Reliability of Transmission Towers under Extreme Wind and Ice Loading

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SUMMARY

This paper presents reliability studies for three high voltage transmission circuits (230 kV, 345 kV and 500 kV) that have had collapsed towers under high wind and ice loading events.

An "average long term acceptable" rate of transmission tower failure is suggested (0.00005 failures per tower per year) for population areas of 5,000,000 to 10,000,000 people. At this rate of failure, the short term and long term consequences of resulting power outages appears to be "reasonable" and within what society is willing to pay for initial robust construction of towers versus the downstream occasional, but still rather rare, outages due to storm-induced tower failures.

This paper describes a reliability model that is used to forecast failures of transmission towers, using three case studies for wind events that damaged transmission towers in Washington and Idaho, USA and one ice loading event that damaged towers in New Brunswick, Canada. The model is set up to use easily obtained input design parameters, so that the reliability analysis can be performed in a very short time. The fragility of existing towers to withstand extreme wind and ice loading is described in terms of nominal design wind speeds, and glaze ice thicknesses, and actual distances between towers.

The model can be used to reasonably forecast end-to-end circuit reliability, in perhaps just a few hours of effort per circuit. These types of results can often be suitable for emergency planning purposes. The model can also incorporate refinements to take into account local topographic effects, as well as tower-specific weaknesses. With this type of refinement and calibration, the model can provide the transmission engineer with rational quantified information from which decisions can be made about selecting cost effective design wind (ice) loads and placement of dead-end towers to limit cascade type failures. The model is implemented in SERA, a special-purpose GIS for the evaluation of large scale high voltage transmission systems including towers and substations, for wind, ice and seismic loads.

INTRODUCTION

All modern transmission towers in Canada and the USA have been designed for some level of wind and ice loads. There are various industry guidelines and codes that set rules and procedures for such design [1]; these guidelines and codes have evolved over time, but it is rare (almost never) that older transmission towers are upgraded to the latest standards.

A model is described to examine the reliability of each transmission tower in a transmission circuit. The model is geared to examining reliability for extreme wind, wind + ice; or ice only loading. The model can factor in local wind speed-ups due to topographical effects. The model allows the user to include tower-specific weaknesses such as locally weak soil conditions under saturated conditions, or construction defects, or other factors that were not reflected in the original design of the tower. The model allows spatial variation of wind and ice at different locations along the transmission line. The model accounts for apparent reliability increases (or decreases) due to as-installed horizontal spans that are shorter (or longer) than originally assumed for design.

The model is tested using three specific transmission lines that have been damaged by past storms: two examples are for high wind events (Bonneville Power Administration (BPA) 230 kV and 500 kV transmission lines); one example is for an ice loading event (New Brunswick 345 kV transmission line).

Using suitable parameters, the model is shown to have reasonable capability to forecast actual tower failures in past storms.

RELIABILITY GOAL

Transmission towers sometimes fail. The problem is to decide how strong (and how costly) one should design the towers. A system-wide long term reliability goal is suggested as follows. BPA has had a number of towers collapse due to high wind and ice loads. For the period from 1948 to 2009, a total of 161 towers were damaged due to high winds, and another 61 towers damaged due to ice loads (Figure 1). Of these, there have been a few cases where the damage was a broken conductor (under 3% of the time). In some cases the damage was dropping the conductor due to failure of the porcelain insulators. The large number of wind-tower failures in 2001 was on a line near Pasco, where high winds failed 61 towers on one wood pole line (wood poles snapped near their base).

Figure 1 does not distinguish between towers that were damaged due to high wind and those adjacent towers that were damaged due to the unbalanced conductor loads that occur once the first tower collapses. With the exception of the one wood-pole event in 2001 with more than 50 collapses due to cascading effects, it is apparent that unbalanced-load tower failures have not been common (in a few initiations, perhaps 1 or 2 adjacent towers collapsed; and in 1 ice event in 2005, 10 towers collapsed) in the BPA system. BPA designs its lattice-type transmission towers with the intent to contain cascade-type failures.

The BPA evidence over 50+ years shows that an average long term failure rate of 0.00005 per year (5 tower failures per 100,000 towers, per year), appears reasonably cost effective and to have no serious long term impact to society. As evidenced in the Montreal ice storm of 1998, a failure of 1,000 steel lattice-type transmission towers in one storm event does not appear acceptable to society. Reliability models can be used to help distinguish between these two cases.

