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Patch loading for differential line tension in transmission line structures

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Abstract

The difference in tension between two adjacent spans of a high-voltage transmission line system, is a critical load for the insulator string, and for the longitudinal load on the supporting tower. This has a potential to cause breaches in clearances in the cases of swivelling cross arms, and thus cause outages.

Effective static wind load distributions (ESWL), appropriate to the differential tension, were derived theoretically based on Kasperski's LRC equation, and simplified in the form of a 'patch' loading. The 'patch' loading, of 100% design load on one span, together with 50% of the design load on the adjacent span, was shown to be an acceptable approximation to the calculated theoretical effective load distributions, for a pair of 500 metre spans, and a conservative approximation for shorter spans

Introduction

ElectraNet initiated a hazard mitigation project to replace defective insulators and cross arms on feeders F1910, F1911 and F1961 Para - Templers West – Brinkworth - Davenport 275kV line (East Circuit).

Figure 1: East Circuit Feeder in South Australia

The objective of the project is to ensure minimum network reliability performance expectations are satisfied while replacing defective insulators and removing unsafe cross arms. Design solutions are thereby required to satisfy existing electrical and structural reliability levels. The preferred option for replacement of cross arms and insulators on suspension towers is to use a polymer-swivel-horizontal-vee insulator assembly. Separate studies have been undertaken on line stability and on individual structure analysis.

The SA-type suspension towers are rectangular based structures with limited longitudinal load capacity and fitted with a "tension-valve" cross arm designed to relieve unbalanced longitudinal loads to reduce the risk of tower collapse. Some cross arms are fitted with a reinforcement kit to allow for maintenance access.

Figure 2: Towers with tension valve cross arm (original)

Figure 3: Towers with pivoting cross arms (modified)

Considering the fact that an unbalanced longitudinal pull would be a critical factor, it was necessary to study wind actions in more detail. Of particular interest is the 'patch wind phenomenon' in which two adjacent spans may not be uniformly acted by wind - thus producing an unbalanced longitudinal pull. In the case of suspension structures with pivoting cross arms, after excessive rotation of pivoting cross arms and the inability of the cross arm to restore to its neutral position, there is potential risk of transmission line outages, caused by breaching of electrical clearances. ElectraNet has adopted a norm of wind acting on 100% span loaded on one side and 50% loaded on other side of the structure. It was decided to get a rational theoretical basis for this norm, and JDH Consulting was requested to assist with this.

Methodology

In turbulent wind, the differential tension is a fluctuating one, and is dependent on the properties of the turbulence in the approaching flow. Kasperski's LRC equation (Kasperski and Niemann, 1992) provides a method for determining optimum wind load distributions to maximize any defined load effect for which the influence line is known. To maximise performance of the line, a serviceability conductor design wind pressure of 500Pa has been applied equal to the "ultimate" load condition at which suspension tower collapse is likely to be initiated. The following derivation describes the methodology.

Derivation

Wind loads in synoptic storms can be conveniently subdivided into a mean, or steady state, component and a fluctuating component.

Thus, at any point on a transmission line the pressure can be written:

$$p_{total} = \bar{p} + p'(t) \qquad (1)$$

where $\bar{p}$ is the mean pressure and $p'(t)$ is the fluctuating component with a mean value of zero.

The expected *peak* pressure at any point is given by:

$$\hat{p} = \bar{p} + g\sigma_p \qquad (2)$$

where σ_p is the standard deviation of fluctuating pressure which can be assumed to be constant along a span, and g is a peak factor which is usually in the range of 3 to 4.

However, since fluctuating wind pressures are not fully correlated, Eq. (2) should be modified when considering the load distribution along a complete span. Furthermore, the effective pressure distribution that is associated with a maximum (or minimum) of a load effect will vary for each load effect according to its influence line. That pressure distribution can be written as (Kasperski and Niemann, 1992):

$$\hat{p}(y) = \bar{p} + g r_{LRC}(y).\,\sigma_p \qquad (3)$$

$r_{LRC}(y)$ is a load and resistance correlation coefficient that varies with position along the span (y), and is dependent on the influence line $\mu(y)$ for the load effect of interest.

