulted from the exclusion of the conductors in the numerical modelling. Downbursts are significantly larger than tornadoes and as such they are expected to engulf a larger portions of the conductors compared to tornadoes. Shehata et al. [26] and Darwish and El Damatty [27] studied the behaviour of guyed and self-supported transmission line systems subjected to downburst loadings, respectively. Both studies were conducted in a quasi-static manner where the time variations of the mean component of the downburst field was considered. The two studies reported possible loading scenarios of the downburst causing peak internal forces in the towers' members. These studies showed that the spatial parameters of the downburst control the intensity of the loads imposed on the transmission line. Fig. 1 illustrates the spatial parameters of the downburst that affect the loading acting on a tower and the attached conductors. Those parameters are the downburst jet diameter (D_J), the radial distance (R), and the angle of attack (Θ). Wang et al. [28] conducted a quasi-static analysis where they utilized an empirical lateral force model to assess the dynamic response of a high rise transmission tower, with no conductors attached, to downburst forces. Mara et al. [29] compared the load-deformation curve of a transmission tower when subjected to both downburst and normal winds. Their study showed that normal wind capacity curves can be used as an approximate alternative for those capacity curves resulting from downbursts. Elawady and El Damatty [30] assessed the longitudinal response of the conductors of transmission lines to the oblique downburst cases. The oblique downburst loading scenarios occur when the downburst acts with an angle of attack Θ, illustrated in Fig. 1, where $0° < \Theta < 90°$. In their study, Elawady and El Damatty [30] provided a simple approach to estimate conductor's longitudinal forces using a number of charts and linear interpolation equations. Yang and Zhang [31] analyzed two transmission towers under both normal and downburst winds. In their study, Yang and Zhang [31] considered the wind loads acting on the conductors as a simplified resultant vertical and lateral forces at the insulators' connections while ignoring the spatial localization of the downburst winds.

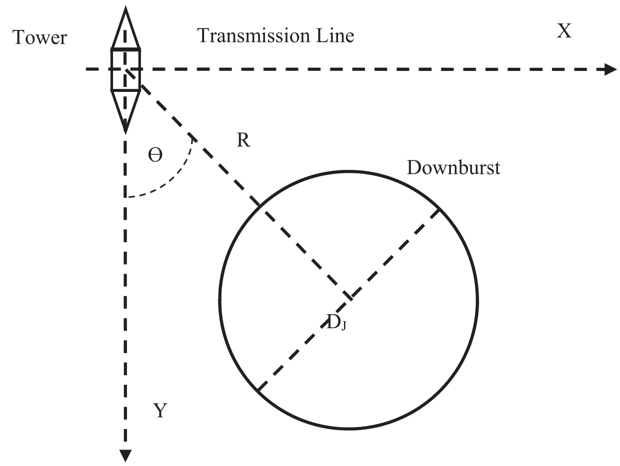

Fig. 1. Downburst characteristic parameters.

The characterization of the downburst wind field showed that the frequency of the mean component of the wind field is less than 0.05 Hz [15]. This frequency is much less than the frequency of the towers, which is typically higher than 1 Hz [32]. Darwish et al. [33] found that the conductors' frequencies ranged between 0.06 and 0.1 Hz, which indicates a potential sensitivity to dynamic excitations. Darwish et al. [33] utilized the field measurements reported by Holmes et al. [23] and extracted the turbulent component, which was assumed to not vary spatially. This was used to assess the dynamic response of the transmission line conductors. The study showed that the aerodynamic damping of the conductors tends to attenuate its vibration and, therefore, no dynamic response is anticipated for the conductors. This was confirmed by Aboshosha and El Damatty [34] who showed that the transverse and the longitudinal forces transmitted from the conductors to the tower increased by only 5% and 6%, respectively, with the