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A review of transmission line systems under downburst wind loads

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ABSTRACT

Outages of power due to transmission tower failures can cause social and economic disasters. Investigations of transmission line failures around the world have recorded that they are generally from high intensity winds from downbursts and tornadoes. Downbursts represent the greatest threat due to the extreme and extended wind events that they generate. Many studies have investigated the applications of these events on transmission line systems (TLS). However, the wide ranges for the different downburst parameters and the varying representations of downburst wind speeds, which are different from boundary layer wind profiles, have complicated the investigation of transmission line failures under these types of loads. This study reviews the research to date on TLS under downburst wind loads. It explores downburst wind loads, their simulation models and the structural behaviour of TLS under downburst wind loads. Modelling of TLS, static and dynamic analysis are all reviewed. Failure analysis, critical downburst parameters, ideal retrofitting methods to avoid such catastrophic failures, and optimization criteria of TLS are also discussed. Finally, recommendations for future research are made.

1. Introduction

More than 90% of transmission tower failures in Australia are due to severe thunderstorm events that include downburst winds (Li, 2000), and the situation is similar in several regions around world which have comparable climatic conditions. The interruption of electricity due to failure of transmission towers can generate social and economic disasters. In addition the failure of one or two towers can trigger a long chain of failures, which can destroy several transmission towers in one event (Dempsey and White, 1996).

Savory et al. (2001) introduced the first model for isolated transmission towers under localised wind loads, but the unbalanced distribution of these types of loads on entire transmission line systems (TLS) pushed researchers to study the structural behaviour of entire TLS. However, these studies were limited to stationary downbursts, which are different to the transient downbursts that are more usual for these events. The translation speed increases the downburst velocity in the front of the storm and reduces the downburst speed in the rear. There are also suggestions that the translation speed causes some forward and backward gaps in distributions of horizontal wind, which could cause different distribution of wind speed on several panels of a TLS.

Earlier studies focused on guyed transmission towers and treated a TLS as two separate parts: transmission line conductors and transmission towers. Transmission line conductors have been studied alone and their reactions have been imparted to towers at the connection points, and towers have been investigated alone using a linear or nonlinear static analysis (Shehata et al., 2005; Shehata and El Damatty, 2007; Darwish. 2010). By contrast, Yasui et al. (1999), Battista et al. (2003) and Gani and Légeron (2010) highlighted the importance of the fluid flow–cables–structure interaction when evaluating the towers' behaviour under wind forces.

Several studies investigated the structural response and failure analysis of transmission towers under downburst loads, but they did not consider retrofitting procedures. Some reinforcement methods exist for upgrading transmission towers, such as the leg retrofitting method, diaphragm bracing, friction-type reinforcement and x-brace type. The efficiency of these methods, convenience of the reinforcement, cost and optimal distribution of reinforcement through the TLS subjected to downburst, are questions that need answers.

Assurance of structural safety with optimal design is a basic objective in structural design and therefore modern TLS must be upgraded to confront this case of loading. The best or optimal arrangements of towers in TLS as well as the best orientation in front of wind loads need discussion.

Several questions are suggested about the behaviour of TLS under downbursts, starting from modelling downburst events, modelling TLS,

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applying these types of loads, developing the design parameters and retrofitting old towers. This paper provides a comprehensive review of earlier studies, including those of the authors, and then several proposals for further research.

2. Downburst wind loads

Design specifications which assume that the atmospheric synoptic wind is the basis of wind loads put TLS at risk due to localised wind events such as tornadoes and downbursts. These two events pose a significant threat to transmission towers. The probability of occurrence of localised wind events in a specific area is low, but the threats to an overall system grow due to the extension of TLS over long distances, thus increasing the probability of one of these events crossing the transmission line (Holmes et al., 2008).

Downbursts occur when warm air ascends through a cloud, and then rises above the top of the cloud, creating a dome of warm air. The air cools at this level and then begins to drop, collapsing the dome and rushing back to the ground, creating an outburst of damaging air ("Downbursts' of air are called danger to aircraft' 1979). The practical diameters of downburst are roughly 1 km and the extent of the outburst flow is 1.0–6.0 km (Wilson et al., 1984). Hjelmfelt (1988) showed that the downdraft diameter ranged from 1.5 to 3.0 km, based on 11 events. Analyses of extreme wind speeds in Australia showed that downbursts are the extreme wind type at the height of 10 m (Holmes, 2002). Boss (2010) reported that for every tornado damage report, there are almost 10 downburst reports.