The correlation coefficient between the load effect and the pressure at y_1 can be written (Holmes, 2002):

$$\boldsymbol{r_{LRC}} = \frac{\int_{-L_S}^{L_S} \overline{p'(y_1).p'(y_2)}\,\mu(y_2)\,dy_2}{\sigma_p \sigma_L} = \frac{\int_{-L_S}^{L_S} \overline{p'(y_1).p'(y_2)}\,\mu(y_2)\,dy_2}{\sigma_p\left\{\int_{-L_S}^{L_S}\int_{-L_S}^{L_S} \overline{p'(y_1).p'(y_2)}\,\mu(y_1).\mu(y_2)\,dy_1 dy_2\right\}^{1/2}} \qquad (4)$$

where L_s is the line span.

The covariance between fluctuating pressures at two points in Equation (4) is the product of the variance, σ_p^2, and the correlation coefficient between the pressures, the latter being conveniently fitted by an exponential decay function of the separation distance, Δy, i.e.

$$\rho = \exp\left(\frac{-|\Delta y|}{l_y}\right) \qquad (5)$$

where l_y is a lateral length scale of turbulence.

Influence line

For the present case, an influence line for the differential tension between spans on opposite sides of a support tower is required.

Because a line or cable is structurally non-linear, the influence coefficients will vary with parameters such as the initial tension and sag of a line, as well as the magnitudes of the applied loads. However, only the *shape* of the influence line is required to determine the effective pressure distribution, and the load distribution is not sensitive to the detailed variations in the influence line. Hence, a 'representative' influence line was calculated for a massless taut cable by applying a moving point load along the span. A span of 500 metres was selected, for a line with tensile stiffness, i.e. product of Young's Modulus and area (*EA*), equal to 10^7 N. A point load of 100 Newtons was moved along the span, and the horizontal tension calculated by numerical iteration for each case. The resulting influence line is shown in Figure 4.

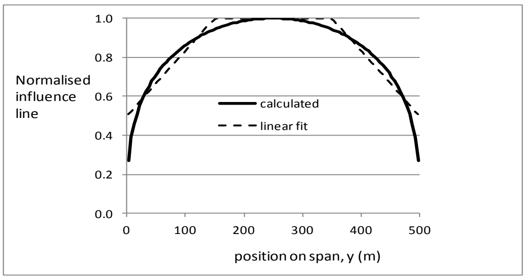


Figure 4. Calculated and approximated influence line for a stretched cable under a moving load

Also shown in Figure 4 is a segmented linear approximation to the influence line. The approximate form was used for the calculations of the effective wind pressure distribution. For the influence line for the maximum difference in tension between two adjacent 500 m spans, the form in Figure 5 was assumed – i.e. the adjacent span has a negative or 'mirror image' version of the approximate form for a single span in Figure 4.

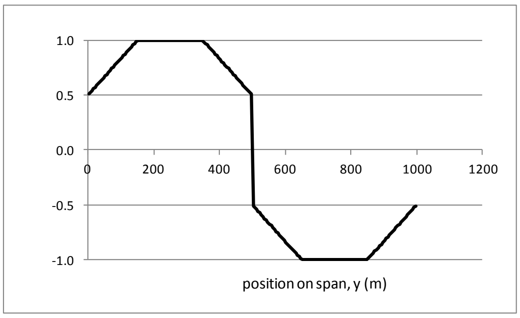


Figure 5. Assumed influence line for maximum differential tension

Calculated load distributions

The effective pressure distribution for a 1000m double span with average height of 40m, in rural (TC2) terrain, was derived using Equations (3), (4) and (5). A mean wind speed of 30m/s, turbulence intensity of 0.156, and a pressure coefficient of 1.0 were assumed for these calculations

Figure 6 shows the calculated effective distribution for maximum differential pressure, together with the mean value, and the upper and lower limits of pressure derived from Equation (2).

