13 Transmission lines

13.1 Introduction

Electrical transmission lines and their supporting towers are, like other structures, subjected to severe wind storms of various types, and their safe and economic design for wind loading is of concern to the power utilities. There are significant differences between the response of high-voltage transmission towers and other structures to wind:

- They are structurally designed with generally lower safety margins against collapse than other structures
- The overall length of a transmission line system is relevant when considering probability and risk of receiving strong winds from localised wind storms such as thunderstorm downbursts and tornadoes.

This chapter deals with the wind loading of the transmission lines themselves, and risk issues associated with a long transmission line as a system. The wind loading of the supporting towers and poles is covered elsewhere in the book, in particular Chapter 11.

13.2 Structural response and calculation of wind loads

Basic design data for wind loads on transmission line conductors in temperate synoptic winds has been compiled by the American Society for Civil Engineers (ASCE, 1990), and CSIR in South Africa (CSIR, 1990).

13.2.1 Nature of the response

Fortunately resonant dynamic response does not appear to be a major problem with transmission line systems. Although the suspended lines themselves usually have natural frequencies less than 1 Hz, the resonant response is largely damped out because of the very large aerodynamic damping (Section 5.5.1) (e.g. Matheson and Holmes, 1981).

The natural frequencies of supporting towers up to 50 m in height are normally greater than 1 Hz, and hence the resonant response is also negligible. Thus, except for extremely tall supporting towers and long line spans, we can safely compute the peak response of a transmission line system, neglecting the resonant dynamic response. Then the peak response is directly related to the instantaneous gusts upwind, and hence transmission line structures can be designed using gust wind speeds. However, because of the non-uniform spatial gust structure, assumption of the same peak gust along the full span is conservative; this leads to the concept of a *span reduction factor*.

For those cases where resonant response is significant, i.e. very high supporting towers, and very long spans, a simplified random response model of the tower-line combination, based on the gust response factor concept is available (Davenport, 1979).

13.2.2 Wind forces on conductors

The nominal wind force acting on a single conductor perpendicular to the span can be taken to be:

$$F_c = q_{zc}.C_D.A_c\sin^2\theta.\alpha \qquad (13.1)$$

where q_{zc} is the free-stream dynamic wind pressure $\left(= \frac{1}{2}\rho_a \hat{U}_{zc}^{\ 2} \right)$ at a suitable mean conductor height, z_c. A suitable value for z_c is shown in Figure 13.1, taken from the South African recommendations for transmission line loading (CSIR, 1990).

C_D is the drag force coefficient for the conductor; A_c is the reference area, which may be taken as $s \times b$, where s is the wind span (see Figure 13.1), and b is the conductor diameter; θ is the horizontal angle of incidence of the wind in relation to the direction of the line; and α is a span reduction factor.

The ASCE guidelines show experimental data for the drag force coefficient as a function of Reynolds number, Re, (Section 4.2.4) for several conductor types, based on wind tunnel tests. These data are reproduced in Figure 13.2. The Reynolds number can be calculated by:

$$\mathrm{Re} = \frac{U_{zc}b}{15 \times 10^{-6}} \qquad (13.2)$$

where U_{zc} is the design gust wind speed in metres per second at the mean conductor height, z_c. The conductor diameter, b, is in metres.

The South African design recommendations (CSIR, 1990) have simplified the data to give the design line shown in Figure 13.3.

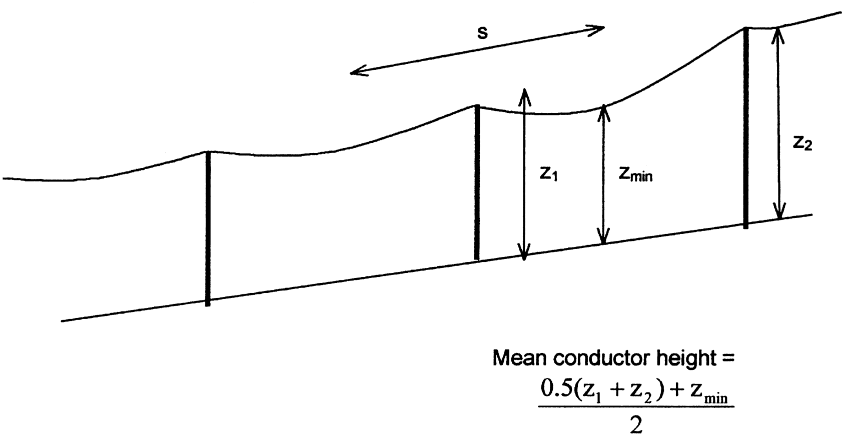

Figure 13.1 Mean conductor height for calculation of wind loads (CSIR, 1990).

