DEVELOPMENT OF CRITICAL LOAD CASES SIMULATING THE EFFECT OF DOWNBURSTS AND TORNDOS ON TRANSMISSION LINE STRUCTURES

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ABSTRACT

In the past decades, many failure incidents for transmission line structures were observed during High Intensity Wind (HIW) events, in the form of downbursts and tornados, in North America, Australia, and other locations around the globe. Examining design codes pertaining to this type of structures reveals the lack of procedures to determine the wind loading acting on transmission tower systems due to High Intensity events. A major challenge in the analysis and design of structures under HIW is the localized nature of these events, which makes the forces acting on the towers and lines dependent on the location and characteristics of the event. Motivated by the failure of number of transmission towers in Canada, an extensive research program was initiated at the University of Western Ontario (UWO) a decade ago and is still progressing with final aim for developing knowledge and information for designing transmission line structures to sustain HIW events. The current paper covers the two types of HIW events: tornados and downbursts. For each event, a literature review is provided followed by a summary of the outcomes of the research conducted at UWO and a description of the wind field. The main contribution in this paper is the introduction of procedures to account for the critical effects of HIW on transmission line structures. Using the knowledge gained from years of research on this subject, critical load cases and load profiles simulating the downburst and tornado configurations that are critical for transmission towers are identified and presented in a format that can be implemented in design codes and can be used by practitioners.

Keywords: Tornados, Downburst, Transmission lines, Finite Element, Loads

Introduction

Localized severe wind events in the form of tornados and downbursts are referred to as “High Intensity Wind” (HIW) events. They are usually associated with thunderstorms, which contain masses of rising air (updrafts) and descending air (downdrafts). The updrafts are formed by warm moist air and downdrafts are formed by colder air. Downbursts occur at the downdrafts, while tornados occur at the updrafts. HIW events are believed to be responsible for more than 80% of all weather-related transmission line failures worldwide (Dempsey and White, 1996). Many transmission towers have failed in Canada during HIW events, including several belonging to Manitoba Hydro near Winnipeg in 1996 and others more recently in Ontario. In Australia, out of 94 reported transmission line failures, more than 90% of the failure events were induced by downbursts and tornados (Hawes and Dempsey, 1993). Kanak et al. (2007) studied a downburst event that occurred in South-Western Slovakia in 2003 where at least 19 electric self-supported transmission line towers were destroyed. In China 2005, 18 transmission line structures of 500 kV and 57 transmission line structures over 110 kV collapsed due to strong wind events such as downbursts, tornados and typhoons [Zhang, 2006].
Despite these failures, codes of practice and design guidelines for transmission line structures remain based on the wind loads resulting from large-scale synoptic (straight-line) winds. The challenge in predicting the response of transmission line structures to HIW events results from: 1) the difficulty in predicting the wind field associated with those events, which is different from the conventional boundary layer wind profile of large-scale events, and 2) the localized nature of the events, such that the forces acting on a tower and its attached conductors vary depending on the size of the event and also on its location relative to the tower.

An extensive research program focusing on studying the behaviour of transmission line structures under HIW events was initiated a decade ago at the University of Western Ontario, Canada, as a response to the failure of a number of towers. The research was funded by the company Manitoba Hydro, the Centre of Energy Advancement through Technological Innovation (CEATI), which represents utility companies from 14 countries on 4 continents, and more recently the company Hydro One, the main supplier of electricity in the province of Ontario. The research involved computational fluid dynamics as well as structural analysis modeling. An experimental program was also conducted to validate various components of the numerical models. The research covered both downbursts and tornadoes. In addition to providing an insight about the behaviour of transmission towers under HIW and the causes and modes of failures, an approach for estimating critical load cases simulating the effect of downbursts and tornadoes on transmission line structures resulted from this research. The main focus of this paper is to present the background behind the development of the critical load cases and to illustrate those cases. In the paper, research related to downbursts and tornadoes are provided separately. For each type of HIW event, a literature review and main findings of the research conducted at the University of Western Ontario are provided. This is followed by a presentation for the proposed design load cases.

