Vulnerability of High Voltage Electricity Transmission Towers Subjected to Cyclonic Winds

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1 INTRODUCTION

Overhead transmission lines are a key element of the electrical power system for transferring bulk power from generators to communities. Lattice type transmission towers carrying conductors form the physical backbone of the power transmission system. Transmission tower safety and reliability assessment is necessary to plan for minimisation of the risk of disruption of power supply resulting from in-service tower failure.

Lattice type transmission towers are constructed using angle section members and are eccentrically connected. They are regarded as one of the most difficult forms of lattice structures to analyse for dynamic loads. Analysis is difficult due to fabrication errors, inadequate joint details and material properties being hard to quantify as a combination. Proof loading and full-scale tower testing is a traditional form of design validation for lattice type towers [1]. However, loading conditions experienced in severe wind events are dynamic and relatively short term loads and this behavior is confirmed in a limited way through full scale measurements of aero-elastic models in wind tunnels [2].

2 METHODOLOGY

Transmission tower failures experienced in the field provide valuable feedback for the mode and threshold of failure to practicing engineers. However, definite wind velocities resulting in failures are not readily available due to a general lack of instrumentation and records of local wind gusts at tower locations. The wind velocity is estimated from some structural damage in many cases, rather than the reverse. To compensate for the lack information on wind measurements corresponding with tower failure, heuristic methods were found to be an appropriate method for determining the vulnerability of transmission towers in this study. The information used in the methodology proposed in this paper is tower design features, structural age, wind spans, levels of containment and maintenance levels. Conductor types were also considered in secondary failure modes referred to as pull-down analysis.

2.1 Conductor Load Savings in Electricity Transmission Towers

Tower assets are designed to a specified wind speed (V_d) and wind span (S_d), however due to conductor length being shorter in most cases, than the designed wind span in the actual installation, the actual wind span (S_w) could be significantly lower than S_d. This increases its wind resistance and hence the actual wind capacity of a tower is higher than the designed wind capacity. A utilisation factor (u) is defined to account for the conductor load savings in comparison to the designed capacity. The wind speed is further adjusted to a 10 m reference height rather than the nominated height of the tower using boundary layer wind profile for terrain categories 3/4 for Cyclonic regions C & D as specified in the Australian Standard [3]. Hence, the utilisation factor is defined as,

$$u = 1 - k\left(1 - \frac{S_w}{S_d}\right)$$

where, 'u' is percentage utilisation, 'S_w' is the average wind span on either side of a tower in m, 'S_d' is the design wind span for the tower at a design wind speed in m, and 'k' is proportion of conductor load based on the type of circuit the tower is carrying, 0.33 for single circuit line and 0.5 for double circuit line.

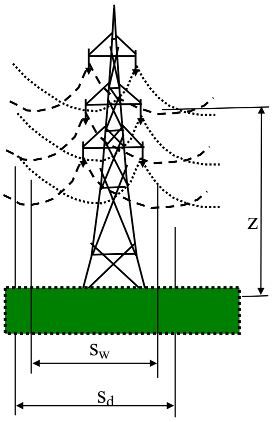

Figure 1. Schematic showing the designed wing span and actual wind span in a lattice type double circuit suspension tower.

The adjusted tower capacity,

$$V_c = \frac{V_{d(h=Z)}}{\sqrt{u}} \times \frac{M_{Z,cat(h=10m)}}{M_{Z,cat(h=Z)}}$$

where, 'V_c' is adjusted failure wind speed for a transmission tower in m/s, '$M_{z,cat(h=10m)}$' is boundary layer flow factor at 10m read from the Australian Standard for cyclonic winds in regions C or D, '$M_{z,cat(h=Z)}$' is boundary layer flow factor at Z read from the Australian Standard for cyclonic winds in region C or D, 'Z' is the nominated height of the transmission tower, 'u' is percentage utilisation of the transmission tower, and 'V_d' is the design wind speed of the transmission tower in m/s at the nominated height.

2.2 Mechanisms of transmission tower failure

The primary mechanism of failure for towers under wind loads is due to the direct action of wind. Cyclonic wind tends to swing in direction of flow and in magnitude over a period of transition at a defined location producing dynamic loads on transmission towers [2, 4]. The methodology presented in this paper uses heuristic techniques to determine the probability of collapse of towers. The electricity transmission line consists of ordinary suspension towers where the transmission line travels in a straight line and strained or angled towers where there are changes in direction. Strain towers are additionally reinforced in comparison to suspension towers. The primary mechanisms of transmission tower failure are – failure of suspension towers and failure of strain or angled towers. The secondary mechanisms of failure arise from connectivity with neighbours or through proximity to other transmission lines. Collapse of one tower leads to additional pulling load on other towers connected to it in addition to wind load. A cluster of transmission towers may fail from initiation of a primary failure due to direct wind and then pull down of others, the phenomenon is referred to as cascade failure [5]. Other mechanisms of failure are towers falling on parallel or intersecting transmission lines in close proximity. Only the cascade failures are addressed in this paper.

2.3 Directional wind effects on rectangular based suspension towers

Lattice transmission towers are designed to resist wind loads directed normal to the transmission line. The towers are stronger along the transmission line by virtue of conductors connecting them to their neighbours. However, rectangular base suspension towers are weaker at an oblique angle in a narrow sectored band off the normal direction [4]. The weaker sector is referred to 'vulnerable direction' in this paper lying within 11.5^{o} to 28.75^{o} and 191.5^{o} to 208.75^{o}. On the other hand, square based suspension towers and strain towers have only two zones to be considered –

conductor direction and the normal direction, by virtue of the symmetry of square towers and reinforcements in strain towers.