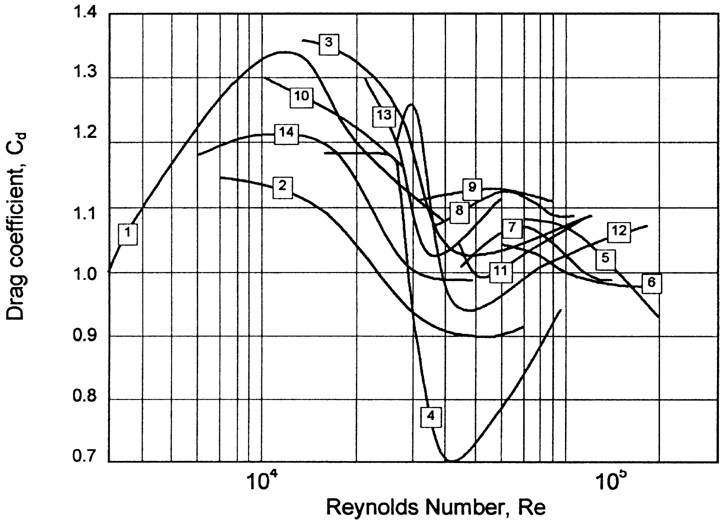

Figure 13.2 Drag force coefficients for conductors (ASCE, 1990).

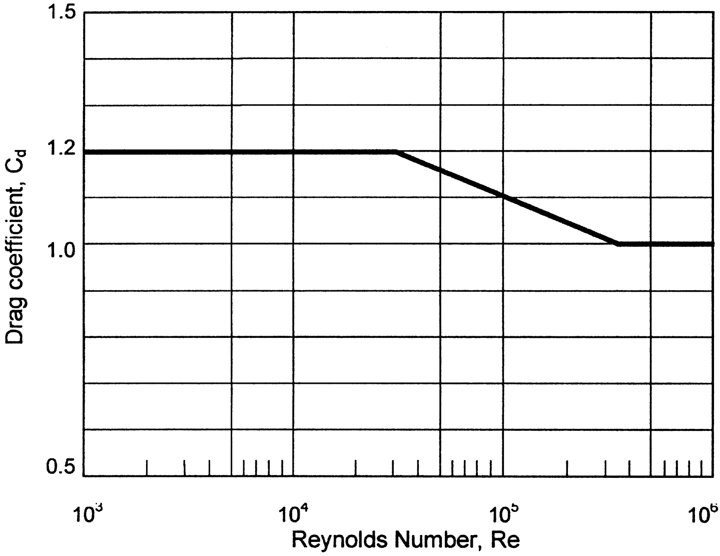

Figure 13.3 Design values of conductor drag coefficient (CSIR, 1990).

13.2.3 Span reduction factor

The span reduction factor, α, allows for the reduction in peak wind along the span of a conductor, due to the non-simultaneous action of the gusts. Since it is determined by the structure of turbulence in the approaching wind flow, the span reduction factor is a function of the approach terrain, the mean conductor height and the span. This factor has a direct relationship with the gust response factor *G* (Section 5.3.2). The relationship is as follows:

$$\alpha = G\left(\frac{\bar{U}_z}{\hat{U}_z}\right)^2 \qquad (13.3)$$

where $\bar{U}_z$ is the mean wind speed at height z, and $\hat{U}_z$ is the gust speed at the same height.