The thick blue line in Figure 6 can be regarded as the expected instantaneous pressure distribution at the time of maximum difference in horizontal tension between the two adjacent spans.

It forms the basis for a simplified ‘patch’ load distribution as required by ElectraNet. This is discussed further in the following section.

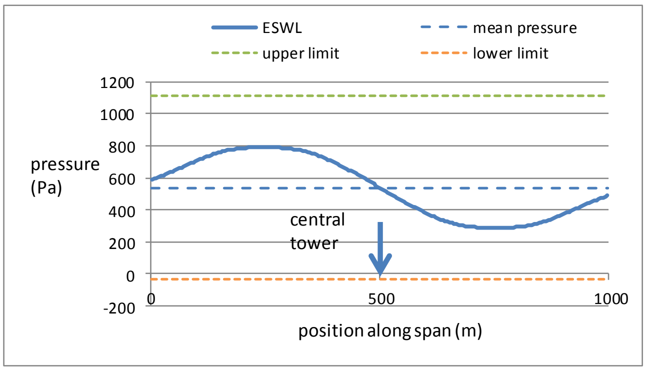


Figure 6. Effective pressure distribution for maximum differential tension for two adjacent 500m spans

Simplified ‘patch’ loading for design applications

To produce a simplified version, the effective load distribution of Figure 6 was, first of all, normalized by dividing by the ‘normal’ design loadings for the two spans – i.e. the ‘upper limit’ loading in Figure 3 factored down by a span reduction factor, SRF, which allows for the reduced correlation of turbulent wind loads over a span (Standards Australia, 2010). For example, for a 500 m span, in open terrain, the SRF is 0.628.

The resulting load ratio – i.e. the ratio of the equivalent static wind load to the peak design load - is shown in Figure 7. Also shown in that figure is the simplified ‘patch’ load proposed and adopted by ElectraNet – i.e. 100% of the design load on one span, together with 50% of the design load on the adjacent span.

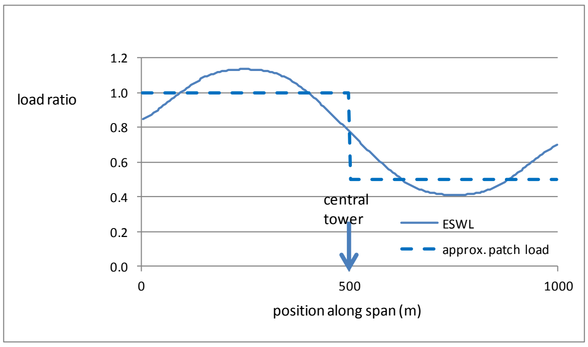
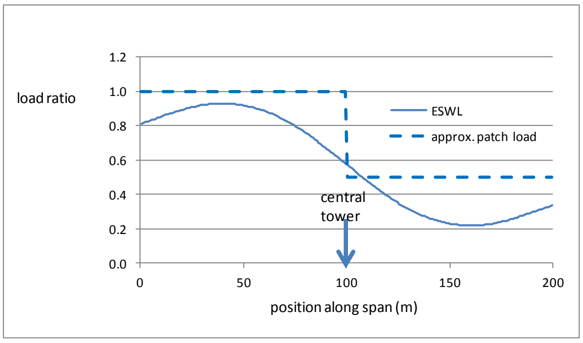


Figure 7. Patch load approximation to the calculated effective pressure distribution for maximum differential tension

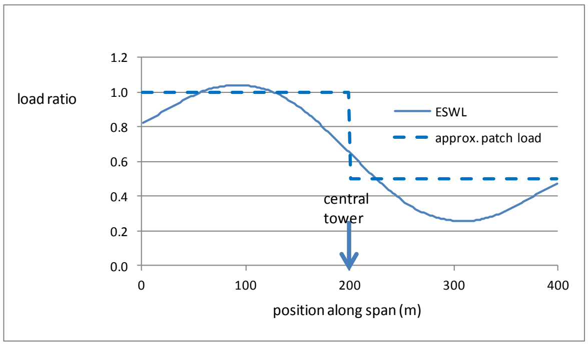
It can be seen from Figure 7 that the ‘patch’ loading used by ElectraNet is a reasonable engineering approximation to the calculated distribution for maximum differential tension, the derivation of which itself involved some approximations.

