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Effect of High Intensity Winds on Overhead Transmission Lines

by Sébastien Langlois
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and Applied Mechanics

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Abstract

This report presents an overview of the literature concerning high intensity winds (HIW) and their effect on overhead transmission lines. Wind loading considered in the design of overhead transmission lines is based on extreme values of synoptic boundary layer wind. High intensity winds such as tornadoes or thunderstorm downbursts often hit lines in off-design conditions, causing failures of towers and even sometimes transverse cascades. High intensity winds and their flow properties are now actively studied. Risk assessment of those wind events is also of great interest to the transmission line industry. The probability of such small-scale storms of striking a line system is much higher than the probability of hitting a single point. In response to that hazard, some design guidelines editors and line utilities have developed simple loading models to account for tornadoes and downbursts.

Sommaire

Ce rapport présente un résumé de l'état de la recherche sur les vents de forte intensité et leur effet sur les lignes aériennes de transport d'énergie. Les charges de vent considérées pour la conception des lignes aériennes de transport d'énergie sont basées sur des vents synoptiques en accord avec la théorie de la couche limite. Les vents de forte intensité comme les tornades ou les rafales descendantes accompagnant les orages frappent souvent les lignes dans des conditions n'ayant pas été prises en compte dans la conception, causant ainsi des bris de structures et parfois même des cascades transversales. Les vents de forte intensité et leurs propriétés dynamiques sont le sujet de nombreuses études récentes. L'industrie des lignes de transport d'énergie porte également un grand intérêt à l'évaluation des risques causés par ce type de tempête. La probabilité de voir des vents aussi localisés frapper une ligne est beaucoup plus grande que les voir frapper une structure localisée. Devant ces risques, certaines organisations et utilités ont développé des modèles de charges simplifiés pour la conception de lignes contre les tornades et les rafales descendantes.

Acknowledgements

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1 Introduction

This report presents an overview of the literature concerning high intensity winds and their effect on overhead transmission lines.

Wind is a serious challenge for the transmission line industry. Based on records of wind speed found in different regions, basic design wind speeds are chosen for various components of the line system. Those design values represent an expected maximum average wind speed over a time period varying from 3 seconds to 10 minutes. Wind speed is then converted to a static pressure through Bernouilli's equation where the pressure is proportional to the square of the wind speed. Wind pressures are applied to the conductors, towers and insulator strings. Among other factors that multiply the wind speed, there is a gust response factor proposed by Davenport and accounting for the dynamic effects of gusts on the response of transmission lines.

Extreme winds recorded at weather stations are generally those called synoptic winds, which affect a large area. Those winds exhibit conventional characteristics and their vertical profile is usually best described by the boundary layer theory and its well known power law where the value of the exponent depends on terrain roughness. Another type of wind event is more localized and has very different wind velocity fields. Those wind events are usually induced by local thunderstorms and are often referred to as high intensity winds (HIW). Two damaging wind phenomena of this type are the downburst and the tornado.

Thunderstorm winds usually cover such a small footprint area that they are very rarely recorded by anemometers. They only go reported due to the observation of damages or to radar detection. In recent years, increased awareness and improved detection technologies have led to better understanding of the risks involved. The probability of any power line support being hit by those extreme winds is usually quite small. However, due to the elongated geometry of these systems, transmission lines are prone to suffer the effects of high intensity winds. In fact, transmission lines are thought to be the most effective human construction in intercepting and recording such events (Dempsey & White, 1996).

According to Dempsey and White (1996), many utilities reported that 80-100% of all weather-related failures were due to high intensity winds. In spite of this, wind design codes continue to base their calculations on synoptic winds. In the last decades, the problem has been recognized and more research has been done to assess the risks related to such events and to determine the flow field of thunderstorm winds. Utilities like Hidronor in Argentina, Eskom in South Africa, and Hydro One in Canada have developed simplified loadings to account for the possibility of a tornado striking a line (Behncke & White, 1984; Behncke, White, & Milford, 1994; Ishac & White, 1995). In the American Society of Civil Engineers (ASCE) Manual 74 (1991), recommendations are made to design against high intensity winds. The draft revision (ASCE, 2005) brings some refined recommendations. Australian standards (Electricity Supply Association of Australia [ESAA], 2003) give more precise instructions to account for downbursts. Many authors and organizations have looked at the problem, but much remain to be solved.

2 Definitions

2.1 High Intensity Wind

There is a need to define the limits of the concept of "high intensity wind" as used in this report. Throughout the literature, several different definitions are found. There are basically two types of definitions: one that includes all winds over a threshold wind speed, and one that is limited to high winds due to localized effects.

The first type of definition is found in a recent review on design practices for overhead lines subjected to high intensity winds. It states: "high intensity winds are those having velocities exceeding 45 m/s or those likely to cause structural damage to property" (CIGRÉ WG B2.16, 2004, p. 4). With such a definition, all types of storms induced by thunderstorms can be included, as well as large-scale tropical and extratropical storms, such as hurricanes, cyclones, typhoons and gales. A study by Hoxey, Robertson, Toy, Parke, and Disney (2003) identifies hurricanes, tornadoes and downbursts as being the three basic types of high intensity winds. However, their research focuses only on the last two types. The advantage of this definition is that the threshold wind speed parameter is a precise criterion for the identification of high intensity winds.

The ASCE Draft Revision of the Guidelines for Electrical Transmission Line Structural Loading (ASCE, 2005) treats only of tornadoes, microbursts and downbursts in its section specifically titled "High Intensity Winds". Much attention is given to the narrow-fronted characteristic of those winds. Several authors, including Behncke, White, and Milford (1994), Dempsey and White (1996), and Savory, Parke, Zeinoddini, Toy, and

Disney (2001), accept a similar definition. The present report will also follow this restricted definition of high intensity wind.

The purpose of the study is to identify the effects of high intensity winds and assess how they are different from synoptic winds used in codes. Large-scale storms such as hurricanes are typically covered by codes and design practices in regions prone to such events. In this report, the expression “high intensity wind” refers only to severe winds resulting from localized thermal activity generally created in thunderstorms.

2.2 Thunderstorm

A thunderstorm covers only a small surface area. However, those storms frequently produce structural damages. A general understanding of the physical phenomenon is needed.

The important process in the physics of thunderstorms is convection. The instability of the air, caused by cold air over a warm surface, generates a convection where warm moist air rises from the ground (updraft) and is substituted by dry colder air from aloft (downdraft). Due to adiabatic cooling the rising air becomes saturated and the water vapor condenses into the convective clouds. The updraft is usually strengthened due to the release of latent heat during condensation.

The thunderstorm process is divided into three stages: the cumulus stage, the mature stage, and the dissipating stage (Battan, 1984). During the cumulus stage, several cumuli clouds converge and combine, forming a large cell with precipitation particles. This formation is dominated by updrafts. That moist air can ascend up to several kilometers. As it cools down and loses its buoyancy, a downdraft is initiated. This is the beginning of the mature stage during which both strong updrafts and downdrafts are present. The dissipating stage is characterized by a weak downdraft and the dissipation of the storm cell. Thunderstorms are generally accompanied by heavy rain or hail. The whole process is illustrated in Figure 1. “Severe storm” is another expression that sometimes replaces the term “thunderstorm” to describe more generally and probably more accurately the storms able to create damaging winds.

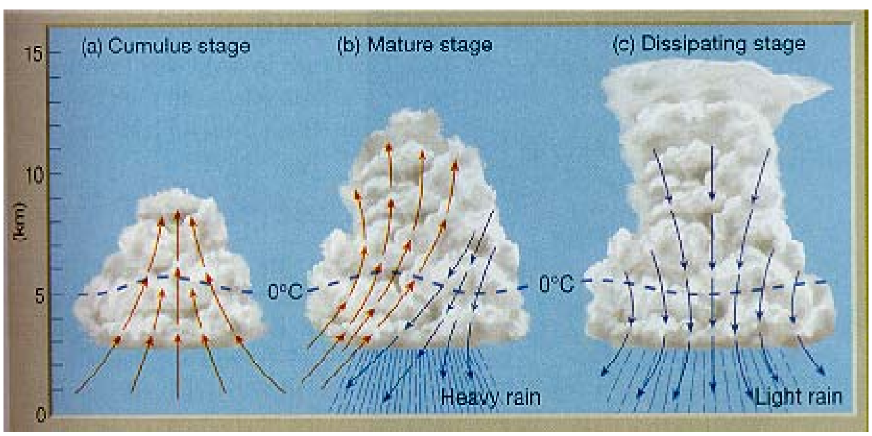

Figure 1: The three stages of a thunderstorm (Lutgens & Tarbuck, 2001)

Two types of storm cells are the ordinary cell and the supercell (CIGRÉ WG B2.16, 2004). The latter covers a larger area and can produce the most devastating of all thunderstorm wind events: the tornado. Tornadoes originate from the updraft part of the cell. The downdraft part can also produce high velocity winds as it reaches the ground. When this mechanism is strong enough, it is called downburst. Tornadoes, downbursts and their respective characteristics are further defined in the following sections. In general, severe storms have a 1-3 hours duration and the cell travels at 20-40 km/h. High winds will rarely last more than 15 minutes at a particular location (Hawes & Dempsey, 1993).

Much is still to be learned from the wind field of thunderstorms. Letchford, Mans, and Chay (2002) summarize the extent of the research done on the subject prior to 2002, outline the most important characteristics of thunderstorm winds, and differentiate them from synoptic winds which form the basis for all current wind loading codes. Those differences are: their non-stationary nature, their complex three-dimensional flow, their velocity profile with height, the lesser role of turbulence, and their smaller spatial and temporal extents.

2.3 Downburst

As defined by Fujita (1981), a downburst is a strong downdraft which induces an outburst of damaging winds on or near the ground. The downdraft makes contact with the ground and then spreads outwards, causing severe winds at low altitudes. Downbursts can be further subdivided in microbursts and macrobursts. Microbursts have damaging winds extending less than 4 kilometers and macrobursts have damaging winds extending more than 4 kilometers (Fujita, 1990). The lifetime of a downburst is generally between 5 and 30 minutes for a macroburst and between 5 to 10 minutes for a microburst (McCarthy & Melsness, 1996). The highest downburst wind speed ever recorded is 67 m/s in 1983 at Andrews Air Force Base near Washington, D. C. (Li & Holmes, 1995). An anemograph of this wind event is presented in Figure 3. Downbursts are often observed through damages to the vegetation. An example of downburst damage pattern is provided in Figure 2. Damages often have an elliptical shape and are said to be divergent, as trees affected usually fall away from the center of the damaged area. From anemometer records, downbursts are recognized through two distinct velocity peaks and a rapid change in wind direction.

Figure 2: Effect of a small downburst on a pine forest (Reid & Revell, 2006)

2.4 Tornado

The most severe winds that can be produced by thunderstorms occur through tornadoes. A tornado is a rotating column of air originating from a convective cloud (Twisdale, 1982). It takes the appearance of a narrow funnel, cylinder or rope that extends from the base of the thunderstorm cloud to the ground. The visible shape of the tornado is mostly due to the presence of water droplets. The width of path of damaging winds in tornadoes, that covers a distance much larger than the funnel itself, is generally smaller than a few hundred meters, and rarely reaches one kilometer (Battan, 1984). Their path length varies according to their strength, and can exceed 50 kilometers (Holmes, 2001).

Even though they have been recorded more frequently in North America, tornadoes occur in all subtropical or temperate land masses. Some result from isolated storm cells, while others result from very complex storms that can cause damages over a relatively large area and create several tornadoes and downbursts. Large tropical storms can produce thunderstorms and tornadoes as well. For example, the remnants of Hurricane Danny in 1985 spawned over 20 tornadoes in Mississipi, U.S.A (McCaul, 1987). There also exist tornadoes, often called waterspouts, occurring over water.

The most widely used tornado intensity scale is called the Fujita-Pearson (FPP) scale (Fujita, 1973). Each tornado can be assigned a number between 0 and 5 for each of the following intensity indicators: maximum wind speed, path length (along the direction of propagation), and path width (perpendicular to the direction of propagation). For example, the smallest recorded tornado would be scaled FPP 000. Tornadoes exceeding the criteria for level 5 are possible but very unlikely. As explained in the ASCE Manual 74 (1991), it is common practice to characterize tornadoes based only on wind speed. This is why they are often scaled between F0 and F5. A large portion of the recorded tornadoes are relatively weak and described as F0 or F1. The different ranges of the scale are given in Table 1.