Using equation (13.3), the values of gust response factors recommended in the ASCE guidelines for Electrical Transmission Lines (1990) have been converted to span reduction factors for various terrain types, conductor heights and spans. The resulting factors are insensitive to the conductor height, and the following equations can be used to predict values of α.

$$\alpha = 0.58 + 0.42\exp\left(\frac{-s}{180}\right) \text{ for rural terrain} \qquad (13.4)$$

$$\alpha = 0.50 + 0.50\exp\left(\frac{-s}{140}\right) \text{ for urban terrain} \qquad (13.5)$$

where s is the span in metres.

In Table 13.1, values of span reduction factor for various spans have been calculated using equations (13.4) and (13.5). Clearly the span reduction factor reduces with increasing span, and with increasing terrain roughness. In the latter case, the reduction occurs because of the increased fluctuating component in the peak load on the line.

13.2.4 Conductor shielding

In both the ASCE guidelines (ASCE, 1990) and the CSIR recommendations (CSIR, 1990), no allowance for shielding for individual conductors in a bundle is permitted. Such shielding effects would be small, and would not be present for every angle of attack of the instantaneous wind to the line.

13.2.5 Wind forces on lattice supporting towers

The calculation of wind forces on lattice towers typical of those used in high-voltage transmission line systems is discussed in Section 11.3.2. The overall drag coefficients for lattice towers depends upon the solidity of the towers. Higher solidity results in greater mutual interference and shielding, and a reduction in drag coefficient, based on the projected area of members.

Table 13.1 Span reduction factors for transmission line conductors

Conductor span (metres)	*Rural terrain ($z_0 \cong 0.02$ m)*	*Urban terrain ($z_0 \cong 0.2$ m)*
200	0.72	0.62
300	0.66	0.56
400	0.63	0.53
500	0.61	0.51

13.3 Risk models for transmission line systems

Transmission line systems often extend for several hundred kilometres, and are prone to impact by small intense local windstorms, such as tornadoes (Section 1.3.4) and downbursts (Section 1.3.5). There has been a history of failures of transmission line systems from these events – especially in large continental countries like Australia, Brazil and Argentina (e.g. Hawes and Dempsey, 1993). Figure 13.4 shows the result of one such event. The risk of failure of *any one tower* along a line is much greater than that for a single isolated structure. Design of the supporting structures requires knowledge of the total risk of the complete line to these small intense windstorms. Knowledge of the risk of failures enables a balance to be made between the cost of failures, and the cost of replacement towers. This may vary from country to country, as in some cases there are alternative routes for power transmission.

13.3.1 Tornado risk model

Twisdale and Dunn (1983) describe several tornado risk models for point and 'lifeline' targets and Milford and Goliger (1997) developed a tornado risk model for transmission line design which considered normal intersection of a tornado with the line direction.

Since the width of tornado tracks (usually less than 100 m) is almost always less than the span length between towers, the critical factor in line failure is intersection of a tornado with a tower. Thus the rate of intersection with a tower is required, rather than with the conductors.

Consider a region specified by its area, A (square kilometres), in which there is an