2.1. Simulation of downburst loads

The spread of downburst winds have been modelled using three different models: ring vortex, impinging jet model and cooling source model. The ring vortex model forms a vortex ring before touching the ground. The impinging jet model forms a radial out-flow after touching the ground similar to the wind field, and the results from simulated microburst events by using a large impinging jet were more consistent with full-scale data (Letchford and Illidge, 1999). The impinging jet model has been further developed to include the formation of the ring vortex, but these models are not able to describe the buoyancy effects that the cooling source models have succeeded in doing (Selvam and Holmes, 1992; Vermeire et al., 2011a). Earlier studies have used three approaches for simulating downburst wind speeds: experimental, numerical and analytical/empirical models. These will be considered in turn.

2.2. Experimental and numerical simulation models

Experimental and numerical simulation procedures have been conducted by many researchers. Bakke (1957) started an early experimental simulation for a wall jet. Holmes (1992) and Cassar (1992) modelled downburst wind speeds in a wind tunnel; Wood et al. (2001) employed the impinging jet models for different embankment heights; Chay and Letchford (2002) studied the profiles of downburst winds using a stationary wall jet tunnel then a moving downburst in a wind tunnel (Letchford et al., 2002). Kim and Hangan (2007) investigated different scales of downbursts in wind tunnels and concluded that the impinging jet simulations are scale dependent. Mason et al. (2009) utilized the cooling source model to study downburst storms. They used a dry, non-hydrostatic, sub-cloud and axisymmetric model. The sensitive wind field parameters relating to variations in downburst size, initiation height, and intensity, in addition to forcing duration and downburst shape were determined. Later Mason et al. (2010) developed the previous model from an axisymmetric model to a three-dimensional model.

Table 1 summarises previous experimental and numerical simulation findings. In the course of applying downburst wind loads to TLS, adopting numerical or experimental models present several difficulties. In addition to the complication of coupling numerical or experimental simulation with structural analysis, there are other reservations. One is scale dependency. Kim and Hangan (2007) and Xu and Hangan (2008) evaluated the scale effects for steady state and unsteady state simulation and confirmed the scale dependency.

2.3. Analytical/empirical models and turbulence component

The downburst wind speed is described as the sum of the mean wind component ($\overline{U}$), and turbulent wind component (u). Oseguera and Bowles (1988) and Vicroy (1991) developed an analytical model for the mean speed of a downburst wind in two components: radial speed and

Table 1
Experimental and numerical simulation findings.

Author	Height of maximum horizontal velocity	Radial position of maximum horizontal velocity	Comments/Findings
Hjelmfelt (1988)	50–100 m	0.75D to 1.0D	Hjelmfelt (1988) investigated 11 field events and estimated rough dimensions for downburst wind and vertical profiles of horizontal downburst wind speeds
Wood et al. (2001)	0.016D	1.5 D	The height of maximum velocity increases with increasing radial distance.
Chay and Letchford (2002)	50–100 m	1.0D	The mean pressure distributions on objects immersed in downburst events differ from those in traditional boundary layer studies.
Hangan et al. (2003)	0.08D (numerical simulation) and from 0.02D to 0.03D (experimental simulation)	1.0D (numerical simulation)	Conducted experimental and numerical simulations and concluded that the height of the maximum velocity decreases as Reynolds number increases.
Chay et al. (2006)	0.023D to 0.025D	1.0D to 1.25D	Developed an analytical model for describing downburst mean and turbulent wind components.
Kim and Hangan (2007)	less than 0.05D	1.1D	Conducted numerical simulations of impinging jet steady state and unsteady state and concluded that the maximum velocity increases and the height of the maximum velocity decreases as the Reynolds number increases.
Xu and Hangan (2008)	0.03D	1.1D	Conducted numerical simulations and examined the different downburst parameters, including cloud-base height, boundary conditions, scale and terrain roughness
Mason et al. (2009)	0.011D	1.25D	Conducted numerical simulations using cooling source model and concluded that the height of the maximum velocity decreases with increasing downburst diameter.
Vermeire et al. (2011)	0.015*D*	1.425*D*	Compared between the impinging jet models and the cooling source models. They found that the impinging jet model is not accurate, particularly for the near surface out flow, and the magnitude of wind components are over-predicted above the height of maximum radial velocity
Abd-Elaal et al. (2013a)	0.016D	1.46D	Analysed several observed downburst events to estimate the time periods of downbursts events