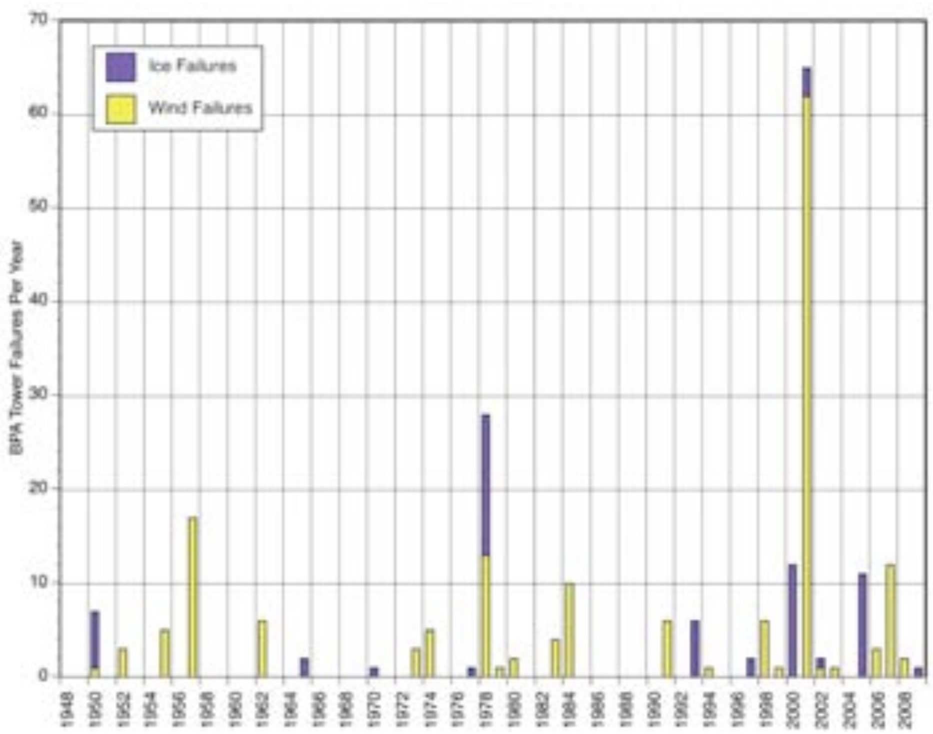

Figure 1 Reported Tower Failures (BPA), 1948 - 2009

THE RELIABILITY MODEL

The model assumes that the failure of transmission towers in extreme storms is due to one of the following mechanisms: extreme wind acting horizontally and transverse to the transmission line; a build up of glaze or rime ice, followed by moderate wind acting horizontally and transverse to the transmission line; or a build up of glaze or rime ice resulting in high dead weight on the line, possibly unbalanced. These failure modes are believed to cover more than 90% of all observed gross failures; with the remainder due to breaking of the conductors / ground wires or their attachment hardware.

Assume that the tower was designed for extreme wind. For example, say the design-level wind velocity V = 44.7 m/s (100 mph) applied to the conductors / ground wires, with a design span L = 366 m (1,200 feet). Even though some designers will set V = 53.6 m/s (120 mph) on the exposed surface of the tower, it is found that the governing overturning moment on the tower is controlled mostly by the wind speed on the conductors; so this parameter is used as the independent variable. At this wind speed, the tower is designed to have a factor of safety of 1.0 against nominal yield; with balanced design applied for foundation uplift and bolted connections. Assuming that this design follows ASCE 10 [1] (or its predecessor, ASCE 52), then full scale tests [2] suggest that should such a tower be exposed to V = 44.7 m/s (100 mph), that there is a very small (non-zero) chance of collapse; but if this tower is exposed to V = 50.1 m/s (112 mph), there is about a 50% chance of collapse. As load applied to the tower is a function V**2, then the *average* tower has an over strength capacity of about 25%.

Once the strength capacity is determined, how does one assign the fragility level? For extreme wind loading, a truncated 4-parameter fragility model is used ($\hat{V}$, β_u, β_r, $D/C_{cut-off}$): $\hat{V}$, the wind velocity that will result in collapse of 50% of similar towers (excluding cascade failures); $\beta = \sqrt{\beta_u^2 + \beta_r^2}$, where β is the lognormal standard deviation of the variance in $\hat{V}$, which is the vector sum of the standard deviations for items that are uncertain and items that are random; $D/C_{cut-off}$, to avoid spurious results, the distribution is truncated at a lower bound level. D represents the demand on the tower, and C represents the capacity of the tower. For example, the chance of tower failure under applied wind speed = V = 4.47 m/s (10 mph), for any tower built to ASCE 10 with V(design) = 44.7 m/s (100 mph), is, by observation, 0. Any continuous distribution (including the lognormal) will always return a chance of failure at D/C = 0.10; so truncation is used to avoid such spurious results.