Table 1 : The FPP tornado scale (Fujita, 1973)

Scale	Max. wind speed (m/s)	Path length (km)	Path width (m)	Expected damages
0	less than 33	less than 1.6	less than 15	light
1	33-50	1.6-5.0	15-50	moderate
2	50-70	5-16	50-160	considerable
3	70-92	16-50	160-500	severe
4	92-116	50-159	500-1600	devastating
5	116-142	159-507	1600-5000	incredible

Damages from tornadoes might be similar to those induced by a downburst, and therefore, after-the-fact identification of the phenomenon based on observations of damages can be difficult. However, tornadoes generally show near straightline damage pattern and have highly convergent flows (CIGRÉ WG B2.16, 2004). A narrow path of damage is usually expected.

3 Research on Wind Characteristics

3.1 Extreme Wind Speeds

Estimations for the maximum wind speeds that can occur in downbursts or tornadoes are difficult to assess. Because of their relatively small horizontal extent, very few were actually recorded. An anemograph of the famous downburst recorded on August 1st 1983 at the Andrews Air Force Base is presented in Figure 3. The peak gust recorded is 67 m/s. This is the highest wind speed ever measured from a downburst. A fair estimation is that, downburst winds, especially microburst winds, could go as high as 75 m/s (Letchford et al., 2002).

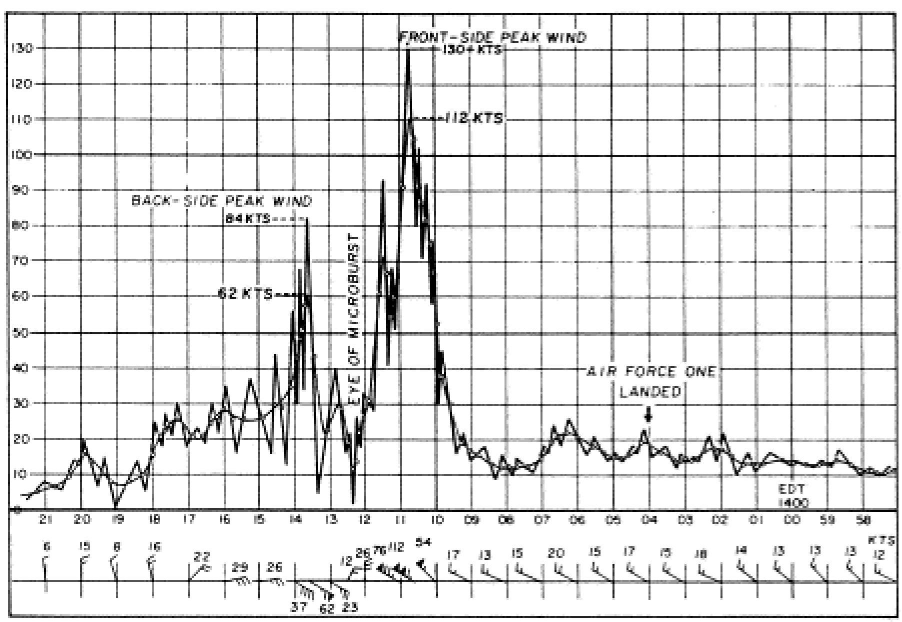

Figure 3: Recorded Downburst at Andrews Air Force Base (Holmes & Oliver, 2000)

Tornadoes have been studied for a much longer period and many estimates were given for what is thought to be the ultimate wind speed. Most measuring devices being unable to sustain such powerful winds, there remain only three ways to measure extreme wind speeds: photogrammetric analysis using videos of moving objects in tornadoes, research Doppler radar, or damage survey (McCarthy & Melsness, 1996). Traditionally, experts studying damage surveys from tornadoes have given very high evaluations of the maximum wind speed. Some even thought it could reach the speed of sound (340 m/s) (Battan, 1984). However, with new techniques to evaluate wind speed and a more objective approach towards damage surveys, specialists rarely state an ultimate value over 125 m/s. In the elaboration of his intensity scale, Fujita (1990) did not expect to ever record a F6 tornado, that is a wind speed over 142 m/s. In an extensive report, Minor, McDonald, and Mehta (1993) estimate the upper limit to be in the range 111-123 m/s.

3.2 Wind Field

It is the conclusion of many articles on the subject: More research must be done to understand the flow field of high intensity winds. These winds were often neglected compared to the well-studied, large-scale, boundary layer winds. In their report, Letchford et al. (2002) argue that wind engineering must focus on the fundamental issue of analyzing the flow structure in the strongest winds encountered on earth. This section presents an overview of the research performed on the subject.

3.2.1 Downburst Wind Field

It was Fujita who first observed that thunderstorm downdrafts could produce highly damaging winds. He was able to correlate downburst winds to damages on the ground and aircraft accidents (Fujita, 1990). Before the 1970s, the existence of a downdraft in thunderstorms was known. However, it was believed that, since a current must necessarily slow down and stop before reaching the ground, downdraft winds near the ground were minimal. Based on his observations, Fujita described the phenomenon he called downburst and that he later subdivided into microbursts and macrobursts. Fujita (1990) defined the microburst as being "an anti-tornado storm, consisting of a slow-rotating column of descending air which, upon reaching the ground, bursts out violently" (p. 76).

Following Fujita's observations, three important projects were performed in the United States to accumulate specific data on downbursts. Those projects are: the Northern Illinois Meteorological Research on Downbursts (NIMROD) in 1978, the Joint Airport Weather Studies (JAWS) in 1982, and the Microburst and Severe Thunderstorm (MIST) project in 1986. Instruments used during those projects include anemometers and Doppler radars. Some important characteristics of the phenomenon were recognized due to the Andrews Air Force Base record (see Figure 3). For example, it was observed that the passage of a downburst generally creates two distinct peaks in the history of wind speed. In analogy to the calm region of a hurricane, Fujita named it the eye of the downburst (Letchford et al., 2002). Concretely, these two peaks suggest that the wind speed in the center of the downburst is small and that it increases with radius up to a certain distance.

Other characteristics that were revealed by this record are the short storm duration, and the rapid fluctuations in wind directions during the passage of the storm (Holmes, 2001).

Hjelmfelt (1988) presented an analysis of microbursts recorded during the JAWS project. He characterized the size of those events and concluded that the outflow was similar to the well-studied fluid flow model called “wall jet” for both radial and vertical profiles of horizontal wind velocity. In this model, the flow field is compared to a jet of fluid impinging on a surface. Another conclusion of these observation projects is that “the shape of the profiles are mainly determined by the horizontal location in relation to the downdraft, and much less dependent on the underlying roughness of the ground surface” (Holmes, 1999, p. 1410).

The first concern related to microburst winds was their effect on aviation: The aircraft industry is responsible for some of the early development on the knowledge of downbursts. An alternative to the wall jet model is the “ring vortex” model (Savory et al., 2001), which is useful to aviation because it represents well the flow field of a downdraft before touch down. An example of a model of the wind field adapted to this industry is given in Zhu and Etkin (1985). Performing early numerical simulations, meteorologists were often interested in the whole process of downburst, and did not focus on the distribution of high winds near the ground. From a structural engineering point of view, however, damaging winds are better represented by the wall jet model.

The first numerical simulation using the wall jet model that really focused on low-altitude wind flow over objects was performed by Selvam and Holmes (1992). More recently, Holmes and Oliver (2000) developed a simplified empirical model of a downburst that addresses directly the problem of transmission line wind loading. As shown in Figure 4, it is assumed that the horizontal, radial component of wind speed increases linearly from the center of the storm to a point of maximum velocity and then decreases exponentially. In this model, the resultant wind velocity is obtained from the vector summation of the radial wind velocity and the translational velocity of the moving storm. The maximum wind speed then occurs at the front of the storm where both components add up. An example of a downburst footprint as described in the model is shown in Figure 5. As observed in the different records, the translational component of velocity can represent a significant component of the peak wind speed measured. Along with the radial and vertical profiles of velocity, the non-stationarity of the wind field makes the downburst winds very different from boundary layer winds

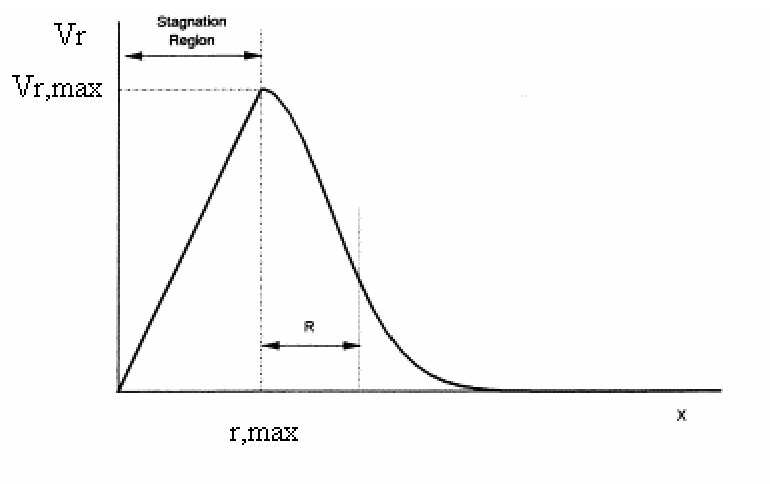

Figure 4: Downburst model horizontal radial profile of wind velocity (Holmes & Oliver, 2000)

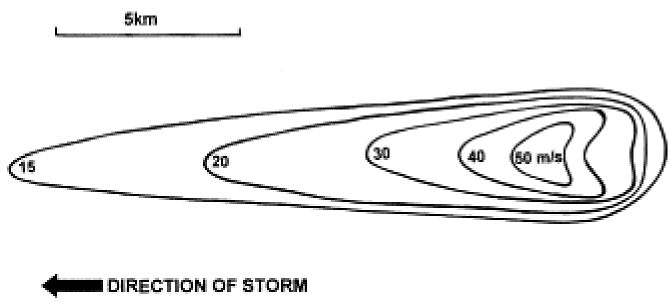

Figure 5: Footprint of a downburst (Holmes & Oliver, 2000)

From the beginning, one major issue has been to find how the wind speed varies with height during a downburst event. As opposed to the boundary layer winds, downburst winds reach their maximum intensity at relatively low altitudes. In general, it is believed that the vertical profile shows a peak between 50 and 100 meters above ground (Holmes, 1999). Early observations by Fujita and Hjelmfelt during the 1980s are among the very small number of full-scale measurements available to verify the vertical profiles. Work by Wood, Kwok, Motteram, and Fletcher (2001) gives an empirical formula to approximate the distribution of high winds with height. Figure 6 shows the difference between the empirical formula and a typical boundary layer wind formula, along with other profiles resulting from numerical simulations of a downburst at different scales performed by Hangan (2002). The graph is normalized with respect to the maximum wind speed and the height where the wind speed is at one half of its maximum value.