**Downbursts**

**Literature Review**

A downburst can be defined as an intensive downdraft air that induces very strong wind in all directions when striking the ground. Fujita (1985) defined a downburst as a mass of cold and moist air that drops suddenly from the thunderstorm cloud base impinging on the ground surface and then transferring horizontally. The diameter ($D_J$) of this initial cold air jet can vary between 600 and 1700 m as stated by Hjelmfelt (1988).

A limited number of full-scale measurements for downbursts are available in the literature. These include measurements done by the Northern Illinois Meteorological Research (NIMROD) reported by Fujita (1990), by the Joint Airport Weather Studies (JAWS) reported by Fujita (1990), and by the FAA/Lincoln Laboratory Operational Weather Studies (FLOWS) reported by Wolfson et al. (1985). The localized nature of those events makes full-scale measurements a hard task to achieve. Therefore, most of the research has relied on reduced-scale physical modeling or numerical modeling to predict the downburst wind field as well as the response of structures to such events. In terms of numerical modeling for downbursts, three approaches currently exist in the literature. Those are: the Ring Vortex Model, the Impinging Jet (Impulsive Jet) Model, and the Cooling Source (Buoyancy Driven) Model. The Ring Vortex Model was used by a number of researchers like Vicroy (1992), Savory et al. (2001), Ivan (1986) and Zhu and Etkin (1985). As indicated by its name, this model simulates the vortex ring that is formed during the descent of the air column. As reported by Savory et al. (2001), the Ring Vortex Model is not accurate in simulating the downburst field near the ground after the air column touches the ground. The Impinging Jet Model was proposed by
Fujita (1985) when he studied the analogy between the impulsively impinging jet towards a flat surface and the falling downburst. Selvam and Holmes (1992) developed a two-dimensional steady numerical model that simulates an impinging jet. Their model did not predict the transient characteristics and the buoyancy-driven effects of the downbursts, as indicated by Vermeire et al. (2011b).

Hangan et al. (2003) developed a CFD model simulating the spatial and time variations of the wind field associated with downbursts. An experimental program was carried out using an impinging jet facility, where pressure and velocity measurements were employed to validate the assumptions used in the CFD simulation. Kim and Hangan (2007) validated this model by comparing the wind profile along height with a semi-empirical results based on full-scale data (Wood et al., 2001) as well as experimental results (Didden and Ho, 1985; Donaldson and Snedeker, 1971). The resulting axisymmetric downburst outflow had two velocity components: a radial (horizontal) component and a vertical (axial) component. The CFD model produced a time series for the velocity field of these two components. The values of the two velocity components at a specific point in space are functions of its location relative to the centre of the jet and its height relative to the ground.

Shehata et al. (2005) established a procedure to scale-up Hangan et al. (2003) wind field in order to estimate the spatial and time variations of full-scale downbursts. A number of studies (Shehata and El Damatty, 2007, 2008, Shehata et al. (2008), Darwish et al. (2010), Darwish and El Damatty (2011), and El Damatty and Aboshosha (2012)) were conducted to assess the behaviour and the failure modes of self-supported and guyed transmission line systems. Most of the studies conducted to assess the transmission tower behavior under downburst loading adopted the static analysis procedure. Shehata et al. (2005) reported that the downburst loading frequency ranged between 20 and 22 seconds while the transmission tower and conductors’ frequencies were 0.58 sec and 8.25 seconds, respectively. As such, the dynamic effect was neglected. Wang et al. (2009) studied the dynamic effect for downburst on transmission towers and reported only minor effect due to the relatively high natural frequency of the towers compared to the event natural frequency. However, they stated that the conductors might be affected by the dynamic effect due to its relatively low natural frequencies. Aboshosha and El Damatty (2013a) reported that the difference between conductors’ tensions is the main cause of failure of transmission towers under downbursts. Their study also revealed that that the longitudinal force transmitted to the tower due to the unbalanced tension can reach up to 60% of the transverse force.