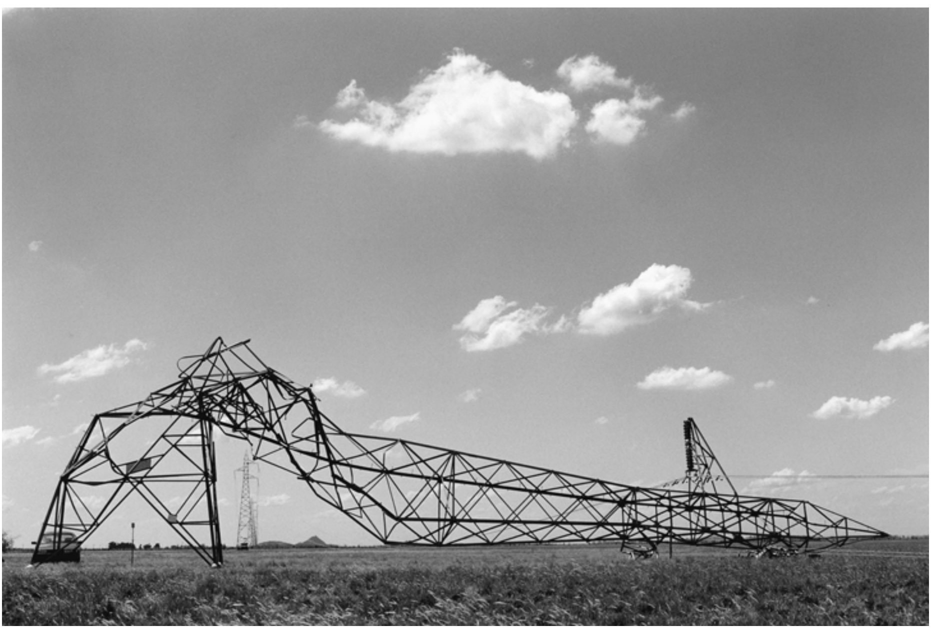

Figure 13.4 Failure of a high-voltage transmission tower following a local downburst event.

average tornado occurrence of n events per year, so that the per square kilometre rate for the region is

$$\nu = n/A \tag{13.6}$$

Normal intersection of a tornado path of length ℓ with a line of overall length L occurs only for those tracks whose centre falls within the zone of area, $L \times \ell$, adjacent to the line (see Figure 13.5), giving a rate of intersection, r,

$$r = \nu L \ell \tag{13.7}$$

This model can be extended to variable intersection angle as follows.

For a tornado path intersecting the transmission line at an angle β to normal (Figure 13.6), the width of the zone of intersection reduces to $\ell \cos \beta$ and the rate of intersection (with the line) per annum is now given by:

$$r = \nu L \ell \cos\beta \tag{13.8}$$

Now the width of the intersection zone along the line is given by $w/\cos \beta$ and the probability of a *given single point* on the line falling within this zone is $w/(L \cos \beta)$ which may represent a single tower. Thus the number of intersections of tornadoes with this tower per year is given by:

$$r = \nu L \ell \cos\beta . w/(L\cos\beta) = \nu w \ell \tag{13.9}$$

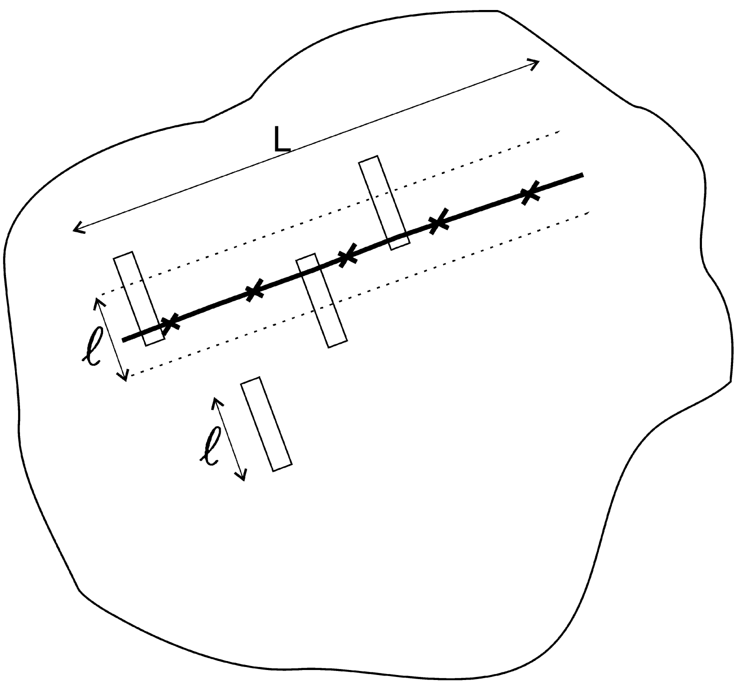

Figure 13.5 Normal intersection of a tornado with a transmission line system.