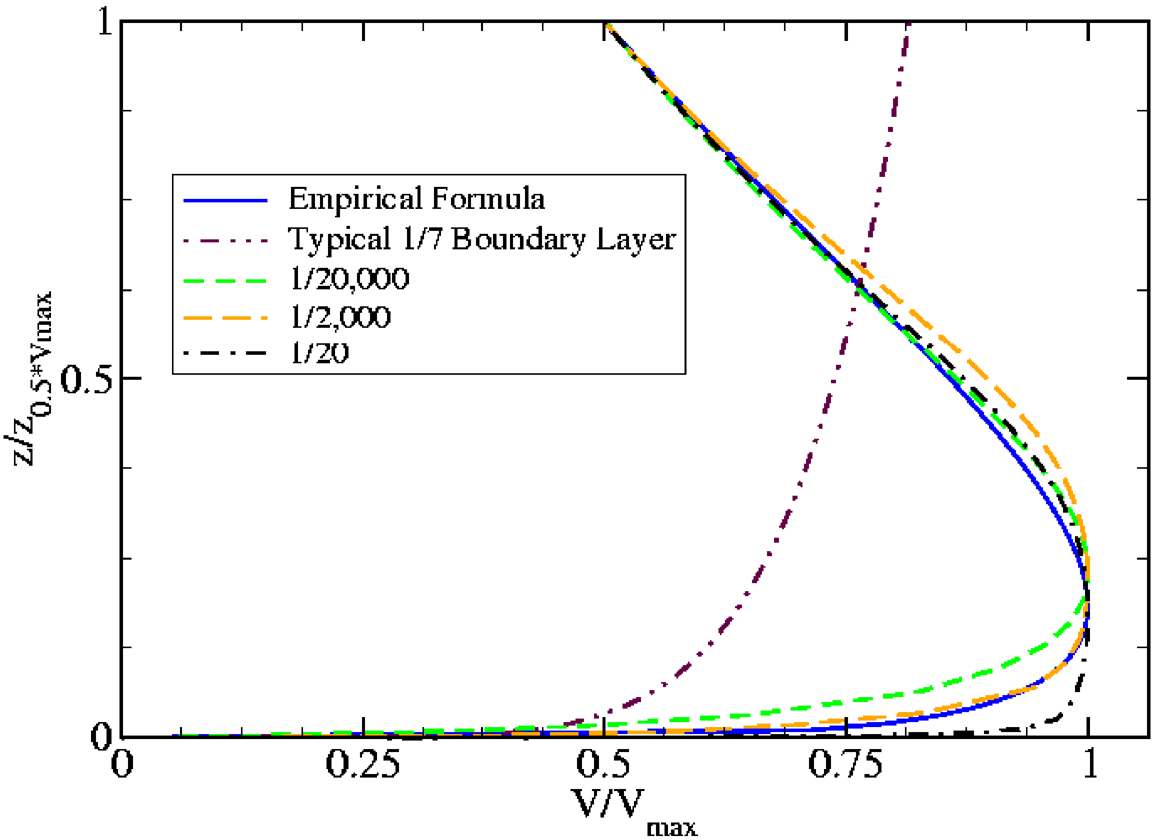

Figure 6: Downburst vertical radial velocity profiles (Hangan, 2002)

With the development of computational fluid dynamics (CFD), numerical simulations now take into account many properties of downbursts. The challenge is to generate, from those simulations, wind loads applicable to structures. Chay, Albermani, and Wilson (2006) attacked this problem and attempted to develop "a comprehensive model of a downburst that is suitable for the generation of wind loads in a time domain structural dynamic analysis" (p. 240). The work by Hangan (2002) provides another numerical downburst model.

Along with numerical simulations, some laboratory simulations have been tried. The research is still very limited and does not compare to the well-developed boundary layer wind tunnel work. One way of simulating a downburst is to use an outlet jet from a wind tunnel impinging on a vertical board. This technique was used for example by Wood et al. (2001). The method represents well the velocity profiles but fails to demonstrate the transient characteristics of the flow (Holmes, 2001). One major problem is that the source, contrary to a real storm, is stationary. Recent progress includes the development of a moving jet method (Mason, Letchford, & James, 2005). The milestones of this development are explained by Letchford et al. (2002), and a large part of the work has been done by the same authors at University of Queensland in Australia and Texas Tech University in the United States. There are also ongoing research developments on downburst simulations at the Boundary Layer Wind Tunnel Laboratory of the University of Western Ontario in Canada (Lin, Novacco, & Savory, 2006).

3.2.2 Tornado Wind Field

Tornadoes are more easily identified than downbursts due to their visible narrow funnel. The phenomenon has been studied for a long time and the general structure of the wind flow is well known. The flow field of tornadoes was studied through observations, numerical simulations, and physical simulations. Analysis from observations is useful, but limited by the rarity and unpredictability of events. If today, research using computer modeling is dominant, a large part of the basic knowledge on tornadoes was revealed through laboratory simulations.

A complete review of the evolution of physical modeling of tornadoes is available in Letchford et al. (2002). The first serious modeling attempts were made during the 1960s and in the 1970s, Davies-Jones (1976) reviewed the work in the field and concluded that the simulator developed by Ward (1972) was the most realistic. The Ward-type simulator was further developed by some authors including Church, Snow, Baker, and Agee (1979). Others used it to verify the effects of tornadoes on structures: For example, Jischke and Light (1983) studied the pressures on a rectangular model structure in a Ward-type simulator. Recent advances in tornado simulators include translation of the simulated storm and development of multiple vortices (Letchford et al., 2002).

The tornado is characterized by a vortex of high-speed air. Wind speeds are affected by a solid boundary: the ground. It is convenient to decompose the wind velocity into three components, namely the tangential (T), radial (R) and vertical (W) components, as shown in Figure 7. Velocity profiles are developed with respect to height (z) and radius (r). Note that the tangential velocity increases with radius up to a certain distance. Radial velocities have maxima at relatively low heights. The wind flow of tornadoes can become complex, and all the different components can be expected to have large velocities at some point. Based on this representation, Wen (1975) developed a loading model that was later used by several authors (Council for Scientific and Industrial Research [CSIR], 1992; Savory et al., 2001).

As for a downburst, the direction and speed of the storm producing the tornado will affect the maximum wind velocities. ASCE Manual 74 (1991) provides a simplified diagram of the regions of higher winds within a tornado (Figure 8). It is assumed that the rotary and translational components sum up as vectors. That creates an area of high winds in the right-hand side of the tornado for a counterclockwise rotating wind field.

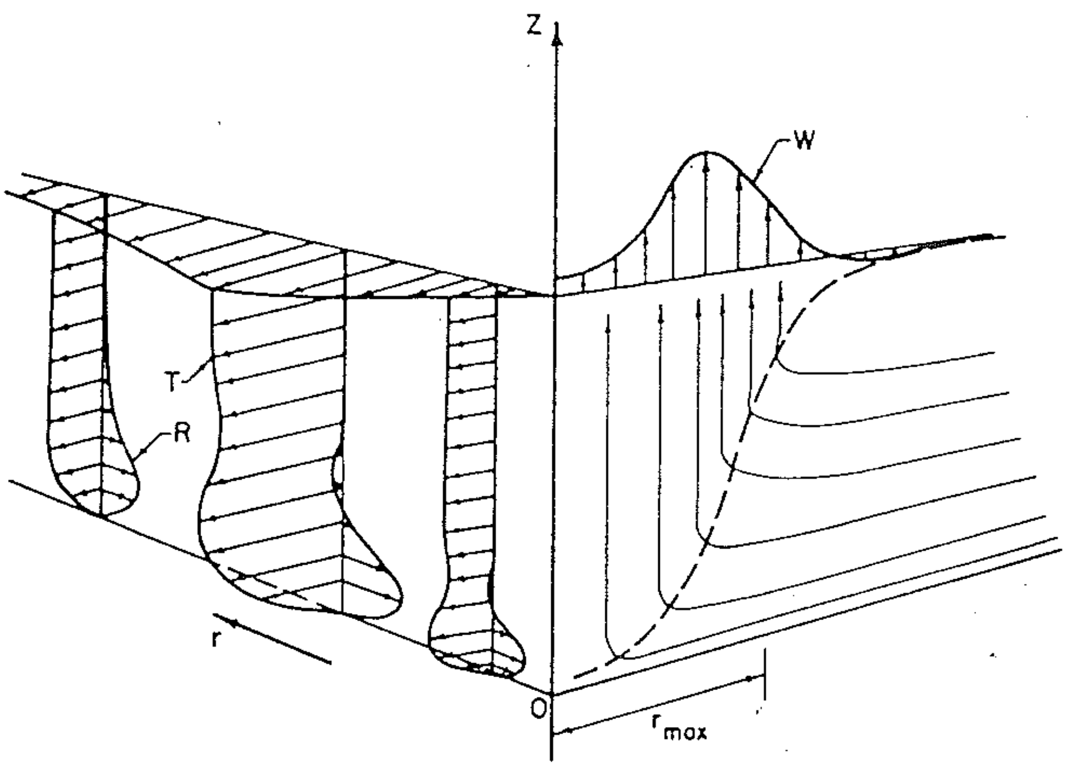

Figure 7: Schematic representation of the boundary layer in a tornado vortex (Kuo, 1971; Wen, 1975)

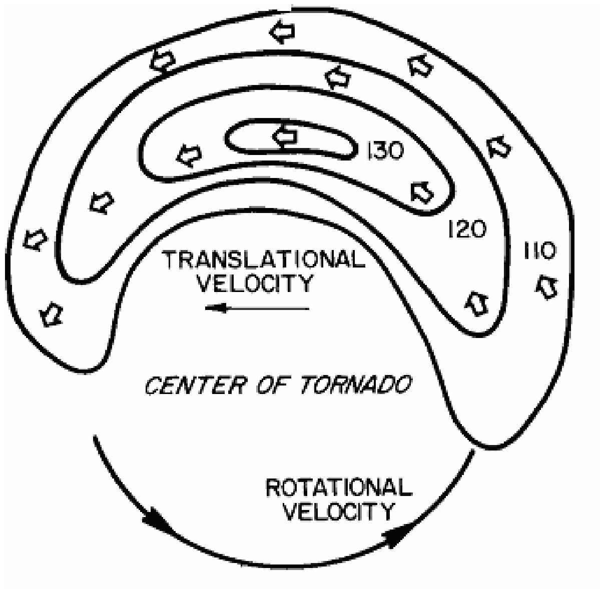

Figure 8: Hypothetical pattern of tornado wind velocities and directions (ASCE, 1991)

Another important feature of tornadoes is the presence of very low pressures near the center due to extremely high wind speeds. The difference between pressures at the center and outside the storm can be as high as 200 mbar (National Research Council [U.S.] - Committee on Atmospheric Sciences, 1973). This is not a major threat to transmission structures, but extremely low pressures can have devastating effects when they occur nearby buildings with closed doors and windows. Roof and walls can be blown out as large forces are created by the unequal pressures inside and outside the building.

As accounted for by recent laboratory simulations, large tornadoes can have more than one vortex. Those small-scale vortices were called suction vortices by Fujita (1981) and are represented in Figure 9. They explain the fact that damages are generally not homogeneous over a region. Suction vortices have diameters of about 10 m (Battan, 1984).

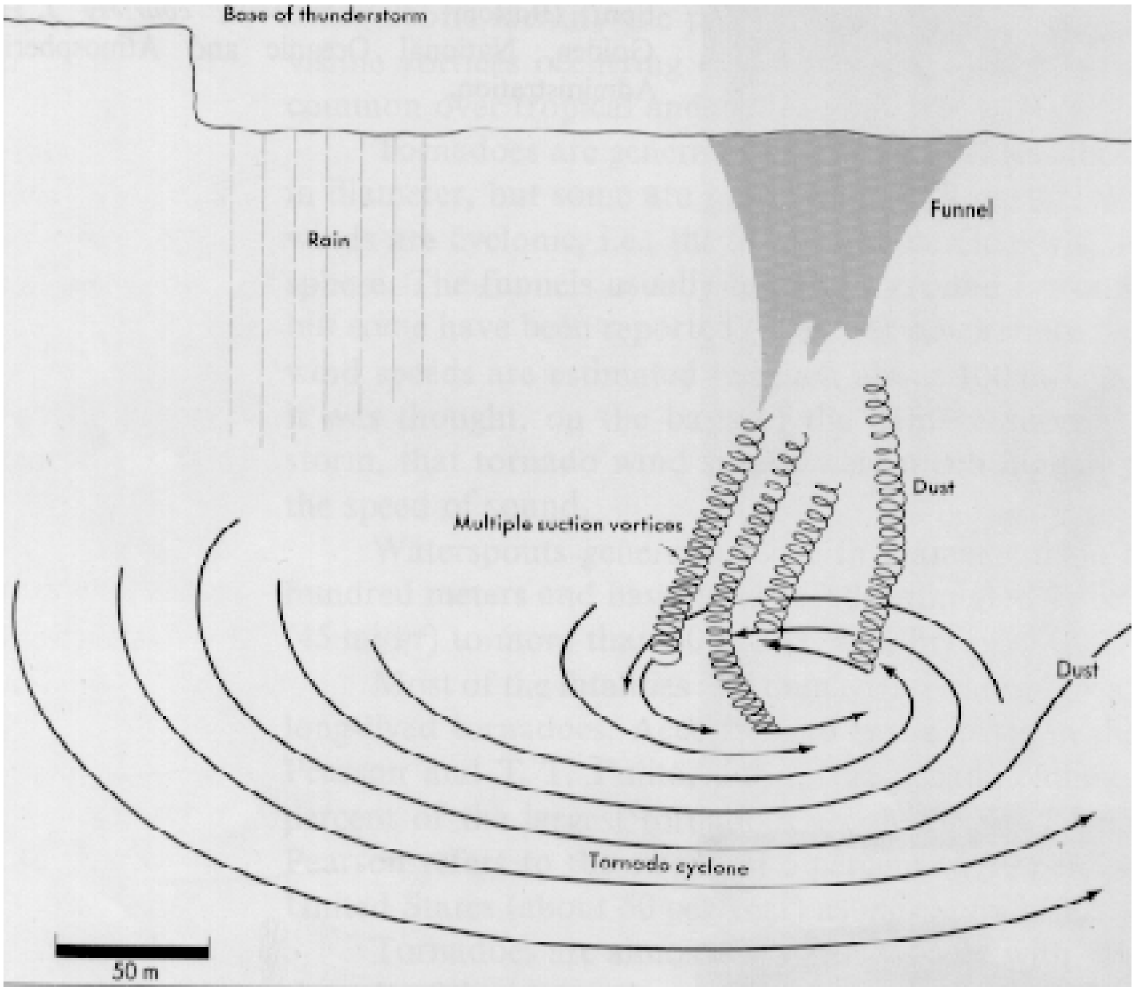

Figure 9: Schematic representation of tornado cyclone, funnel, and suction vortices (Battan, 1984)