**Downburst Wind Field**

The velocity at an arbitrary point in space has two components; a radial component $V_{RD}$ and a vertical component $V_{VR}$. Figure 1 illustrates the profile of the radial velocity, normalized with respect to the jet velocity, along the height. The maximum velocity profile occurs at an $R/D_J$ value of 1.2. The absolute maximum velocity is approximately equal to 1.1 $V_J$ and is almost equal to the reference basic wind speed at 10 (m) above ground, $V_{10}$. Figure 2 shows that the maximum vertical velocity occurs at $R/D_J$ equal to zero when the downburst jet is directly above the measurement point. Shehata and El Damatty (2007) concluded that the vertical velocity component has a negligible effect in comparison to the radial velocity component. Therefore, the current section focuses on describing the wind field associated with the radial velocity. Figure 3 shows the variation of the reference velocity, $V_{10}$, normalized with the jet velocity $V_J$, for different values of jet diameters. The figure indicates that the absolute maximum velocity, which occurs at an $R/D_J$ value of 1.2, increases with the decrease of the jet diameter. Regarding the time variation, Shehata and El Damatty (2007) reported that both the radial velocity component $V_{RD}$ and the vertical velocity component $V_{VR}$
exhibit a typical trend characterized by a maximum peak, followed by a minimum peak, followed by a constant value as shown in Figure 4 and 5. The time at which the maximum radial velocity occurs is directly proportional to the ratio \( \frac{D_f}{V_f} \).

Fig. 1 Vertical profile of the radial outflow wind associated with a downburst. [Shehata et al (2005)]

Fig. 2 Vertical profile of the vertical (axial) outflow wind speed associated with a downburst. [Shehata et al (2005)]
Development of Critical Load Cases Simulating the Effect of Downbursts and Tornados

Fig. 3 Downburst reference horizontal velocity ($V_{10}$) at 10 meters height. [Shehata et al. (2005)]

Fig. 4 Time history of the downburst radial velocity for different $R/D_J$ ratios. [Shehata and El Damatty (2007)]

Fig. 5 Time history of the downburst axial velocity for ratio $R/D_J=0.00$. [Shehata and El Damatty (2007)]
Main Findings from Previous Research Conducted at UWO

The main findings obtained from the research conducted during the previous years at the University of Western Ontario can be summarized in the following points:

- In addition to the downburst parameters, $V_J$ and $D_J$, the forces acting on a transmission line depend on the location of the downburst relative to the tower of interest, which is defined by the radial coordinates $(R, \Theta)$ as shown in Figure 6.
- Considering six cables spans in the analysis of the transmission line provides an accurate prediction for the cables reactions acting on the tower.
- Insulator flexibility is important in quantifying the amount of forces transmitted to the tower.
- The most critical downbursts have the following configurations:
  - $\theta = 30^\circ$, $R/D_J = 1.60$, $D_J = 1000$ m
  - $\theta = 0^\circ$, $R/D_J = 1.20$, $D_J = 500$ m
  - $\theta = 90^\circ$, $R/D_J = 1.20$, $D_J = 500$ m
- The wind field associated with the radial component has velocity magnitudes that exceed those associated with the axial component. The effect of the axial component on the towers turns to be negligible compared to that of the radial component.
- Special consideration to downburst loading must be taken into account when designing the conductors cross arms zone.
- Due to the significant difference between the frequencies of the tower and the downburst loading, the dynamic effect on the towers can be neglected.
- Due to conductor’s aerodynamic damping, the resonant component associated with turbulence is negligible.
- The turbulence associated with downburst is more correlated than turbulence associated with normal winds, (Holmes (2008) and Aboshosha and El Damatty (2013c)).
- The load span reduction factor commonly used to decrease the loads applied on the conductor spans is closer to unity when compared with that under normal winds (Aboshosha and El Damatty (2013c)).

Proposed Critical Downburst Load Cases

In view of the above results, the following three critical load cases are proposed for the analysis and design of transmission line structures under downbursts:

Load case #1, $\Theta=0$

This case corresponds to a velocity profile perpendicular to the tower line as shown in Figure 7. The velocity profile associated with this load case can be described as follows:

1. The vertical distribution of the radial velocity along the height of the tower, normalized with respect to the jet velocity $V_J$, is provided in Figure 8. The distribution can be approximated to a uniform profile with a value equal to 1.1 the jet velocity $V_J$, which is found to be approximately equal to the velocity at 10 m above the ground, $V_{10}$. 
2. The non-uniform distribution of the radial velocity along three spans from each side of the tower of interest is shown in Figure 9. This symmetric distribution leads to a transverse force acting on the tower of interest. It is found that an equivalent uniform distribution with a magnitude of approximately 0.92 $V_J$ can be used to calculate the transverse force on the tower.
Load case # 2, $\Theta = 90^\circ$

This case corresponds to a velocity profile parallel to the tower line as shown Figure 10. The velocity profile associated with this load case can be described as follows:

1. The vertical distribution of the radial velocity along the height of the tower, normalized with respect to the jet velocity $V_J$, is shown in Figure 11. This symmetric distribution can be approximated to a uniform profile with a value equal to 1.1 the jet velocity $V_J$, which is found to be approximately equal to the velocity at 10 m above the ground, $V_{10}$.

Fig. 9 $V_{RD}$ distribution over six conductor spans $\Theta=0^\circ$, $R/D_J=1.2$, and $D_J=1000$ m

Fig. 10 Load case # 2, $\Theta=90^\circ$, $R/D_J=1.2$, and $D_J=1000$ m
2. No force acts on the conductor due to this load case.

Load case #3, $\Theta=30^\circ$

This case shown in Figure 12 is associated with a profile for the radial velocity that acts on oblique angle relative to the transmission lines.

Apparently, this is the most critical load case which, according to different studies, Shehata and El Damatty (2008), Darwish and El Damatty (2011), and Aboshosha and El Damatty (2013a), and is responsible for the failure of many of transmission towers in the past. The velocity wind field associated with this configuration will lead to the following effects:

1. Velocity profile along the height of the tower in the direction perpendicular on the line. This distribution can be approximated to a uniform velocity of $0.75 \, V_{J}$ as shown in Figure 13.

2. Velocity profile along the height of the tower in the direction parallel to the line. This distribution can be approximated to a uniform velocity of $0.43 \, V_{J}$ as shown in Figure 13.

3. Velocity profile that acts on the conductors which has an unequal distribution on the spans adjacent to the tower of interest as shown Figure 14.
This profile will lead to a transverse force as well as the longitudinal force on the tower. Realizing that the conductor force (specially the longitudinal force) will be difficult to calculate by design engineers, an extensive parametric study covering the most used conductor types (based on information provided by Hydro One) was conducted to calculate the longitudinal conductor force for various spans. A sample of this study is shown in Figure 15 and Table 1. Figure 15 illustrates the main parameters that affect the conductor’s longitudinal force. These parameters are the conductor’s material, cross sectional area, projected area, and span as well as the insulator length. All these parameters are covered in
the parametric study.

Table 1115 KV conductor samples

<table>
<thead>
<tr>
<th>TYPE</th>
<th>KCMI</th>
<th>DIAM(m)</th>
<th>AREA (m²)</th>
<th>W (N/m)</th>
<th>EF (N/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>12/7 ACSR</td>
<td>110.8</td>
<td>0.0122174</td>
<td>8.89E-05</td>
<td>4.0279164</td>
</tr>
<tr>
<td>C2</td>
<td>26/7 ACSR</td>
<td>648.2</td>
<td>0.0254</td>
<td>0.000382</td>
<td>12.988571</td>
</tr>
<tr>
<td>C3</td>
<td>54/19 ACSR</td>
<td>1192.5</td>
<td>0.0339852</td>
<td>0.000681</td>
<td>22.7202914</td>
</tr>
<tr>
<td>C4</td>
<td>84/19 ACSR</td>
<td>3360</td>
<td>0.05588</td>
<td>0.001841</td>
<td>56.88118464</td>
</tr>
</tbody>
</table>