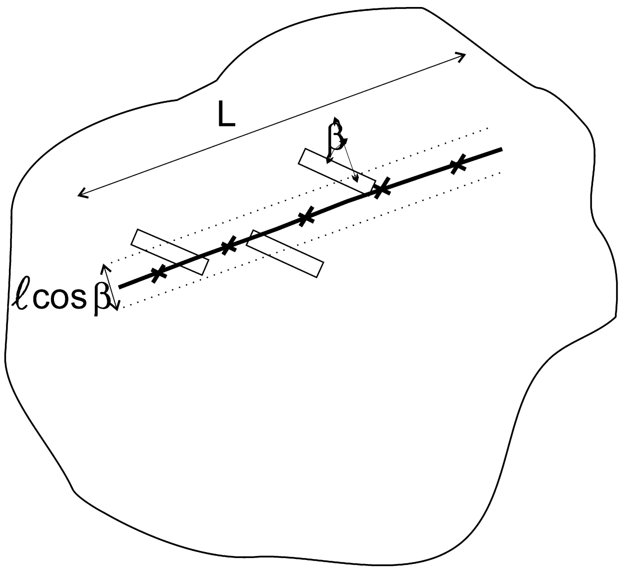

Figure 13.6 Oblique intersection of a tornado with a transmission line system.

If the span length between towers is s, the number of towers along a line of length, L is equal to L/s, and assuming that intersections are independent (i.e. only one tower is intersected by any tornado), then the total number of intersections with *any* tower along the line per year is given by:

$$r_t = (\nu w \ell)(L/s) \tag{13.10}$$

It should be noted that the rate of intersection is independent of the intersection angle, β. Equation (13.10) may also be written as:

$$r_t = n(a/A)N = \nu a N \tag{13.11}$$

where n is the number of events per year in an area A, a is the area of tornado path and N is the number of towers in the area.

Example

Assume: $L = 500$ km; $s = 0.5$ km; $\ell = 5$ km; $w = 0.1$ km; $\nu = 10^{-4}$ per km^2 per year. Then, from equation (13.10), the number of intersections with this line per year $= 10^{-4} \times 0.1 \times 5 \times (500/0.5) = 0.05$, i.e. average of 1 intersection every 20 years.

13.3.2 Downburst risk model

Damage 'footprints' produced by severe thunderstorm downbursts (Section 1.3.5) are usually wider than those produced by tornadoes. The lengths of the damaged areas produced by downbursts, are generally shorter than those of tornadoes, however. The increased width usually results in several transmission line spans being enveloped by damaging winds, and several adjacent towers often fail as a group. The direct wind load on the conductors themselves is therefore a significant component of the overall wind load in downburst events. This must be incorporated into a risk model.

Oliver *et al.* (2000) describe a downburst risk model for transmission lines, which allows the prediction of an event frequency, where an event is the intersection of a region of wind above a given or design wind speed with a line of some defined length. The probability of such an event is dependent on:

- the overall length of the line, L;
- the relative angle, θ-φ, between the direction of the downburst path, θ, and the line orientation, φ;
- the probability of exceedence of the threshold wind speed of interest, U, at any point in the surrounding region, derived from the anemometer records, and
- the width of the path of winds above the threshold, w_u.

The return period, $R_{U,L}$, of the event was shown (Oliver *et al.*, 2000) to be given by:

$$R_{U,L} = (w_u/L)/\left\{\sum_{i=1}^{N} \Pr(u > U/|\sin(\theta_i - \varphi)|).\Pr(\theta_i)|\sin(\theta_i - \varphi)|\right\} \qquad (13.12)$$

where it is assumed that:

- There is an average or characteristic downburst damage footprint width associated with each wind speed U, given by w_u
- For each direction, all downburst tracks can be represented in discrete directional ranges, centred on a characteristic direction θ_i and the summation is over each of these directions
- The relative probability that the downburst should lie along each of these directions is directly related to the directional frequency of measured gusts, and
- The distribution of wind speed, given a direction, is independent of the directional sector.

The presence of the overall line length, L, in the denominator of equation (13.12) indicates that as the overall transmission line length increases, the return period for damaging intersections decreases. Thus, for very long lines orientated at right angles to the prevailing directions of severe thunderstorm winds, the risk of failure may be very high, if these parameters have not been accounted for in design. This is the experience in large continental countries such as Australia and Argentina, where many failures have occurred (e.g. Hawes and Dempsey, 1993).

An alternative model of downburst risk for transmission line systems has been developed for Argentina by Schwarzkopf and Rosso (2001).

13.4 Summary

The available data for the specification of wind loads on transmission line structures have been critically reviewed. Risk models which consider the risk of intersection of small intense storms such as tornadoes and downbursts with long transmission line systems are also discussed.

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