4 Risk Assessment

To perform the design of transmission towers is to balance the costs of initial construction or reinforcement with the costs of power interruption and tower replacement. Twisdale (1982) expressed the opinion that for the United States, the risk of failure of transmission lines under tornado loads was generally too high. In some continental areas where icing is not a concern, 80-100% of all weather-related failures to lines are due to high intensity winds (Dempsey & White, 1996). In response to these failures, one first step is to find when, where and how often high intensity wind events occur. Those questions have proven to be difficult to answer.

The nuclear power industry is also highly concerned with the risk of a tornado striking a plant. However, what makes overhead lines particularly vulnerable to high intensity winds is the line-like geometry of the system. The probability of a severe local wind event striking any point on a line is much higher than the probability of that wind striking a single point.

Many challenges are encountered when assessing the risk of thunderstorm wind events. Several factors affect the quality of data records: Downburst and tornado recording has a limited time span, varies with density of population, is affected by the great complexity of thunderstorms and finally, depends on the level of expectation of a phenomenon in one particular location.

The observation time span is an important factor for the development of reliable high intensity winds risk models. Records are often limited to only a few decades of observations. For example, before the 1960s, the unknown phenomenon of downburst would often go unreported, while some downburst events would be reported as tornadoes. Changes in definitions and in the level of awareness of specialists and of the population led to a non-uniformity of records over time.

Another factor affecting the records is the density of population. Since high intensity winds are small in extent, many events are not noticed when they occur in open space. Recording of wind speeds by anemometers, which is much more reliable than evaluations based on damages, is limited due to the possibility of measuring wind speed at a precise point only. Since the probability of a severe wind striking a point is very small, it would take many years of data from an anemometer to predict with some accuracy the risk of that severe wind striking a line system of several hundreds of kilometers. Specialists generally rely on direct observation of the phenomenon to build databases. Hence, the risk of high intensity winds is often underestimated in sparsely populated regions. One way to solve this problem is to combine anemometer records from similar regions. This exercise was performed in Australia for the development of a downburst risk model by Oliver, Moriarty and Holmes (2000).

A third challenge is the complexity of those wind events. High intensity winds can take the form of many slightly different types of winds. In fact, every severe storm event has a different wind field and therefore, the exact prediction of wind loadings is impossible.

Wind speed and direction vary rapidly over time and the duration of the storm is difficult to predict. The only way to obtain useful data is to categorize wind events and to study common patterns in their wind field.

One last problem lies in the interpretation of the categorization of high intensity winds. It can be expected that a data set will tend to become overly standardized. For example, in the central United States, where tornadoes are expected to occur often, there could be a bias towards identifying non-tornadic winds as tornadoes. The quality of data records in a region must be carefully verified before attempting any serious high intensity wind risk assessment.

For developing a proper risk model, an adequate probability distribution must be chosen. Traditionally, the Type I Extreme-Value distribution, also called Gumbel distribution, is used to analyze annual extreme wind speeds. However, according to Holmes (1999), this distribution should not be used for winds originating from local storms which occur as discrete events. The distribution proposed by Holmes is a Type III Extreme-Value distribution. The latter is more realistic when return periods need to be extrapolated beyond the data limits.

The question of the choice of distribution also points out the problem of dealing properly with extreme wind data in climates where different types of severe wind events occur. Twisdale (1982) argues that: "the most accurate prediction of wind-loading risk is obtained from a separate analysis of each wind-producing phenomena" (p. 44). Separate analysis of wind gusts from thunderstorms in the region of Sydney was performed by Gomes and Vickery (1976). They later developed a technique to analyze separately the wind speeds from different storm types and combine them into a single design wind speed (Gomes & Vickery, 1978). The importance of thunderstorm winds was demonstrated when Twisdale and Vickery (1992) showed that those winds dominated the records of many weather stations in the United States. The fundamental issue is to statistically describe high intensity winds as a distinct population of wind event: This is a first milestone towards the development of probabilistic methods to design against high intensity winds.

The distribution of high intensity winds is not uniform over the planet: They are more common in large continental areas and their occurrence varies with latitude. Severe thunderstorms are critical in sub-tropical regions, i.e. at latitudes between 25 and 40 degrees. In regions located between latitudes 10 and 25 degrees, severe winds can occur due to both thunderstorms and occasional tropical cyclones (*Notes on meeting*, 1993). In the equatorial region (about 10 degrees North to 10 degrees South), most extreme winds occur in thunderstorms, but peak gusts are generally lower than in other regions (Holmes, 1999). In colder climates wind is not the only weather-related threat, and failures in transmission line systems are often caused by ice accumulation or by a combination of wind and ice (Nolasco, 1996). Failures due to high intensity winds have occurred in various climates where they have hit structures in off-design conditions, i.e. under loadings that were not specifically considered in design. In effect, most regions of the world should be concerned with the risk of high intensity winds, while mitigation for those winds should be different from one climate to the other.

Several risk models have been developed for high intensity winds and some of them are directly applied to transmission lines. Most of them consider only tornadoes, or only downbursts. A review of those models is provided in the following sections.

4.1 Downbursts

Downburst risk modeling is a new area of research. It is limited by the short period of data records. Only a few regions of the world, including the United States and Australia, have been studied for the probability of occurrence of downbursts. During the NIMROD and JAWS projects in the United States, tens of microbursts were recorded, and statistical analyses were performed. In Figure 10, the yearly probability of occurrence is plotted as a function of wind speed: It is seen that few observations are available for high wind speeds. Fujita (1990) notes that “because of higher frequencies and large individual area of a microburst, probabilities of structural damage by microbursts with 50 to 100 mph (22 to 45 m/s) range of windspeeds could be much higher than those of tornadoes” (p. 85).

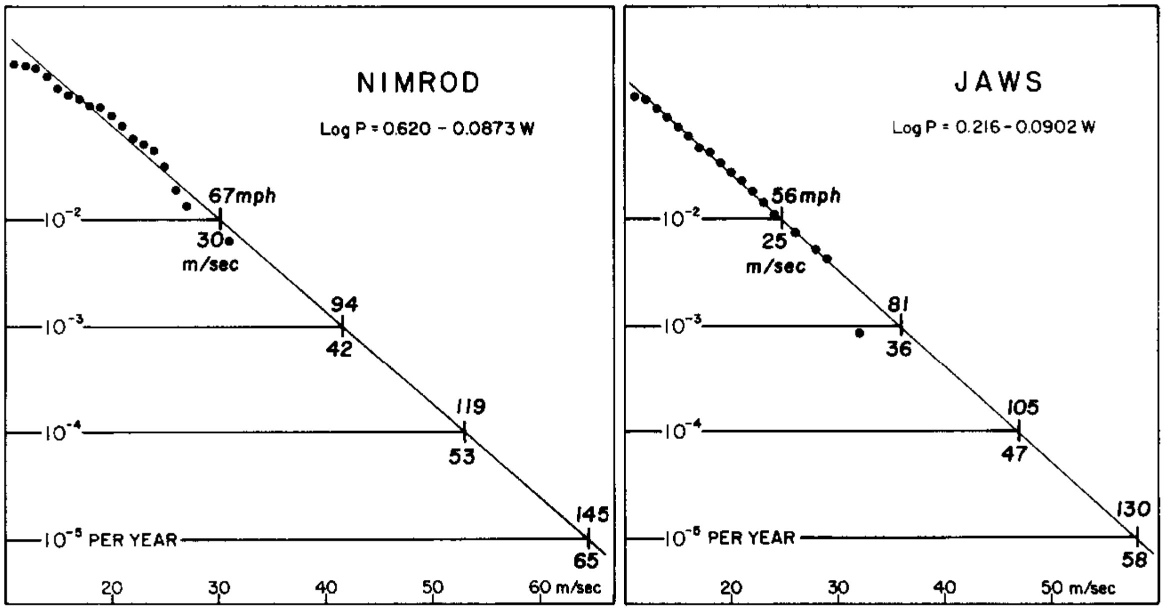

Figure 10: Microburst wind speeds in the NIMROD and JAWS projects plotted as functions of the occurrence probability per year (Fujita, 1990)

In Australia, downbursts and their resulting damages are observed frequently. Holmes and Oliver (2000), based on a ESAA report, evaluated that for the state of New South Wales, the yearly average occurrence of downbursts producing winds higher than 20.6 m/s at a recording station is 2.0. The peak gust recorded for such events was 42.2 m/s. Similarly, in Queensland, the average is 2.35 per annum with a maximum recorded wind velocity of 51.5 m/s. Hawes and Dempsey (1993) added that for New South Wales, the frequency of microbursts is similar to that found during the NIMROD and JAWS projects and that a return period of around 100 years per hundred kilometers of overhead line is expected for a wind speed of 45 m/s.

Based on their observations of downbursts, Australians have developed risk models for the intersection with transmission lines. A conceptual model is presented by Li and

Holmes (1995) and Li (2000). The model attempts a realistic simulation of wind loadings due to thunderstorms. Among other factors, it takes into account the size effect of thunderstorm. A less complex and well-accepted model is the one by Oliver, Moriarty, and Holmes (2000). From the following simple formula:

$$R_{V,L} = (w_v / L) * [\sum_{i=1}^{N} \Pr (v \geq V / \left| \sin (\theta_i - \varphi) \right|) * \Pr (\theta_i) * (\left| \sin (\theta_i - \varphi) \right|)],$$

one can obtain the return period ($R_{V,L}$) of a downburst event with wind speed (v) greater than threshold wind speed (V) crossing a line, given the following variables: the length of the line (L), the relative angle between the direction of the storm and the direction of the line (θ-φ), and the average width of path of downburst (w_v). That last variable is assumed to be directly related to the threshold wind speed. In the formula, the length variable is in the denominator, which shows that "as the overall transmission line length increases, the return period for damaging intersections decreases" (Holmes, 2001, p. 266). This model, or more precisely an earlier version of it, is used in the works of Letchford (1998) to study a line that had failed twice under high intensity winds. Using the same model, Letchford and Hawes (2000) assessed the risk of failure of the entire high voltage transmission line network due to downbursts in Queensland, Australia. The model generally predicts more failures due to downbursts than what is really observed. This is due to both a conservative design process and a conservative extreme wind speed analysis.

Some other risk models were developed in other countries. For example, de Schwarzkopf and Rosso in Argentina developed the return period graph in Figure 11.