The lognormal distribution shape is selected for two primary reasons: First, it is mathematically convenient. For any value of applied wind speed V the lognormal distribution will always provide a positive cumulative density function, no matter what value is set for β. For example, if a normal distribution were taken, a typical value of σ (standard deviation) would allow that there is a finite cumulative probability that the tower will collapse when exposed to V = 0 m/s (mph); clearly a nonsensical result. Second, failures in the world tend to have lognormal distributions.

In developing the reliability model, it is observed that full scale tower tests have shown, than on average, $\hat{V}$ is about 12% higher than V(strength capacity). In other words, if V(strength capacity) is 44.7 m/s (100 mph), then 50% of similarly-designed and installed towers should fail at 50.1 m/s (112 mph). This implies that the average tower fails at 125% of the design load. Where does this extra 25% come from? It is a combination of the conservatisms built into the elastically-based design; coupled with some post-yield capacity of a typical tower to accept more load before it actually collapses.

Figure 2 shows the strength criterion that combines both wind and ice loading. For specific towers loaded with ice thickness r and transverse wind speed V, and with actual horizontal distance between towers L, the demand-to-capacity checks for wind, moderate wind and ice, high wind and ice, and ice loading alone, are described as follows, shown conceptually in Figure 2.

$$D/C_{wind} = \left(\frac{L_{actual}}{L_{design}}\right)\left[\left(\frac{V_{actual}}{\hat{V}_{fragility}}\right)\right]$$

[Eq. 1], Extreme Wind

$$D/C_{wind+ice} = \left(\frac{L_{actual}}{L_{design}}\right)\left[0.5\left(\frac{r_{actual}}{\hat{r}_{fwind+ice}}\right) + 0.5\left(\frac{V_{actual}}{\hat{V}_{wind+ice}}\right)^2\right]$$ [Eq. 2a], Moderate Wind + Concurrent Ice

$$D/C_{wind+ice} = \left(\frac{L_{actual}}{L_{design}}\right)\left[\left(\frac{r_{actual}}{\hat{r}_{fwind+ice}}\right) + \left(\frac{V_{actual}}{\hat{V}_{fragility}}\right)\right]$$ [Eq. 2b], High Wind + Concurrent Ice

$$D/C_{ice} = \left(\frac{L_{actual}}{L_{design}}\right)\left[\left(\frac{r_{actual}}{\hat{r}_{fragility\ dead}}\right)\right]$$ [Eq. 3], Ice Loading Only

and the chance of failure is: $w = \frac{-\ln\left(D/C\right)}{\beta}$, where w is the number of standard normal deviates: for $w = 0$, p(fail) = 50%; for $w = +1$, p(fail) = 84%; etc.