Fig. 16 Different longitudinal conductor force, Θ=30, Span=500 m

Tornadoes

Tornado Literature Review

Tornadoes are categorized by the damage-based Fujita scale (Fujita and Pearson 1973), or the modified Enhanced Fujita scale (EF-scale). Both have six categories, 0 to 5 representing the damage level, and taking into account tornado characteristics, such as path width, length, and wind speed. Due to the complexity and difficulty of obtaining full-scale data, especially for the near ground region, laboratory simulations such as Tornado Vortex Chambers (TVC) are used, in which tornadoes are presented as vortices (Wan and Chang 1972, Ward 1972, Davies-Jones 1973, Church et al. 1977, Baker and Church 1979, Church et al. 1979, Rotunno 1979, Lund and Snow 1993, Wang et al. 2001, and Sarkar et al. 2005). The TVC provides a good simulation of the characteristics inside a tornado, but the results are sensitive and are affected by the applied boundary conditions and the experimental limitations. For the near ground region, numerical simulations can be done using Computational Fluid Dynamics (CFD) simulations. The field data for the 1998 Spencer South Dakota F4 tornado and for the 1999 Mulhal F4 tornado were used to validate the numerical (CFD) simulations of F4 and F2 tornadoes (Hangan and Kim 2008 and Hamada, et al. 2010).
Few studies related to the behaviour of transmission line systems under tornado wind loads are available in the literature. The failure of a self-supported lattice tower under tornado and microburst wind profiles was investigated by Savory et al. (2001). The analysis was done for the tower alone, without modelling the transmission lines, and without considering the vertical velocity component. Ahmed (2009) and Hamada et al. (2010) studied the behaviour of guyed transmission line systems under F4 and F2 tornado wind fields. In addition, the study presented a procedure to estimate the velocity field for F2 tornados using CFD data. Hamada and El Damatty (2011) conducted a comprehensive study to assess and understand the performance of transmission line structures under tornado loading. The study investigated the variation of the tower members’ internal forces with the tornado locations relative to the transmission line system. The dynamic effect associated with the translation motion of the tornado was assessed and the results of the parametric study were used to assess the sensitivity of the members’ peak forces with the parameters defining the location of the tornado relative to the transmission line. Alatalmas et al. (2012) and El Damatty and Hamada (2013) assessed the transmission lines’ failure mechanisms under critical tornado configurations. In addition, the studies predicted the maximum tornado velocity that various lines can withstand before experiencing global failure. Hamada and El Damatty (2013) assessed the behaviour of two guyed transmission line structures under F2 tornado wind field, boundary layer wind and utility companies’ recommended wind loads. In addition, a comparison was carried out between the internal forces in the transmission tower members resulting from the tornado and those associated with the case of broken wires.

**Description of Tornado Wind Field**

The tornado wind velocity at a certain point in space has three components: tangential velocity, radial velocity, and uplift (axial) velocity. The magnitude and location of the maximum values of the three tornado velocity components of F4 and F2 tornados are provided in Table 2, where $r$ is the radial distance from the tornado center and $z$ is height from the ground level.

<table>
<thead>
<tr>
<th>Tornado</th>
<th>Velocity Direction</th>
<th>Velocity (m/s)</th>
<th>$r$ (m)</th>
<th>$z$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4</td>
<td>Peak Tangential</td>
<td>142</td>
<td>158</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Peak Radial</td>
<td>79</td>
<td>273</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Peak Axial</td>
<td>62</td>
<td>246</td>
<td>158</td>
</tr>
<tr>
<td>F2</td>
<td>Peak Tangential</td>
<td>78</td>
<td>96</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Peak Radial</td>
<td>49</td>
<td>146</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Peak Axial</td>
<td>37</td>
<td>171</td>
<td>127</td>
</tr>
</tbody>
</table>

In order to gain an insight about the F2 tornado wind field, vertical profiles for tangential, radial, and vertical velocity components for the 100 (m) close to the ground are provided in Figures 17 to 19. The vertical profiles of the three velocity components are provided at various radial distances. For radial distance $r < 200$ (m), the tornado wind profile is significantly different than the conventional boundary wind profile. Near to the tornado center, the vertical location of the peak tangential velocity becomes very close to the ground. Away from the tornado center, the vertical location of the peak radial velocity is very close to the ground. In addition, the radial velocity changes direction with height, where negative values act in an inward direction and positive values act in an outwards direction. The axial
component acts in an upward direction and is characterized by a zero value at the ground level. The tangential, radial, and axial velocity components change with the relative location from the tornado center. The vertical wind profile of the three velocity components vary for different values of radial distance $r$.

