7th AWES Workshop on Wind Engineering, Auckland, 28-29 September, 1998

A RISK MODEL FOR TRANSMISSION LINES IN SEVERE THUNDERSTORM WINDS

S.E. Oliver [1], W.W. Moriarty[2], J.D. Holmes[3]

[1] Weather Solutions Pty. Ltd., Mount Eliza, Victoria, 3930
[2] Moriarty Meteorological Services, 143 Reservoir Road, Sunbury Victoria, 3429
[3] Monash University, Clayton, Victoria, 3168, and JDH Consulting, Mentone, Victoria, 3194

INTRODUCTION

Strong wind gusts in Australia may be generated by several types of wind storms : gales generated by large synoptic depression systems, frontal changes, tornadoes and tropical cyclones. However the majority of transmission tower failures are caused by localized downburst gusts. These events are initiated by upward motion of warm moist air, cooling at altitude accompanied by heavy rain or hail, and then the generation of a rapid downdraft of cold air. The initial upward convection may be initiated by a cold front, topography or ground heating.

Although the damaging effects of these storms are localized, they are clearly quite common events so that transmission line systems, hundreds of kilometers long, may be expected to experience them often. Power transmission authorities in all states of Australia have experienced a number of these events in recent years [1]. These events usually result in failure of several towers as span reduction factors derived for large-scale synoptic winds are not applicable to downbursts, which generate peak gusts well-correlated over several transmission line spans. Design of transmission line towers for these events is a balance between the initial structural cost or cost of additional strengthening, and the cost of power interruptions to their customers, and the replacement cost of towers. To enable the authorities to develop a rational risk and design strategy, projects to develop risks model for severe thunderstorm winds in relation to transmission line design were initiated [2,3]. This paper describes the statistical risk models that have been developed for transmission line systems in four states.

DESCRIPTION OF THE MODEL

When a downburst hits the ground and spreads out, there is a limited area around the "touchdown" point where the wind speed increases outward. After that the outward speed decreases radially. In addition to the radial outward speed, there is a component of velocity due to the movement of the storm as a whole. This component is related to the wind velocity in mid-troposphere (about 500 hPa), which adds horizontal momentum to the jet of descending air, momentum which it retains when it spreads out near the ground. Holmes and Oliver [4] have given a simple mathematical model of the way this horizontal momentum combines with the radial component in the near-ground outflow of the downburst.

In general, the area on the ground affected by a downburst outflow is likely to be roughly elliptical in shape (Figure 1). In relation to transmission lines, interest is centred on that part of the area where the wind speeds exceed a given value V. This smaller area is also likely to be roughly elliptical, and in the present context will be referred to as the "footprint" of the downburst. The size and shape of a particular footprint will vary with the given speed V being considered.

As noted, a footprint will usually be roughly elliptical in shape. However, in the model here described it is approximated by a rectangle of the same area, say a_V, with its longer side in the same direction as the long axis of the ellipse. Suppose the length of the rectangle is l_V and the width w_V. For a given value of V, different downbursts will have a range of values of l_V and w_V, but as a first step consider downbursts with particular values, l_V and w_V. There will also be a range of long axis orientations, but initially consider those with a particular orientation θ_V, measured clockwise from the north. The footprints of different downbursts may overlap, and it is necessary to distinguish them in some way. We take the western end of the long axis (or the southern end if the footprint is aligned north-south) as the identifying point of each footprint. It follows that θ_V lies between π and 2π.

Suppose the average annual number of footprints, with characteristics V, l_V, w_V, θ_V, in a regional area A is $\tau_{V\theta}$. Then the annual areal density of such footprints is $\tau_{V\theta}/A$ i.e. there are on average $\tau_{V\theta}/A$ such footprints per year whose identifying point falls within a unit area.

The probability that the wind speed V will be exceeded at any point in the region in a year due to a downburst with the characteristics l_V, w_V, θ_V is

$$P_{lw\theta}(v>V) = \tau_{V\theta}.a_V/A = \tau_{V\theta}.l_V w_V/A \quad \text{.......................} \quad (1)$$

The notation in this equation is designed to underline the fact that P depends on the particular values of V, l, w, and θ being considered.

Now suppose a power line has a length L in the area A, and is normal to the direction θ_V of the long axis of the footprints being considered. Suppose also L is large by comparison with w_V. A particular footprint will intersect the power line if its identification point lies within an area $(L.l_V)$ next to the line. The average number of footprints of the type in question within this area per annum is $(\tau_{V\theta}/A)\, l_V.L = P_{lw\theta}(v>V).(L/w_V)$

Hence the probability that such a footprint will intersect the power line in a year is

$$P_{lw\theta}(a_V \cap L) = P_{lw\theta}(v>V).(L/w_V) \quad \text{.......................................} \quad (2a)$$

More generally, if the footprint long axis is not normal to the transmission line, suppose the line has orientation φ measured clockwise from the north. We take it φ lies between 0 and π. Then a particular footprint with the characteristics being considered will intersect the transmission line if its identification point lies within an area

$$L.l_V \sin[\theta-(\varphi+\pi)] = -\, l_V.L \sin[\theta-\varphi]$$

next to the power line (Figure 2). As φ varies from 0 to π, some values of this area will be positive and some negative, the negative areas being on the south side of the power line. For purposes of calculating the number of footprints, all areas need to be considered as positive. Thus the average number of footprints of the type in question within this area per annum is :

$$(\tau_{V\theta}/A)\, l_V.L\, |\sin[\theta-\varphi]| = P_{lw\theta}(v>V).(L/w_V)\, |\sin(\theta-\varphi)|$$

The probability that one of these footprints will intersect the power line in a year is

$$P_{lw\theta}(a_V \cap L) = P_{lw\theta}(v>V).(L/w_V)\, |\sin(\theta-\varphi)| \quad \text{.............................} \quad (2b)$$

Provided w_V and θ_V are kept constant, this will apply for all values of l_V, and hence of a_V. If we add up the cases for all l_V, we then have

$$P_{w\theta}(a_V \cap L) \;=\; P_{w\theta}(v>V).(L/w_V).\,|\sin(\theta-\varphi)| \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where now $P_{w\theta}(v>V)$ is the probability that V will be exceeded at a point due to a footprint with characteristics w_V and θ_V, and having any l_V, and correspondingly $P_{w\theta}(a_V \cap L)$ is the probability that any such footprint would intersect the power line.