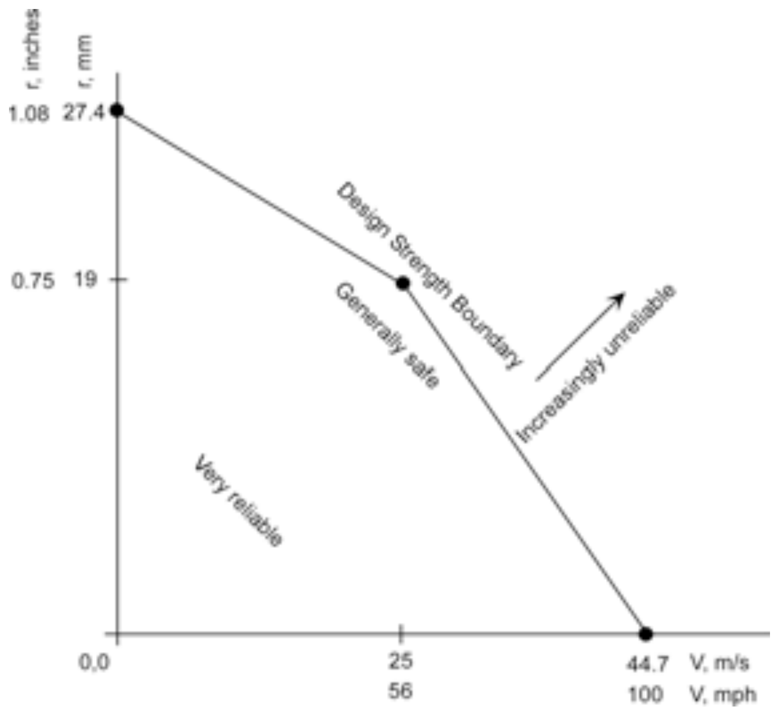

Figure 2. Strength Criterion

CASE STUDY 1. 230 kV Transmission Line, Wind Loading

The Case Study 1 230 kV circuit is in western Washington State. The circuit length is 33.3 km, and has 96 steel lattice-type towers. The conductors are Drake, 1 conductor per phase. The line was constructed in the 1960s. On February 23, 1999, at 11:53 pm, tower number "14179" failed during a high wind event. Failure was characterized as a footing failure. On December 2, 2007, six more towers failed on this line due to high winds. The line had more tower failures due to another winter storm in 2009, Figures 3, 4. The failed towers were all light tangent suspension towers.

Table 1. Case 1 Parameter Study

Case	Exposure C Wind Speed m/s West - East	Beta Wind	Beta Tower	D/C Cutoff	Tower Failures (initiations)	Towers with p(fail) > 10%	Towers with p(fail) > 25%	Tower "14179" p(fail)
1	30 – 20	0.28	0.10	0.50	1.11	0	0	0.07
2	31 – 22	0.28	0.10	0.50	1.86	2	0	0.09
3	30 – 20	0.28	0.10	0.60	0.66	0	0	0.07
4	30 – 20	0.30	0.26	0.60	1.33	11	0	0.13
5	30 – 20	0.30	0.26	0.55	1.95	12	0	0.13
6	25 – 20	0.30	0.26	0.50	0.89	0	0	0.06
7	25 – 20	0.40	0.30	0.50	1.62	14	0	0.11
8	25 – 20	0.40	0.50	0.50	2.56	16	0	0.17
9	25 – 20	0.40	0.50	0.50	8.69	32	14	0.55
10	25 – 20	0.28	0.10	0.50	4.52	11	7	0.60
11	25 – 20	0.28	0.10	0.75	3.22	7	7	0.60
12	25 – 20	0.28	0.10	0.75	3.45	8	7	0.60
13	25 – 20	0.28	0.10	0.75	3.45	8	7	0.60
SERA	25 – 20	0.28	0.10	0.75	1.64	5	2	0.53

Anemometers at nearby airports were examined to quantify the gust speed at the time of tower collapse. Near the western end of the line, recorded wind speed was 30 m/s (67 mph). Near the eastern end of the line, the recorded wind speed was 20 m/s (45 mph). These recorded wind speeds reflect Exposure C type environments at 10 m above ground, at airports. At first glance, it would have to normally be assumed that the towers would have zero chance of failure, as they were nominally designed for 44.7 m/s (100 mph). 11 variations of the reliability model were used to test various hypotheses to help understand the actual failure process. Using the 1999 storm, the key results of these 14 variations are listed in Table 1.