Calculations have also been made for spans, L_s, of 100, 200, 300, and 400 metres. Corresponding graphs to Figure 4 for these spans are presented in Figure 5. The influence lines for these cases were taken as ‘compressed’ versions of that in Figure 4.

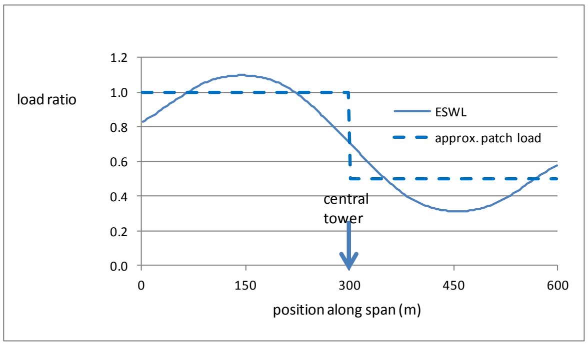
It can be seen from Figure 8 that the 100% - 50% ‘patch’ load simplification is more conservative for the shorter spans than it is for the case of L_s equal to 500 metres, but again is quite adequate for engineering design purposes.



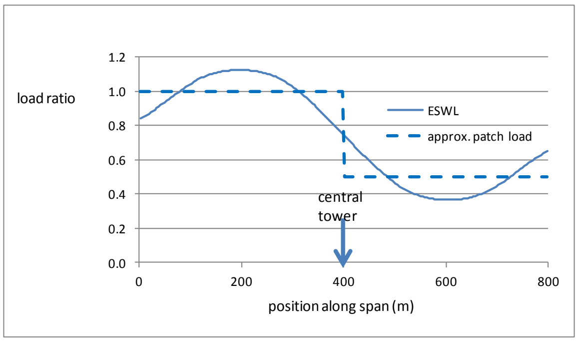
(a) Span = 100m



(b) Span = 200m



(c) Span = 300m



(d) Span = 400m

Figure 8. Effective pressure distribution for spans less than 500m

Conclusions

A theoretical approach to the effective pressure distribution for wind-induced differential tension between two adjacent overhead line spans has been adopted. The assumptions and correlation properties of atmospheric turbulence in synoptic winds are similar to, and consistent with, those to derive the formula for span reduction factor in AS/NZS 7000 (Standards Australia, 2010)

A 'patch' loading adopted by ElectraNet, of 100% design load on one span together with 50% of the design load on the adjacent span, has been shown to be an acceptable approximation to the calculated theoretical effective load distributions for a pair of 500 metre spans, and a conservative approximation for shorter spans.

The rotation of the assembly should be limited to maintain electrical clearances. The hinge angle of the assembly should be ≥ 19^0 to facilitate the assembly to regain its neutral position.

On each of the three feeders, adequate stability cannot be achieved at a few locations where the Akimbo assembly becomes unstable for the patch wind pressure case. Marginal sites with terrain conditions that may magnify patch wind (e.g. steep slopes causing conductor uplift thus reducing weight span) were identified by desk audit of the line profile & topography maps, and verified by site inspections. It was recommended either to replace the existing cross arm with new conventional cross arm, and a new "I" string insulator assembly (to provide sufficient "conductor" stiffness and hence stability e.g. F1911-168) and/or monitor the insulator swing for next 12 months with a time lapse camera (e.g., F1910-276).

Acknowledgments

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Standards Australia and Standards New Zealand, *Overhead line design – detailed procedures*, Australian/New Zealand Standard AS/NZS 7000:2010, Standards Australia, Sydney, and Standards New Zealand, Wellington.