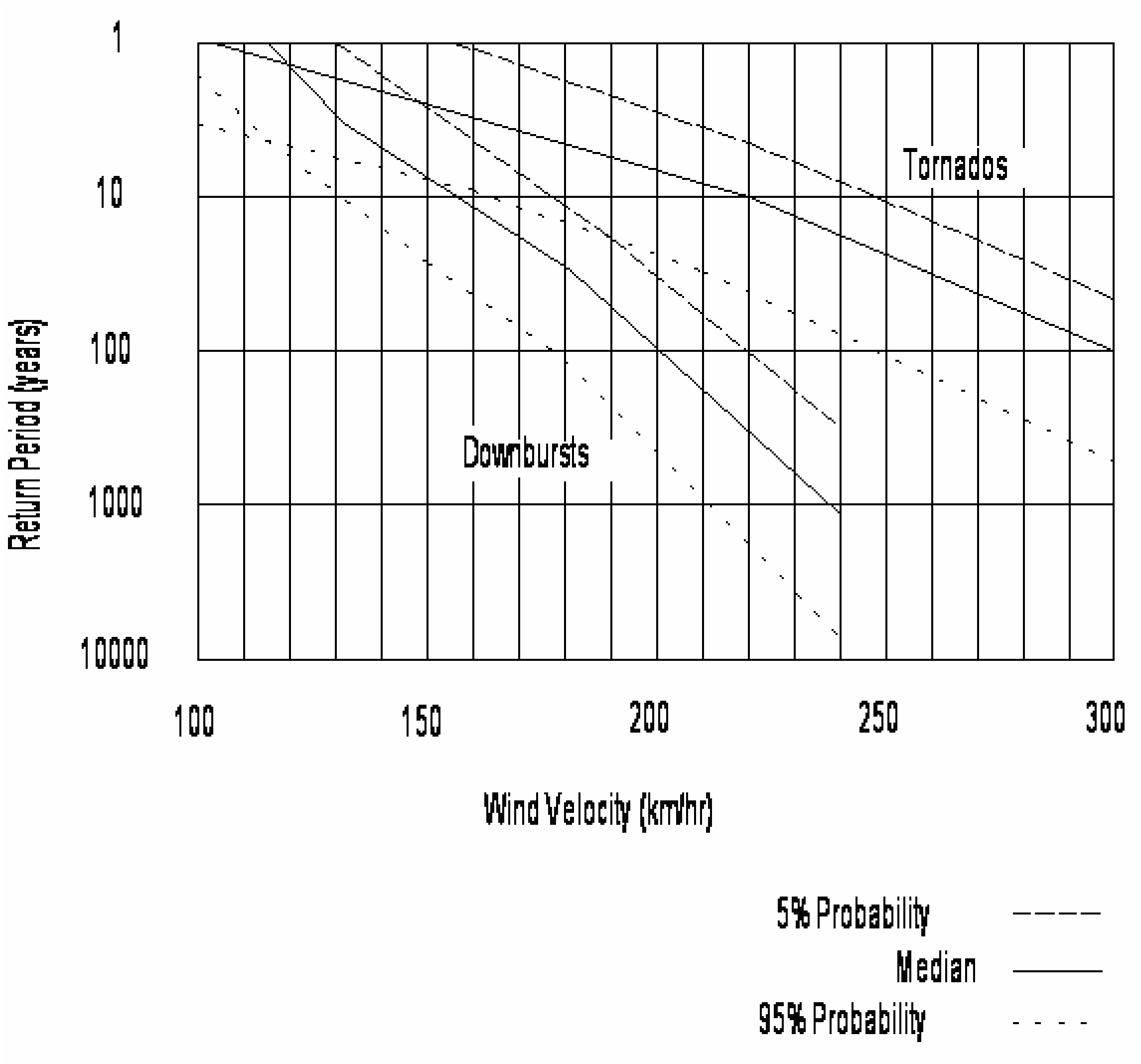

Figure 11: Return period of wind speeds for downbursts and tornadoes traversing a 650 km line section in Argentina (ASCE, 2005)

Downburst risk models are quite similar to, and in fact originate from tornado risk models. However, downbursts are generally larger in extent than tornadoes. Often, more than one span is enveloped by damaging winds and therefore, unlike for tornadoes, the wind loading on conductors is significant. For long lines not specifically designed for high intensity winds and perpendicular to the normal direction of thunderstorms, risk models usually yield very low return periods.

4.2 Tornadoes

Most tornadoes, and more specifically those that are expected to be survived without damages, affect a width much smaller than one line span (wind span). The focus is then given to wind on the towers and wind on conductors is often neglected. This is supported by a very small probability that an entire conductor span is loaded by tornado winds. Hence, risk assessment goes from looking at the probability of an event striking any point on a line, for a downburst, to the probability of an event striking any tower on a line, for a tornado. In general, tornadoes should cause damages less often than downbursts, but could possibly be more devastating due to higher wind speeds.

Tornado records are kept in most developed countries. The United States is by far the country where the largest number of tornadoes is reported with an average of 800 to 1000 each year for the contiguous states (ASCE, 1991). Recently the number of tornadoes was evaluated at 1200 per year for the whole country (Brooks et al., 2003). Shown in Figure 12 is a map of the United States with the number of tornadoes recorded during a 30-year span for each one-degree squares of longitude and latitude. This map was developed by Tecson, Fujita, and Abbey (1979) and is also included in the ASCE Guidelines for Electrical Transmission Line Structural Loading (1991). In the ASCE 7- Minimum Design Loads for Buildings and Other Structures (2002), another map (Figure 13) shows the expected maximum tornadic wind speed for a 100,000 years return period.

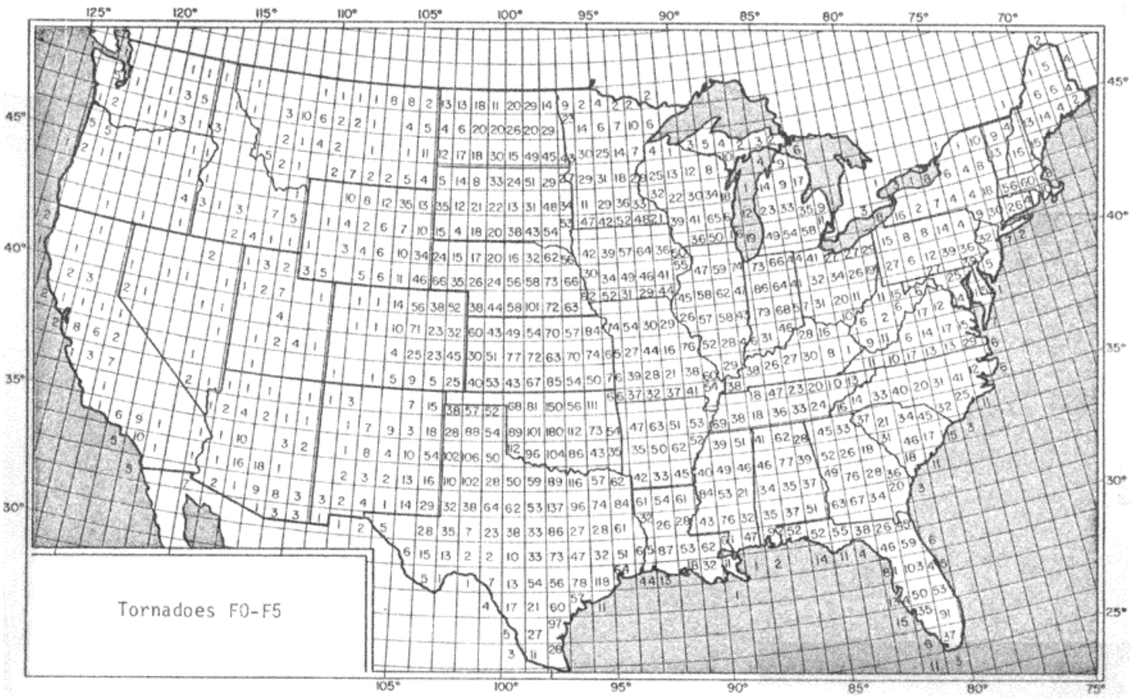

Figure 12: Total number of reported tornadoes during a 30-year period (ASCE, 1991; Tecson et al., 1979)

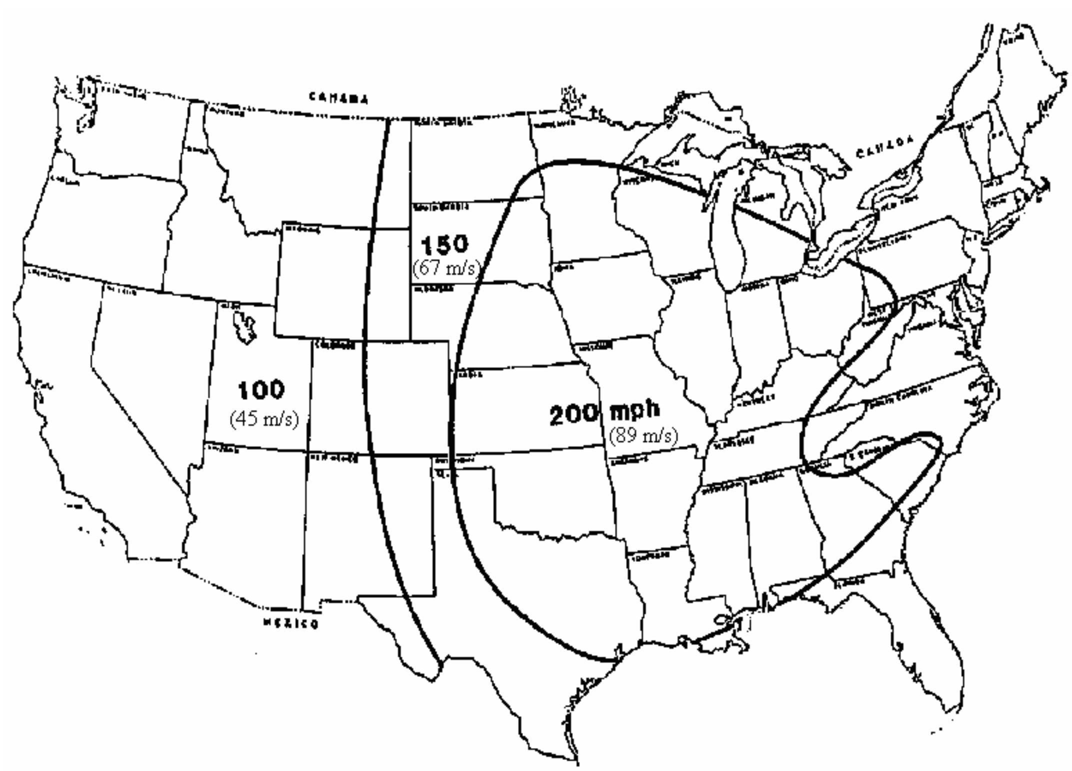

Figure 13: Tornadic gust wind speed corresponding to 100,000 year return period (ASCE, 2002)

Other authors have identified the frequency of tornadoes for South Africa (Milford & Goliger, 1994) and Argentina (Schwarzkopf & Rosso, 1982). In the early 1970s, Fujita (1973) was the first to attempt a review of tornado activity around the world . More recently Goliger and Milford (1998) performed a similar work. These articles identify the North American continent as being the area where most tornadoes occur. The Great Plains of the United States are, without any doubt, an area favorable to the formation of tornadoes. However, due to an increased awareness, a large portion of the tornadoes recorded are very small ones. Those small tornadoes were not reported a few decades ago, and in most parts of the world, are still not reported. Therefore, the difference between the frequency of events in the United States and elsewhere is probably smaller than what is shown in the current records. For example, the recording efforts in Germany have increased the frequency from about 2 per decade before 1950, to 7 in the 1990s, to finally 20 in the year 2000 alone (Brooks et al., 2003). From the point of view of the transmission line industry, it is often more reliable to study risks looking directly at the number of failures of lines in a region. The CIGRÉ Technical Brochure 256 (CIGRÉ WG B2.16, 2004) gives an idea of the frequency of line failures for some countries. In that same report, a useful world map of wind hazard is provided.