Figure 3. Case Study 1 Collapsed Tower Due to Wind Load

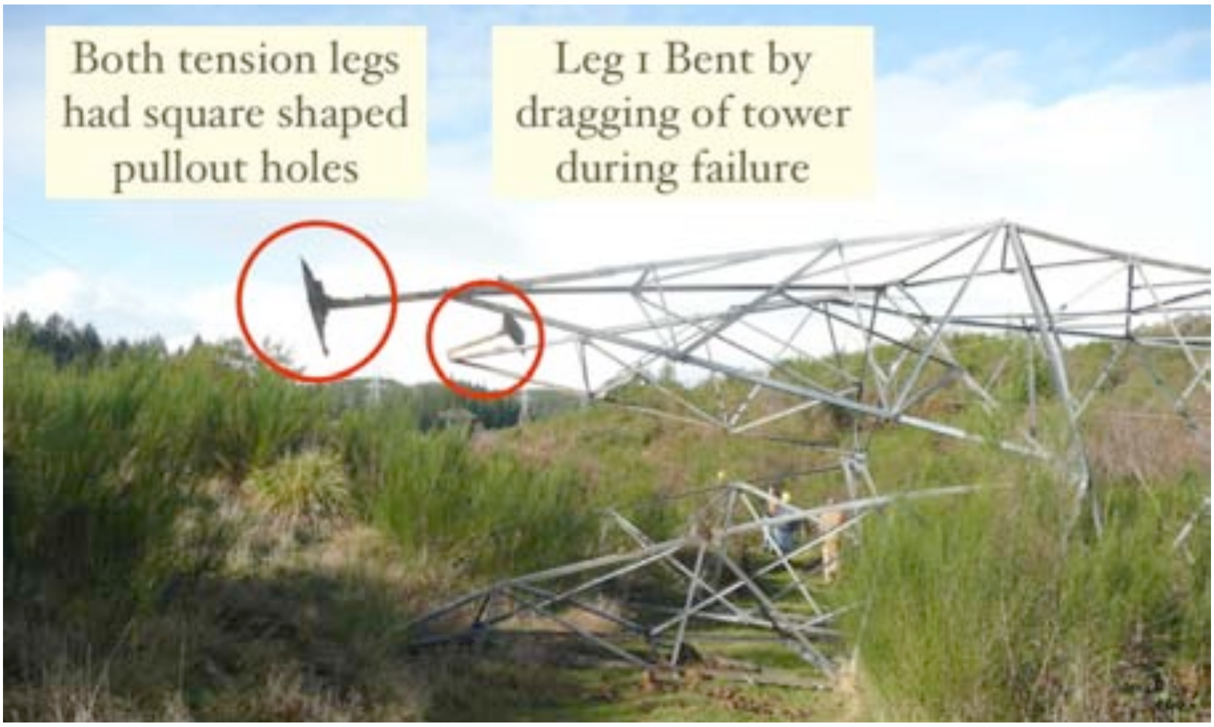

Figure 4. Case Study 1 Collapsed Tower Due to Wind Load

In Case 1, a linear variation in wind speed was applied from 30 m/s to 20 m/s along the circuit, beta (wind) of 0.28, beta (tower) of 0.10, $\hat{V}$ (fragility) of 50 m/s and truncate when D/C is under 0.5. The results from Case 1 seem reasonable: the model predicts 1.11 tower failures, and there was actually 1 failure. Pretty good! But, the model shows just a 6.5% chance that tower "14179" would fail. With such a low forecast chance of failure, the Case 1 model might be useful for overall emergency planning point of view, but not for selecting specific towers for possible retrofit.

In Case 2, the wind speed was increased by 1 to 2 m/s. This increases the forecast of "14179" failure to 8.9%. In Case 3, the truncation D/C ratio is increased to 0.60, which lowers the cumulative tower failures. Case 4 increases the uncertainty parameters for both wind variability and tower capacity; this increases the chance that "14179" fails to 12.8%. Case 5 lowers the D/C ratio to 0.55, increasing total tower failures to 1.95. Cases 6, 7, 8 use lower wind speeds, but increases the uncertainty parameters.

None of Cases 1 through 8 was particularly reasonable, All towers that failed are at or near ridge tops in moutainous terrain; wind speeds from nearby airports neglect topographical factors; and the observed failure modes of the towers were footing uplift failures. This suggested that a topographical factor should be included in the model (term Kzt); which is considered in Cases 9, 10, 11, 12, 13 and 14. The SERA simulation model provies many options to account for various storm types and topographical effects, Figure 5.

In Case 9, it was assumed that certain towers at ridge tops were exposed to nearly 2 times the wind speed (49 m/s) as compared to towers in valleys or in open flat terrain (25 m/s). Case 9 also includes a very large beta for tower capacity, reflecting that there may be some material foundation weakness for these towers. Case 9 predicts a 55% chance of tower "14179" failure. This would seem to be a good result (the tower did fail!), but the model also preducts 7.69 other towers should have failed (6 more did fail in another similar storm 2007). In Cases 10 and 11, the tower uncertainty parameter and the D/C ratio are varied to get a sense of the sensitivity to such model variations. After considering these failures, further examination found that the tower foundations along this specific line were in a volcanic tuff, that when saturated loses much of its strength; and thus provides much less overturning resistance at V = 45 m/s than what was assumed when the tower was designed in the 1960s. Cases 12 and 13 use updated fragility and topographical terrain data. Case 13 is the same as Case 12, except that Kzt factors in wind shadows based on the change in slope between towers, assuming the wind comes from the west. This option is included in SERA by selecting the "Use kZT from delta Slope from W to E", Figure 5.