![Fig. 17 Vertical profile of tangential velocity component for different radial distances from tornado center – F2 Tornado](image1.png)

![Fig. 18 Vertical profile of radial velocity component for different radial distances from tornado center – F2 Tornado](image2.png)
Main Findings from Previous Research Conducted at UWO

The main findings of these studies can be summarized as follows:

- Tornado velocity wind field consists of three velocity components: tangential, radial, and vertical velocity components. The vertical profiles of the three velocity components have patterns that are different than the conventional boundary layer wind profile.

- The internal forces in all tower members change significantly with the variation of the parameters $R$ and $\theta$, which define the location of the tornado relative to the transmission tower, as shown in Figure 20. Different types of transmission tower members, either chord or diagonal, have independent critical values of $R$ and $\theta$ that lead to peak internal forces in those members.

- No significant dynamic effect is shown to be associated with the translation motion of the tornado. This insignificant dynamic effect results mainly from the large aerodynamic damping of the lines and the low vibration period of the tower.

- Some tornado locations result in unbalanced forces acting on adjacent spans of the conductors. This leads to a resultant force that acts on the tower cross-arms along the longitudinal direction of the conductors. This force leads to an out-of-plane bending effect on the cross-arms and, consequently, compression forces in some of the upper chord members. These compression forces might exceed the tension forces that develop in these members due to the self-weight of the conductors. As a result, these members might become subjected to compression forces, which are not typically accounted for under normal wind load cases.

- The transmission tower chords’ peak internal force increases by 22% to 140% due to the inclusion of the conductors and ground-wires in the analysis. Thus, tornado loads acting on the conductor are important and should not be neglected.
Proposed Load Cases

Since F2 tornadoes have a cumulative frequency of occurrence of 86% ((ASCE MOP. 74 (2010)), the current study focuses on providing equivalent load cases for F2 tornadoes. Parametric studies conducted on six transmission line systems identify the critical tornado configurations $R$ and $\theta$ that lead to peak internal forces in transmission towers. Accordingly, equivalent loading cases in the X, Y, and Z directions are recommended, where X is perpendicular to the wires direction, Y is along the wires direction, and Z is the vertical direction. An example of one equivalent critical loading case that represents a critical tornado configuration of $R = 100$ (m) and $\theta = 0^\circ$, is shown in Figures 21 to 24. Figures 21 and 22 show the applied wind profiles on the transmission tower in the X and Y directions, respectively. Figure 23 shows the vertical (Z direction) wind profile on the transmission tower. Figure 24 shows the transverse wind profile on the transmission lines such as conductors and ground-wires.
Fig. 21 Velocity Profile along Transmission Tower Height – X (Transverse) Direction

Fig. 22 Velocity Profile along Transmission Tower Height – Y (Longitudinal) Direction
Fig. 23 Velocity Profile along Transmission Tower Height – Z (Vertical) Direction

Fig. 24 Transverse Velocity Profile along the Transmission Lines
Conclusion

The current study summarizes the major findings of research conducted during the past decade on the effect of downbursts and tornadoes on transmission line systems. As the downburst forces acting on transmission towers depend on the event location, extensive parametric studies were conducted to investigate the critical downburst configurations. In view of these results, three load cases are proposed. For each case, the wind load profiles along the tower height as well as along the conductor spans are provided. As the longitudinal forces in the conductors are highly nonlinear and are difficult to be calculated by design engineers, an extensive study is conducted to evaluate such forces and sample of the results for specific conductor parameters are presented in this paper.

Since F2 tornadoes have a cumulative frequency of occurrence of 86%, the current study presents an equivalent wind load case that simulates the critical effect of F2 tornadoes on transmission line systems. The paper presents a summarized literature review for tornado wind fields and the studies conducted on transmission lines systems under tornado loading. The F2 tornado wind field is discussed, where the tangential, radial, and vertical velocity profiles for F2 tornadoes are described. The main findings of the extensive research that was performed over a decade are summarized. Finally, the details of a critical load case, in terms of velocity profile acting on the tower along the transverse, longitudinal, and vertical directions as well as on the conductors, are provided. The ongoing research developed in total twelve equivalent load cases covering all critical F2 tornado cases and these will be presented in future publications.

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