2.4 Vulnerability of transmission towers

Fragility functions are probabilistic mapping between a physical hazard parameter impacting on an asset, to a level of damage. Probability of collapse of a transmission tower was mapped against the ratio of wind speed from a wind event to the adjusted capacity of a tower. Other damage states for transmission towers such as partial collapse, equipment damage and conductor breakage were not mapped in this study, as tower collapse imparts a greater impost on the electricity system recovery. In a series of four workshops, industry experts consisting of wind and design engineers nominated threshold of wind speeds for tower collapse for different types of towers and conductors. These thresholds were plotted as log-normal curves and then adjusted with data from Cyclone Larry, for which reliable regional wind speeds were available. Sample curves for rectangular based suspension towers are presented in figure 2.

High voltage lattice type transmission towers often collapse in groups. A falling tower tends to pull its neighbors connected through conductors. If the tower being pulled is close to its installed capacity to bear load, then it is likely to collapse as well. This phenomenon is represented in figure 3. Each pull-down event is treated as independent and the following law of survival is applied,
$P_c = 1-((1-P_d)\times(1-P_{S1})\times(1-P_{S2})\times(1-P_{S3})\times\ldots)$
where, 'P_c' is the probability of collapse from all mechanisms, 'P_d' is the probability of collapse from the direct action of wind, 'P_{s1}, P_{s2}, P_{s3}, …' are the probabilities of collapsed from being pulled down by neighbors. For discrete tower collapse, a threshold probability of collapse is applied above which towers are deemed to collapse. This assists in scenario analysis for system recovery following a simulated extreme wind event. The overall probabilities need to be justified within the discrete outcomes, and hence the threshold is constrained.

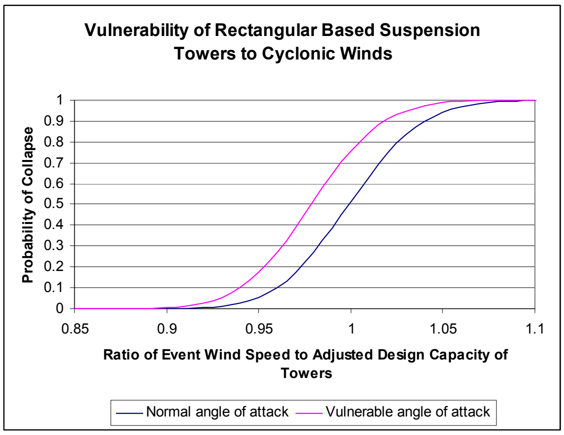

Figure 2. The graph shows fragility curves for rectangular based suspension towers for wind blowing in the normal and vulnerable directions.

3 RESULTS AND DISCUSSION

The tropical cyclone risk model (TCRM) developed at Geoscience Australia was used to simulate a cyclone at a location in Australia [6] to evaluate a scenario of damage to electricity transmission network and response of the Transmission Network Service Provider (TNSP) to muster resources for system recovery. Impacts of the shortfall in electricity on community and industry were then analysed. The transition of winds during the simulated cyclone, at each transmission tower location was sampled to analyse the magnitude and direction of wind. The collapse probability for towers was then estimated. The influence of neighbouring collapsing towers was also analysed to provide an overall probability of collapse for each tower. The outcomes from this analysis enabled determination of recovery times and resources requirements for the TNSP. Various scenarios with different return period cyclones for a particular cyclone track. This enabled evaluation of the threshold of recovery of the electrical system, its flow on consequences on other utilities, community impacts and business impacts.

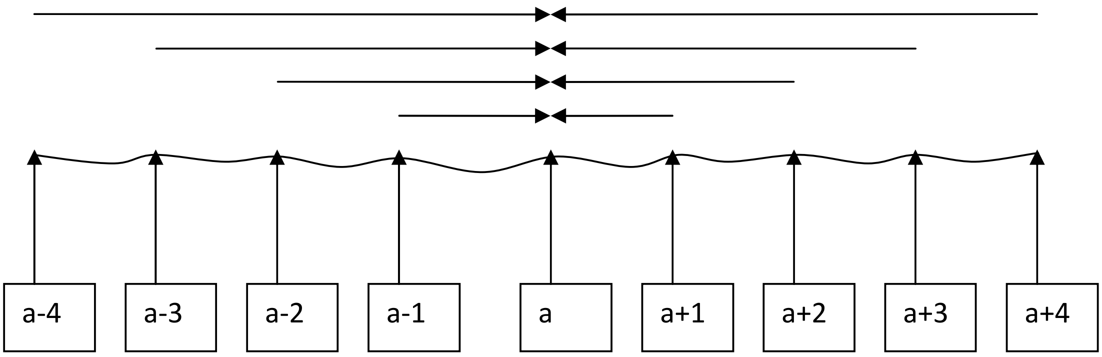

Figure 3. A tower 'a' is likely to be pulled by its collapsing neighbours on either side – 'a+1', 'a+2', 'a+3', 'a+4', 'a-1', 'a-2', 'a-3' and/or 'a-4'.

4 CONCLUSIONS

The paper outlines a methodology for analysing vulnerability of lattice type high voltage electricity transmission towers using heuristic information. There are often reports of actual tower collapse in media and industry journals, however this information cannot be directly used to develop vulnerability relationships to wind, due to the fact that reliable wind speeds impacting on towers are not readily available at the location in question. The methodology presented in the paper enables evaluation of scenarios for a TNSP to develop an envelope for their capability to recover from a cyclonic event with resource constraints.

5 REFERENCES

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