The last row in Table 1 shows the implementation in SERA. The SERA results (Case 14) show 1.64 tower initiation failures; and a 53% chance of failure of Tower 14179. The Case 14 SERA results are reasonable.

There are two key issues observed from these models. First; tower-specific topographical factors should be included in the reliability analysis of transmisison lines through mountainous terrain; if neglected, the models can be useful for emergency planning purposes, but yield little information for purposes of directing tower-specific mitigaiton efforts. Second, site-specific conditions (such as foundations and tower details) should be considered.

The findings from Cases 1 through 14 also show that the reliability model must have the following features in order to be realistic:

- Actual span lengths need to be accurate.
- Design basis for each actual tower must be quantified.
- Local topographic effects for wind speed-up are important. If these are not known, then reasonable results can be predicted for purposes of emergency planning, but the results for individual towers will be too uncertain for purposes of cost effective mitigation planning.

- The D/C truncation is an important parameter. While past tower full scale test data suggest a truncation of perhaps 90%, actual in-situ construction (local geologic conditions or construction defects) can result in much lower capacity than assumed in the design, and thus invalidate the D/C truncation observed from controlled tests.

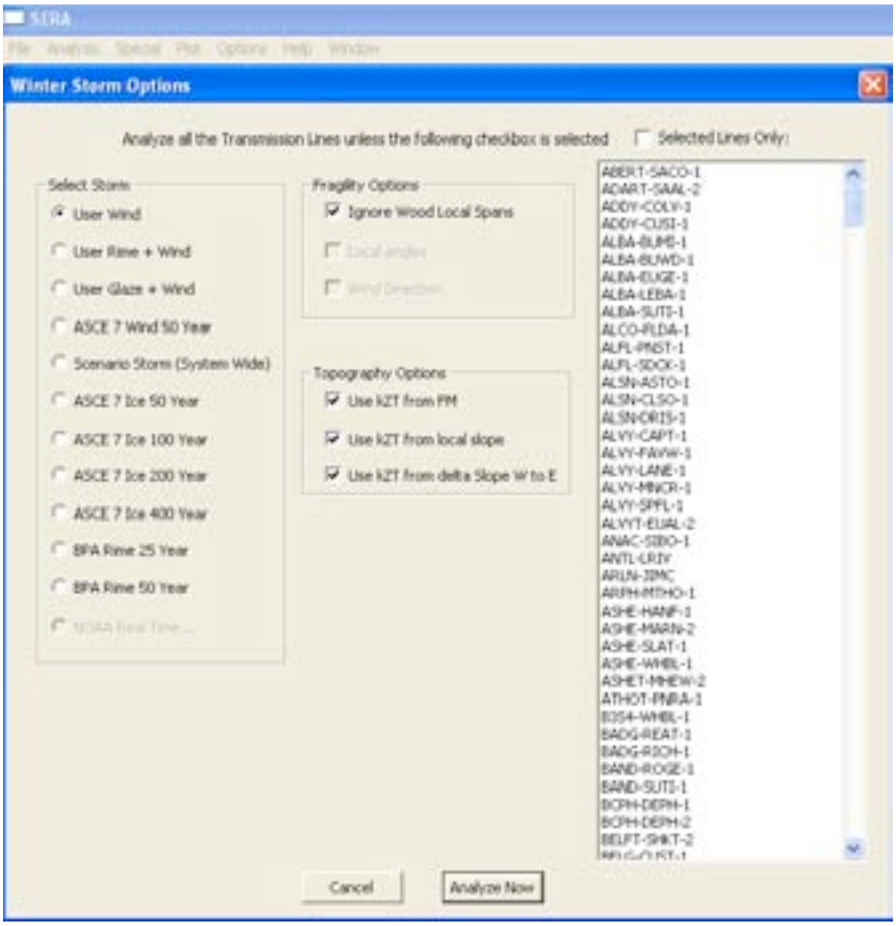

Figure 5. SERA – Winter Storm Options

One of the important findings is that some of the towers may have been constructed with foundations in soils that are considerably weaker than originally assumed during original design and construction. For this particular circuit, some towers have foundations in a volcanic-ash-deposited, material that becomes much weaker when saturated than when the material is dry. This means that the circuit is more reliable for a summer storm (dry conditions) than a winter storm (ground-saturated conditions).