For areas where the tornado records are reliable and statistically significant, it can be useful to derive models for the risk of tornadoes striking a line. Tornado risk models first evolved with the goal of assessing the risk of an event striking an isolated structure; Many authors, including Thom (1963) and Wen and Chu (1973), have developed models of this type. Twisdale and Dunn (1983) produced a tornado wind risk model for both isolated structures and lifelines. Milford and Goliger (1997) developed a simple model for the risk of intersection of a tornado with a transmission line and provided proper values for tornado frequency to apply the model to South Africa. In a book on structural wind loading, Holmes (2001) argued that only the intersection of a tornado with a tower on a line is a critical factor for line failure. He also developed his own simple risk model based on this assumption. At least two utilities, Commonwealth Edison (Teles, Anderson, & Landgren, 1980) and Ontario Hydro (Anders, Dandeno, & Neudorf, 1984), performed their own probabilistic assessment of tornado hazard.

The idea that all tornadoes produce extremely high and devastating winds and that nothing could be built to survive those events is no longer valid. Most records consider not only the number of tornadoes, but also their intensity. The Fujita scale, explained in section 2.4, is almost always used to qualify those events. It is useful to know the percentage of low intensity tornadoes in a record because design criteria should be based on resisting most tornadoes and not all tornadoes. This percentage certainly depends on the quality of the record, but for acceptable data, the number of F0 and F1 tornadoes is very high. For the Canadian Great Lakes region, the percentage of tornadoes less than F2 is about 80 % (*Notes on meeting*, 1993). For the United States, the ASCE Manual 74 (1991) suggests that 86 % of events are F2 or smaller.

5 Failures of Transmission Lines

5.1 Impact on Structures

The knowledge on the effect of high intensity winds on transmission lines is limited. Research on the wind field and of those events has shown that their effect is likely to be very different from the conventional boundary layer wind effect. In general, the wind loading due to tornadoes or downbursts could take any form. Therefore, the most realistic prediction for those wind loads is that they could be anything other than the synoptic wind load usually accounted for in design codes. There are still ways to simplify the effect of high intensity winds and to economically reduce the impact of those winds on structures.

5.1.1 High Intensity Wind Loading

Based on observations of wind damages on transmission lines, Carpena and Finzi (1964) proposed an early design philosophy regarding high intensity winds, and more specifically tornado wind loads. They wrote: "we shall then point out that by increasing the transverse strength of towers the structures may often not be safe enough against actual wind loads and that a certain longitudinal and torsional strength is required" (Carpena & Finzi, 1964, p. 2). Their view of wind loading is that a tower should be able to resist a large number of different loadings, rather than one very high transverse loading. Since most wind events do not cover a very large area, the load on conductors is rarely due to the maximum wind pressure anticipated applied on the whole wind span. Today, most design codes include a span reduction factor to account for the limited width of gust winds. To account for very narrow wind, the loading on conductors can sometimes be further reduced, while the loading on the tower is increased. Furthermore, the wind load should be expected to come from a wider range of directions. The effect on structures for this kind of loading is explained by Carpena and Finzi (1964):

> We must note that transversal loads due to wind pressure on conductors and on towers act in a different way. The former, which are applied to the crossarms, stress leg members foremost and may not stress web members appreciably; the latter, on the contrary, have their resultant applied at mid height and mainly stress web members which may have to be designed specially for these stresses (p. 19).

Hence, one way of increasing performance of lines against high intensity wind would be of increasing the strength of bracing members.

A number of sources have expressed, with respect to transmission lines, the characteristics of a simplified tornado wind loading. Many of them are articles illustrating design practices used by some utilities, or recommendations formulated by transmission line industry organizations, and are further discussed in section 6. One common point to those simplified loadings is that due to the very narrow path of a tornado, the wind load on conductors is neglected. In a synoptic wind loading, the wind on conductors, which is distributed to the structure through the wires, represents a large part of the total horizontal load on the towers. The position of the resultant transverse load is then very high on the tower, near the geometric center of the cables. A tower designer normally specifies, for a self-supporting tower, the intersection of the main leg slopes to coincide with this center of effort (or with the geometric center of the cables). This way, the loading in bracing members is reduced and failures are more likely to occur in the main legs or the foundations. In the event of a tornado affecting a tower, the wind load on conductors is likely to be small compared to the load on the structure itself. The center of effort is therefore lowered and significant forces develop in web members; if buckling of one of those slender members occurs, the tower may fail in a shearing mode. This failure mechanism is often observed for structures suffering a very narrow high intensity wind event such as a tornado (Dempsey & White, 1996). For guyed towers, the complex wind loading patterns on guy wires and lattice sections may have various effects. For a guyed-V tower, a tornado wind loading is likely to increase the bending moments in the masts. Also, the shear distribution in the masts of guyed-Y and Delta-guyed towers can be changed (Ishac & White, 1995).

A simplified downburst loading is found in some works, but there is not yet a consensus on it. Downbursts are known to be larger than tornadoes in extent, i.e. more than one span can be affected by an event. The wind speed at one point is highly dependent on its location with respect to the center of the storm. Also, downburst wind loading varies greatly depending on the development stage at the moment the structure is hit. If a downburst is close to touch down, high downward vertical winds are expected. After touch down, the load is mainly horizontal (Savory et al., 2001) with possibly some upward vertical load due to the formation of a ring vortex. Based on wind tunnel simulations, Letchford and Hawes (2000) argue that since a typical downburst can create high velocity winds up to a height larger than 150 m, it can be assumed that during this type of event, towers are fully loaded over their height. In a worst-case scenario, the cables of an entire wind span could also be fully loaded. Some authors suggested that higher span reduction factors should be used for a downburst loading case (Oliver et al., 2000). This idea is based on observations of very well-correlated high gusts over a large area during downburst events.

Dempsey and White (1996) attempt a more refined version of a simplified load and write: “At this time a patch-wind loading only on the top sections of the tower and conductors would appear to fit observations where microbursts have caused transmission line failures” (p. 40). The recommendations of the CIGRÉ Technical Brochure 256 by Working Group B2.16 (2004) support the same idea. The wind loading below 15 m is neglected due to boundary interaction, and a strong wind is applied to the rest of the tower and the conductors. This represents well the high wind shear expected during downbursts but does not respect the downburst wind profile which predicts very high winds at low altitude.

The most elaborate downburst design loading model is found in the Australian “Guidelines for Design and Maintenance of Overhead Distribution and Transmission Lines” (ESAA, 2003). The loading details are presented in section 6.5. The procedure to apply high intensity winds is very similar to the one for synoptic winds, except that specified wind speeds are based on microburst data records and there are some restrictions to the use of span reduction factors. As for boundary layer wind effects, the structure and conductors are assumed to be fully loaded by high winds.

Along with the observation of line failures, the development of numerical models for wind loading and line structures is a mean to evaluate the effects of high intensity winds. It was shown in section 3.2 that a number of numerical simulations methods were developed to model a downburst or a tornado. Some of those methods were used to perform finite element analyses of towers. Those analyses still need to be refined, but they give an indication of the distribution of forces in a tower due to a high intensity wind loading. At least three analyses of this type were performed in recent years.

The first was done by Savory et al. (2001), who developed a model of a lattice transmission tower and submitted it to both a tornado and a microburst severe loading. The tornado loading created a shear failure as often observed on transmission lines. However, when the microburst wind load was applied to the structure, no non-linearity was observed. It should be noted that the model was limited to one tower and that the load on conductors was neglected. The fact that the model of a severe downburst affected only moderately the tower suggests that wind load on conductors should be considered for this type of wind storm.

In another study, Hoxey et al. (2003) assessed the response of a lattice and a guyed tower to a downburst. The guyed tower seemed less resistant to this type of wind load and exhibited failure of the crossarm and of the primary member above guy fixings.

Finally, Shehata, El Damatty, and Savory (2005), based on CFD work by Hangan (2002), applied a downburst loading on a lattice tower. Among other findings, they proved that "peak forces in the transmission tower members are sensitive to the downburst location with respect to the tower" (Shehata et al., 2005, p. 87). More research by these same authors is in progress at the University of Western Ontario.

5.1.2 Dynamic Behaviour

Thunderstorm winds usually change very rapidly with time, but the possible existence of dynamic amplification effects in transmission line structures due to high intensity winds has rarely been raised. Many current codes, based on the concept of gust response factors (Davenport, 1979), account for the dynamic response of the line. However, for reasonably short tower height and line span, the dynamic response is believed to be very small (Holmes, 2001). Also, for high wind speeds, "dynamic response is not dominant due to high aerodynamic damping" (Matheson & Holmes, 1981, p. 109). This aerodynamic damping limits resonance that could occur in cables due to a natural frequency often below 1 Hz (period over 0.16 seconds), and relatively close to wind forcing frequencies. Classical lattice towers generally have larger natural frequencies (over 1 Hz) and are rarely affected by the dynamic properties of wind (Holmes, 2001).

The small number of complete time history records available makes it difficult to assess the dominant frequencies of high intensity winds. Shehata et al. (2005) evaluate that the dominant period for downbursts is between 20 and 22 seconds, which justifies a static analysis.

Even if dynamic response does not seem to be a major factor in transmission line failures, not enough is known to completely eliminate possible dynamic effects, especially in guyed towers. A study of downburst effects on tall buildings (Chen & Letchford, 2004) gives some important information about the dynamic response of transmission structures to downbursts. Looking at the time histories of some recorded and simulated downburst events, the authors identify a characterizing period of 36 seconds. When the response of a particular building is studied under different downburst loadings, the maximum response constantly occurs for periods around 14 seconds. The fundamental period of the building studied is around 5 seconds, and hence, the maximum dynamic response is probably not reached for tall buildings. The authors suggest that the dynamic response could be more critical for tall towers and masts of around 100 m in height due to their longer natural periods. This work by Chen and Letchford and an article by Holmes, Forristall and McConochie (2005) are among the few documents written on the subject of dynamic structural response to thunderstorm winds.

An important contributor to the advancement of wind engineering in the last decades, Alan G. Davenport, expressed at the meeting of the Task Force on High Intensity Winds on Transmission Lines in Argentina (*Notes on meeting*, 1993), concerning the problem of structure resonant amplification: "Gust must last 30 seconds to be of concern, [and therefore] 2-3 second gusts are generally not a problem but downbursts gusts may be" (p. 8). He also added that: "High Intensity Wind flow had significant 'patchiness'. It is helpful to use influence lines to check effect of wind at different levels" (*Notes on meeting*, 1993, p. 8). The use of influence lines is briefly described in Davenport (1995) and is further developed for the application of synoptic winds on guyed towers by Davenport and Sparling (1992).

In summary, even though it does not seem frequent, some dynamic amplification can possibly be induced in the response of transmission structures to downbursts. Very little research is available on the subject.

5.1.3 Topographical Effects

It is well known that local topography can influence wind speeds near the ground and that structures located on top of a hill could experience an increase in wind pressure. A discussion of the modification of wind flow due to topography is provided in Holmes (2001). It is included in codes as a "speed-up" factor or topographic multiplier, defined as the ratio of the wind speed over a topographical feature to the wind speed at the same height in flat terrain.

Those local topographic effects have been well-studied in boundary layer wind tunnels. The application of speed-up factors to thunderstorm winds could, however, be misleading. A few physical simulations of downbursts, including one by Letchford and Illidge (1999), showed that those multipliers are actually smaller for high intensity winds than for boundary layer winds. On the other hand, this conclusion was found using stationary jet models and could be different for storms with high translational velocities. ASCE Manuel 74 (2005) suggests speed-up factors up to 1.3. Letchford (1998) assumed that speed up factors during a particular downburst event were about 1.2 at ground level and decreased linearly with height up to 100 m.

5.1.4 Transverse Cascades

A major concern in the transmission line industry is the avoidance of line cascades. A cascade is defined as the progressive collapse of a large number of structures (Peabody, 2001). Most cascades are said to be longitudinal and are due to the initial failure of a structural element that maintains tension in the wires. There are sometimes also transverse cascades that are almost exclusively initiated by high intensity winds (ASCE, 2005). A tornado, damaging one or two structures, or a downburst, possibly damaging a few more, are often at the origin of a long chain of support failures that can affect tens of structures. When a tower falls in the transverse direction, the effective span gets longer, and forces are created both in the transverse and longitudinal directions at the adjacent structures. If these towers also fail, the collapse may progress, forming a cascade (Peabody, 2001). Some properties of line systems that enhance the vulnerability to transverse cascades are: short spans, tall structures and short insulator strings (ASCE, 2005).