To find the probability that any footprint with speeds exceeding V should intersect the power line, it would be necessary to integrate the right-hand-side of Equation (3) with respect to w_V and θ_V. This would require an expression for $P_{w\theta}(v>V)$ as a function of w_V and of θ_V.

However, such an expression cannot be directly extracted from the available observational data. In the next section we describe an approach to simplify the problem in order that the available data can be applied to the structural design problem.

A SIMPLIFIED MODEL FOR STRUCTURAL APPLICATION

For structural design purposes, it is desirable to limit the complexity of the design process. Accordingly we propose to make a number of simplifications and assumptions, whereby the resultant design wind speeds will be conservative.

The initial simplifications are :

i) all downburst winds are assumed to take an average value $\bar{w}_V$
ii) in the given region all downburst tracks can be represented in discrete directional ranges, each with some characteristic direction, and
iii) the distribution of wind speed is independent of direction

With these assumptions, Equation (3) yields

$$P_{w\theta}(a_V \cap L) \;\approx\; P_{w\theta}(v>V).\ (L/\ \bar{w}_V).\ \Sigma_{i=1,n}\ (\Pr(\theta_i).\ |\sin(\theta_i-\varphi)| \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where n is the number of discrete directional ranges. θ_i refers to the ith directional interval, and θ_{ic} is the characteristic direction specified for this directional interval. In terms of return periods,

$$(1/R_{V,L}) \;=\; (1/R_V)\ (L/\ \bar{w}_V).\ \Sigma_{i=1,n}\ \Pr(\theta_i).\ |\sin(\theta-\varphi)| \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4a)$$

where R_V is the return period of downburst winds exceeding V, at a station in the region, and $R_{V,L}$ is the return period of the intersection of such events with the line of length, L, and orientation, φ.

Rewiting Equation (4a),

$$R_{V,L} \;=\; R_V\ .\ (\ \bar{w}_V/\ L)\ /\ \Sigma_{i=1,n}\ \Pr(\theta_i).\ |\sin(\theta-\varphi)| \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Equation (5) gives a method of estimating the return period of intersection of a downburst footprint with a transmission line of given length and orientation, from the single point return period, R_V. Clearly, the value of $R_{V,L}$ is much less than R_V.

The final step in the design process is to consider the structural effect of a downburst wind from directions which are not normal to the transmission line. A simple approximation is that only the component of wind speed normal to line is effective in causing failures. Then R_V in the right-hand side of Equation (5) is replaced by $R_{V'}$, where V' is $V/|\sin(\theta-\varphi)|$, i.e. the wind speed whose normal component exceeds the design wind speed, V.

REFERENCES

1. H.Hawes and D.Dempsey. Review of recent Australian transmission line failures due to high intensity winds. Workshop on High Intensity Winds on Transmission Lines, 12-23 April, Buenos Aires, Argentina.
2. S.E.Oliver, J.D.Holmes and W.W. Moriarty. The characteristics of severe thunderstorm winds in Australia in relation to transmission line failures. Final Report. Special Services Unit, Bureau of Meteorology, February 1997.
3. J.D.Holmes, S.E.Oliver. A risk model for severe thunderstorm winds in relation to transmission line design in Victoria and South Australia. Final Report. JDH Consulting and Weather Solutions, August 1998.
4. J.D.Holmes and S.E.Oliver. A model of downburst winds near the ground for transmission line loading. 5th Australian Wind Engineering Society Workshop, Tanunda, South Australia, February 1996.

ACKNOWLEDGEMENT

This work was sponsored by the Electricity Supply Association of Australia, Powerlink (Queensland), and Transgrid (N.S.W.)

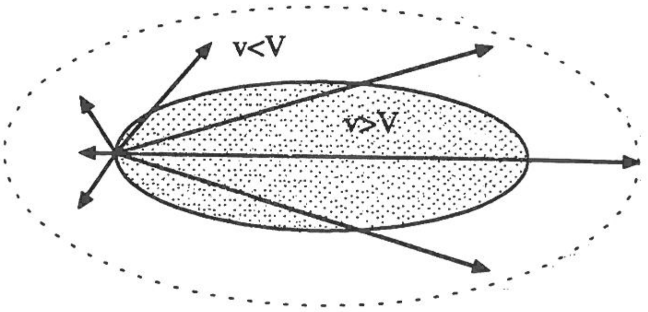

Figure 1. Schematic downburst damage 'footprint'

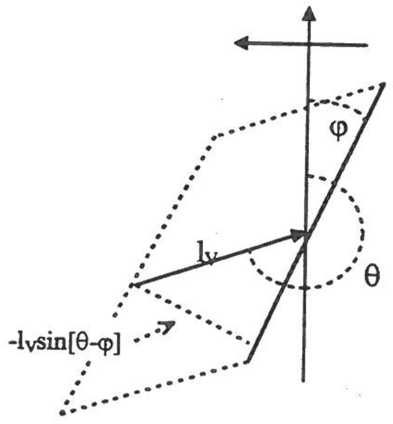

Figure 2. Oblique intersection of downburst footprint with transmission line