Transverse cascading was sometimes in the past mistakenly perceived as “multiple failures caused by a ‘wall of wind’ overcoming all the fallen structures” (ASCE, 2005). In fact, except during cyclones or hurricanes, it is quite rare to observe such large wind events able to cause multiple failures to a line. Prevention of cascades is a critical aspect of line design and is an effective way of minimizing the potential damages due to high intensity winds.

5.2 Reported Failures

Some documents report and sometimes analyze a number of transmission line failures due to high intensity winds. The purpose of this section is not to cover all failures that have occurred, but to give a summary of some case studies where the event was carefully analyzed. Unfortunately, very few of those reports can be accessed publicly.

A survey of transmission line failures was conducted by CIGRÉ (Nolasco, 1996) about 10 years ago and is being updated this year. Although the exercise did not completely reach its objectives due to the limited quality of responses by utilities, it nonetheless gathered information about 299 failure events involving 1731 towers in 24 countries. The data is interesting from a statistical point of view even though it clearly does not cover all failures that occurred to transmission lines, nor always identifies precisely the cause of failure. About 86 % of failures were attributed to climatic loads such as wind, ice, or a combination of wind and ice. Other causes are, for example, broken conductors, hardware failures, and vandalism. Among failures due to climatic loads, 54 % were due to wind alone, with thunderstorm winds often involved.

5.2.1 Argentina

When a first meeting of what was called the Task Force on High Intensity Winds on Transmission Lines (*Notes on meeting*, 1993) was held in Buenos Aires, Argentina, an important failure event had just occurred in that region. Three 500 kV lines were damaged from the Alicura and the El Chocon Power Stations. A total of 56 towers had failed at multiple sites, and damages were observed over a very large area of more than 150 km by 50 km. The cause of failures was attributed to 4 or 5 distinct tornadic cells.

At that same meeting, previous failures were also discussed. There had been another failure on the El Chocon 500 kV line, and one on the Rodriguez 500 kV line. An interesting fact about this last failure is that the estimated damaging winds did not go over 140 km/h (39 m/s), while the line was theoretically designed for winds up to 180 km/h (50 m/s). Other details of failures are available in the notes of the meeting (*Notes on meeting*, 1993).

5.2.2 Australia and New Zealand

An important document in the domain of high intensity winds is a review of failures in Australia by Hawes and Dempsey (1993). It covers some meteorological concepts, gives information on the frequency of failure events, summarizes some research on the subject and finally provides specific observations about some failures.

Relevant statistics given for Australia for the period 1951-1993 are:

- Total length of transmission lines between 110 kV and 500 kV: 53500 km
- Number of major failures reported: 21
- Number of structures failed: 94
- Number of failures initiated in towers: 16

- Number of failures initiated in foundations: 5
- Number of failures due to HIW: 19
- Number of failures due to tornado: 5
- Number of failures with evidence of microburst: 10

In this document, the definition of high intensity winds is broad, and the 19 failures due to HIW could include tropical cyclone related failures. The estimated wind gusts during the failure events range from 41 to 66 m/s and are generally between 45 and 50 m/s. Details of four different failures are reported. In most cases, there was evidence of high wind shear, i.e. high rate of change of wind speed with height.

A more recent document, written by Letchford (1998), presents a complete study of a 275 kV line failure where 5 towers failed due to a macroburst, with possibly the presence of several microbursts within the macroburst.

In New Zealand, a report was recently completed on the loss of two pylons due to a downburst (Reid & Revell, 2006). The estimated maximum wind speed was 43 m/s. The evaluation of damages to the vegetation surrounding the collapsed towers helped analyzing the weather elements in place.

5.2.3 North America

A very large cascade failure that was initiated by high intensity winds was documented in the United States (Oswald, Schroeder, Catchpole, Carrington, & Eisinger, 1994). The failure occurred on a 345 kV wood pole line owned by the Nebraska Public Power District. Over 400 structures failed during a fast-moving storm that produced several small tornadoes and microbursts. In this report, focus is given to the inability of the system to stop the cascade.

In September 1996, Manitoba Hydro in Canada lost 19 towers following high intensity wind events. The failure occurred in a region where wind rarely causes damages without combination with ice. A report by meteorologists (McCarthy & Melsness, 1996), analyzed the weather elements that led to the failure and concluded that the event did not include tornadic winds, but was rather caused by downbursts. Following this failure, research was initiated at the University of Western Ontario (Lin et al., 2006; Shehata et al., 2005) to gain better understanding of the effects of downbursts on line structures.

6 Codes and Design Practices

To date, while it has been proven that in many regions, high intensity winds are a larger threat to transmission lines than boundary layer winds, wind loading codes continue to be based on synoptic winds. More and more designers, however, take into account the possibility of severe thunderstorm winds hitting line systems. Behncke and White (2006) even argue that the whole synoptic wind method should be replaced by a simpler direct wind gust method where 3-second wind gusts would be applied directly to the structure and to part of the cables. Guidelines for the inclusion of high intensity wind risks in design are provided in Australia (ESAA, 2003) and in the United States (ASCE, 1991). Some utilities have developed their own design practices to face the problem. This section provides a review of those design practices.

6.1 IEC 60826-2003

The standards defined by the International Electric Commission (IEC) on the design of overhead transmission lines are based on synoptic wind, while a few mentions to high intensity winds are made.

First, it is recognized that the document does not cover localized events and that those can represent a serious threat to lines due to both direct wind forces and impact of wind carried objects. Second, the IEC recommends that the designer perform a special study on wind extreme values before choosing a design wind speed in regions prone to high intensity winds. Hence, the code suggests that high intensity winds need to be treated separately from synoptic winds, from a statistical point of view.

6.2 Hidronor (Argentina)

Behncke and White (1984) have discussed the design assumptions used for Hidronor's Alicura 500 kV line in Argentina. Wind was identified as the most serious threat to the line. Due to failure experiences with the 500 kV El Chocon line, Hidronor decided to take special considerations for the risks of tornadoes. It was recognized that very severe tornadoes could probably not be resisted by transmission lines. However, it was evaluated that about 85% of tornadoes would exhibit winds equal to or less than 220-240 km/h (60-67 m/s). Static analysis was carried out on guyed-V towers subjected to a wind loading based on those speeds and coming from any direction. The tornado loading required only minor reinforcement to a few members near the top and the bottom of the masts. This marked the first time a special tornado loading was used in transmission line design.

6.3 Eskom (South Africa)

While Hidronor's justification for a tornado load was found in past experiences, Eskom tried to evaluate the actual risk that represent tornado winds for transmission lines based on tornado risk models and event records. The design criteria and the assumptions made are documented in Behncke et al. (1994). The tornado loading chosen is more conservative than the one recommended by the ASCE (1991) and discussed in section 6.6. A tornado wind of 250 km/h (70 m/s) is applied to the tower only. An analysis of the record in South Africa had shown that 90% of all tornadoes were F2 or less on the Fujita scale (see section 2.4).

The effect of the tornado load was calculated for a 400 kV cross rope suspension tower: It resulted in an increase of the bending moment in the mast central portion and the reinforcement needed increased the tower total weight by 2% only. If the tower was short enough, no reinforcement was needed. According to this document, tornado loads are especially critical on guyed towers such as guyed-V and cross-rope towers.

The simplified tornado loading used by Eskom was based on the recommendations of a previous review (CSIR, 1992) of tornado loading models. In summary, the CSIR agrees with the ASCE Manual 74 (1991), except that it recommends to include the dead weight of conductors in the analysis. The ASCE suggests that due to strong vertical wind loads, the self-weight of wires can be ignored.

6.4 Hydro One (Canada)

Ishac and White (1995) have developed the design criteria used by Hydro One (formerly Ontario Hydro) to account for tornadoes. Their tornado loading model is also based on a very high (92%) proportion of small intensity tornadoes (F2 or less) recorded in the region studied. The authors suggested that the tornado wind speed applied to a line segment be proportional to its boundary layer extreme wind speed equivalent. The resulting tornado wind speed is much higher than normal extreme values, but is applied to the tower only. For example, the highest tornado wind speed used is 66.7 m/s (240 km/h) and is suggested only for segments where the extreme synoptic design wind velocity is 44.4 m/s (160 km/h). Other values for design wind speed are shown in Table 2.

Table 2: Hydro One tornado and extreme wind loading (Ishac & White, 1995)

Extreme wind speed (m/s)	22.2	26.7	35.6	40.0	44.4
Wind load on conductor (kPa)	0.29	0.39	0.77	0.96	1.15
Wind load on tower (kPa)	0.8	1.1	2.1	2.6	3.1
Tornado scale	F1		F1/F2	F2	
Tornado wind speed (m/s)	33.3	40.0	53.3	62.2	66.7
Tornado load on conductor (kPa)	0	0	0	0	0
Tornado load on tower (kPa)	1.7	2.4	4.8	6.0	6.5

Designs of two types of towers, one self-supporting latticed 4-leg tower and one guyed-V tower, were revisited while considering that new tornado load. Each tower type was redesigned for the basic and the tallest tower configurations. The basic 4-leg tower did not need any reinforcement, while the tallest configuration was adequate for overturning but needed reinforcement in shear. The total additional weight needed for the tallest configuration was limited to 2.5%. For the design of the guyed-V towers, extra bending moment and shear capacity was needed. The additional weight was also limited to 2.5% for both the basic and the tall configurations.

6.5 Standards Australia ESAA C(b)1-2003

As mentioned earlier, the ESAA (2003) specifies a design procedure for microburst loading that is very similar to that for synoptic wind loading. The country was divided into 11 regions of microburst activity as shown in Figure 14. Table 3 provides for each region a microburst design wind speed varying with the desired line reliability level. All wind speeds in the table are based on a line length of 100 km and a microburst gust width of 500 m. Line reliability is theoretically inversely proportional to the total length of the transmission line.

Wind forces on conductors are not neglected for microbursts and span reduction factors must be not less than 0.9 for spans less than 500 m. The wind speed is further multiplied by a microburst wind direction factor that depends on the region concerned and on the critical wind direction (perpendicular to the line).

Tornadoes are less frequent than microbursts in Australia, but the ESAA still recommends a tornado loading to be used in the case where tornado can be an issue. For a line reliability level of 4 (400 years return period), a wind speed of 60 m/s is recommended for application on the tower only, without any wind force on the supported cables.

Table 3: Microburst wind gust speeds for selected line reliability level (LR) and return period (RP) (ESAA, 2003)

LR (RP Years)	1/2 (25)	1 (50)	2 (100)	3 (200)	4 (400)	5 (1000)
Regions H, I, J, K (NSW and QLD)	42.0	44.0	46.1	48.2	50.2	52.1
Region I1 (S-E QLD)	51.0	56.0	60.1	63.6	66.7	70.8
Region L (VIC)	46.5	48.5	50.2	52.0	54.2	56.6
Region M (VIC)	48.4	50.5	52.2	54.2	56.5	58.9
Region O (SA)	47.0	49.0	50.7	52.5	54.8	57.2
Region N(SA), P and Q(WA)	48.0	50.0	51.7	53.6	55.9	58.3

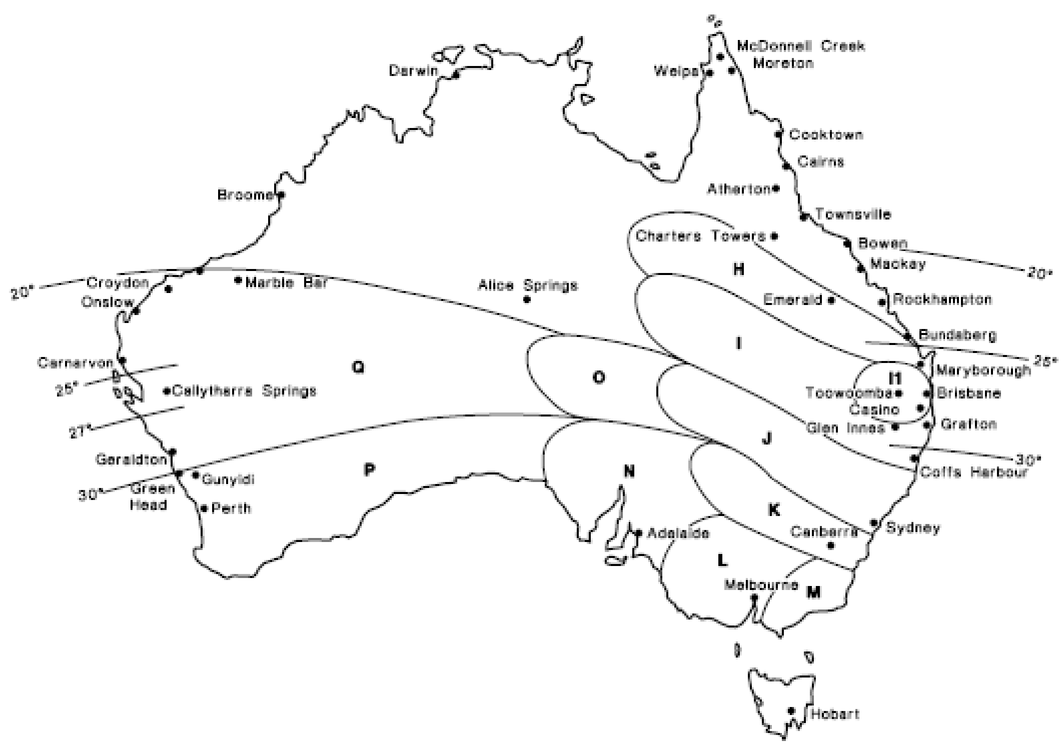

Figure 14: Microburst region boundaries (ESAA, 2003)

6.6 **ASCE Manual 74**

Along with HIW-resistant design criteria, this ASCE document (1991) and its draft revision (ASCE, 2005), provide many useful facts on the subject. This section will focus on the design criteria suggested.

The main suggestion of the document regarding tornadoes is summarized in the following quotation: “One possible ‘tornado’ loading is a wind loading corresponding to a moderate tornado (scale F1 or F2) applied only to the transmission structure over the full structure height from any direction” (ASCE, 2005). The wind load on conductors for this case is neglected because of the limited path size of the event and the complexity of wind force patterns. It is also suggested to consider a wire dead load of zero as the vertical wind component in a tornado can possibly lift the conductors. Tornado winds are gust winds and therefore the gust response factor should be kept to 1.0.

The recommendation for downburst loading varies with the size of the event. For a small-scale microburst, the tornado loading specified should be used. For larger downbursts, it is suggested to use the traditional approach based on synoptic winds with gust response factors close to 1.0.

6.7 **CIGRÉ Technical Brochure 256**

This recent CIGRÉ document (CIGRÉ WG B2.16, 2004), describes the characteristics of all major types of wind events (Table 4). The report suggests: to design overhead lines for a uniform F2 tornado wind on the tower only coming from any direction, and to consider torsional loads.

For downbursts, the CIGRÉ Working Group B2.16 (2004) recommends:

> Design for Microburst and Macroburst winds should consider the effects of surface roughness on the wind approach to the line. This has the effect of introducing high wind shears above ground that may be more onerous on the structure design. It is recommended that no wind be applied below 15 m and the full wind above this level. The wind gust will also engulf the complete wind span of conductor in this case and no reduction in span factor should be considered. Winds gusts must be considered from any direction (p. 42).

Simplified loading for both tornadoes and downbursts are therefore proposed in this document, implying that the effects of the two phenomena are very different. A tornado striking a tower would not create any wind forces on conductors and hence, the location of the horizontal force resultant would be very low. The downburst loading, however, would produce full loading on the conductors, the ground wires and the top portion of the tower: That would produce a large horizontal resultant at or very near the geometric center of the cables.

6.8 **Direct Gust Wind Method**

The recent article named "Applying Gust Loading to Your Lines" by Behncke and White (2006), argues for a complete change of the method used to design overhead lines against high winds. According to them, the synoptic wind method should be replaced by a more direct method where 3-second gusts are applied directly to the structure and to part of the cables as shown in Figure 15. A pressure Q_t is applied to the tower and a distributed force Q_c is applied to the cables over a distance W_G. The user must choose proper drag factors and width of gust (W_G). Unlike in the synoptic wind method, no adjustment for height is made and the wind pressures are not multiplied by gust response factors.

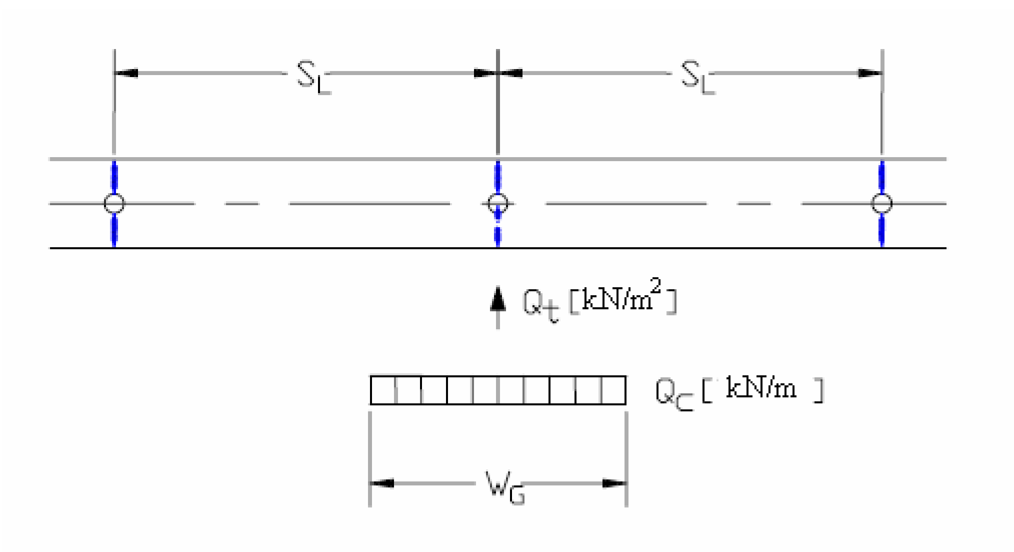

Figure 15: Direct gust wind method (Behncke & White, 2006)

Table 4: Characteristics of wind storm phenomena and design guidelines (CIGRÉ WG B2.16, 2004)

Wind Storm Phenomena Type	Classification	Gust Wind Velocity Range m/s (2-3 s gust)	Potential Wind Gust Width	Predominate Regional Area	Frequency of Occurrence Refer Note 5	Notes on Application to Design
Gust Front		45 - 50	10,000m	All regions	1/50	Normal Design and Span factor
Sub Tropical Thunderstorm				Subtropical Regions Refer Figure 1		
- Down Bursts		50 - 70	1,000m		1/50	Complete span over 1000m and >15m structure (Span factor 1.0) Refer Note 2
- Microbursts		70 - 80	100m		1/1000	
- Embedded tornado	F2	45 - 70	400m		1/1000	Provide for torsional loading and wind from any direction on structure only
	F3	70 - 95	300m		1/1000	Note 1
	F4	95 - 120	200m		1/4000	Note 1
	F5	>120	100m		1/10000	Note 1
Tornado				Severe Tornado Regions		
	F2	45 - 70	1000m		1/5	Provide for torsional loading and wind from any direction on structure only Refer Note 4
	F3	70 - 95	400m		1/1000	Note 1
	F4	95 - 120	200m		1/4000	Note 1
	F5	>120	200m		1/10000	Note 1
Cyclone / Hurricane / Typhoon				Subtropical Regions Refer Figure 1		
	2	35 - 47	20 –50 km		1/10	
	3	48 - 63	20 –50 km		1/100	Note 3
	4	64 - 78	20 –50 km		1/4000	Note 1
	5	>78	20 –50 km		1/10000	Note 1
Extratropical /Winter Storm		50 - 60	500 –3000m	Sea coast and land masses in close proximity to polar oceans	1/1000	Note 3
Instability Depression		50- 60		Northern polar sea coastal regions	1/50	Note 3
Katabatic /Down Slope Winds		40 - 70	1000m	Refer Figure 1	1/100	Refer local conditions

Note 1. Design consideration for wind velocities in this range is low probability and not considered viable for normal security overhead lines

Note 2. Design for Microburst and Macroburst winds should consider the effects of surface roughness on the wind approach to the line. This has the effect of introducing high wind shears above ground that may be more onerous on the structure design. It is recommended that no wind be applied below 15m and the full wind above this level. The wind gust will also engulf the complete wind span of conductor in this case and no reduction in span factor should be considered. Winds gusts must be considered from any direction.

Note 3. Cyclonic wind storms have a pronounced gustiness at maximum wind velocity that most likely will be sustained over a period of several hours. Spatial effects of this is to effectively provide some relief in wind span. A Span factor of 0.7 is recommended.

Note 4. Tornadoes generate high velocity swirling / rotational winds. Towers expected to withstand F2 tornadoes should be designed for torsional winds applied to the structure superstructure. Wind gusts >F2 do occur but are rare events.

Note 5. Frequencies provided are indicative values and may vary from region to region (Refer local Meteorology Office)

7 Conclusions

In this report, the high intensity winds considered are the downburst and the tornado. A downburst is a thunderstorm descending air mass that hits the ground and bursts out violently. The tornado, on the other hand, is a rotating column of air developed in the updraft part of a thunderstorm convective cloud. Maximum expected wind speeds are around 125 m/s for a tornado and 75 m/s for a downburst.

Three ways of gathering information on the wind fields of those phenomena are by direct observation, numerical simulations and laboratory physical simulations. A downburst can be modeled as a jet of fluid impinging on a surface. It is a fair assumption that the wind speed within a downburst increases linearly from the center up to a certain radius, and then decreases exponentially. The translational speed of the storm producing the downburst is itself an important component of the total wind speed. A particularity of the vertical profile of this phenomenon is that, unlike boundary layer winds, it reaches a maximum wind speed at a relatively short height (50-100 m).

The characteristics of the tornado wind field were mostly discovered through laboratory simulations. The Ward-type simulator is the most widely used device. Translation of the storm is also a significant component of wind speed for tornadoes. In large tornadoes, more than one vortex can be found.

Risk assessment for high intensity winds is very difficult due to limited ways of recording events. Four factors affecting the quality of high intensity wind records are: the short period of observation, the density of population, the complexity of storms, and the level of expectation of a phenomenon in a particular location. Line systems are particularly affected by those small-scale wind events. The probability of a tornado or a downburst crossing a line is clearly much higher than the probability of crossing a single point.

When developing downburst risk models, experts are interested in the probability for a damaging event to hit any point along the line. However, due to its narrower path, the tornado draws attention to the probability of any tower, and not any point, along the line being hit. Dealing with high intensity winds starts by considering them as a statistically distinct population of winds.

Tornadoes seem to apply very large pressures on towers combined with low pressures on the conductors. Towers are normally designed to account for very large loads coming from the conductors and are then built to distribute that load down to the foundations mostly through the main legs. When a high horizontal load is applied to the structure only, the distribution of forces is changed, and some web members receive large forces, which may buckle them and lead to a shear failure of the support. The failure pattern for downbursts is less clearly defined. High wind shear is often observed.

Dynamic amplification transmitted to the tower due to conductor response is not a factor. The tower itself could possibly experience dynamic effects due to downbursts, especially in guyed towers. There is no clear evidence of those effects in observed failures.

Some utilities design for a simple tornado loading consisting of large wind pressures on the tower only, with no pressure on conductors: This tornado loading is recommended by the ASCE (1991). A possible simplified downburst loading methodology is to apply uniform high winds to the portion of the tower above 15 m and to the conductors. Some designers deal with downbursts by using the usual synoptic wind procedure, with design wind speeds based on estimated maximum downburst wind speeds.

High intensity winds hitting transmission lines appear to be more frequent than previously anticipated. Utilities are looking at simple ways of reducing the risk of catastrophic failures. Unlike in the nuclear power industry, the goal is not to overdesign so as to reduce to a minimum any risk of failure. However, some studies have shown that most high intensity wind events could be survived with only minor improvements to the lateral load resistance of the structures.

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