CASE STUDY 2. 500 kV Transmission Line, Wind Loading

The Case Study 2 is a 500 kV single circuit transmission line located in Idaho. This circuit includes 131 towers. The length of the circuit is 46 km. The conductor type on this line is Bunting, bundled with 3 conductors per phase, 9 conductors total. The ground wire on this line is a 7 No. 8 Alumoweld.

On November 16, 2010, one tower (number "53462") collapsed during a winter storm, Figures 6, 7. The collapsed tower was a single circuit 500 kV tower, steel lattice-type, light tangent suspension. This tower's original nominal design basis was assumed to be V = 57 m/s with a 366 m span. A reliability model was developed for the entire circuit, and five cases were run (numbered 101 through 105), Table 2. The exposure C highest gust wind speeds for this storm were recorded at two airports located between 26 to 39 km west of the collapsed tower, recorded as 28 m/s and 38 m/s, respectively. Winds were generally out of the west. Over flights of the circuit revealed some roofs blown off farm buildings. Tower "53462" collapsed mid-height. The actual horizontal span for this tower was 229 m.

Table 2. Case 2 Parameter Study, Cases 101 through 105

Case	Wind Speed m/s West - East	Beta Wind	Beta Tower	D/C Cutoff	Tower Failures (initiations)	Towers with p(fail) > 10%	Towers with p(fail) > 25%	Tower "53462" p(fail)
101	36 – 27	0.40	0.50	0.50	6.44	29	10	0.000
102	70 – 27	0.28	0.10	0.75	8.71	21	14	0.000
103L	66 – 27	0.28	0.10	0.75	2.23	7	3	0.232
104L	66 – 27	0.28	0.10	0.75	3.11	7	5	0.526
105L	54 – 27	0.28	0.10	0.75	1.61	4	4	0.268

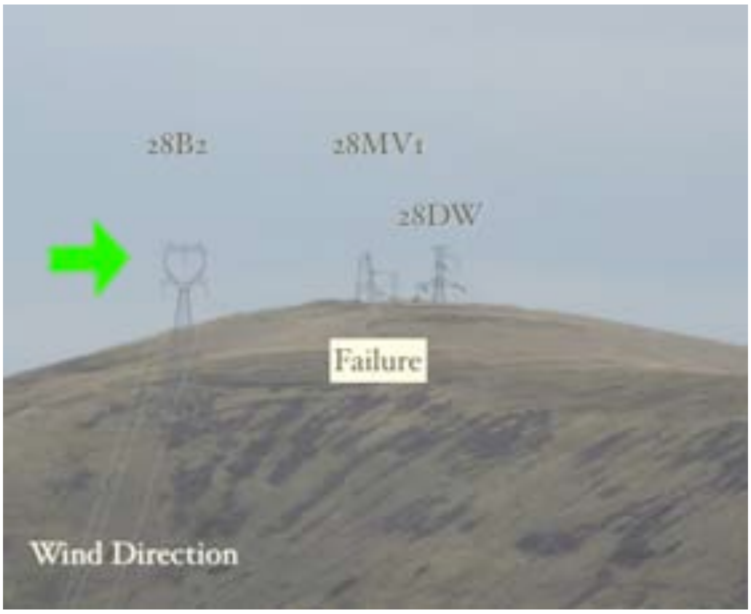

Figure 6. Case Study 2. Collapsed Tower 14179 Due to Wind Load

Figure 7. Case Study 2. Collapsed Tower Due to Wind Load

Case 101 includes 131 towers, assuming a wind speed of 36 m/s at the west end of the circuit to 29 m/s at the east end of the circuit. As there were no wind recordings within 100 km east of the collapsed tower, the decision to attenuate the wind speed along the length of the circuit is perhaps arbitrary. Case 101 ignores local topographic effects, and uses the same assumptions as Case 8 (Case Study 1). Case 101 predicts 6.44 tower failures, but only 1 occurred; Case 101 predicts 0% chance of failure for tower "53462". Clearly, the Case 101 model is missing some important parameter(s).

Case 102 uses the same assumptions as Case 8, using local slope as a proxy for estimating the effects of topography. Case 102 still does not show good results; it was concluded that tower-specific computation of topographic effects was needed. Case 103L uses tower-specific computation of topographic effects. The results (23.2% chance of failure for tower "53462") appear credible.

A structural review of tower "53462" (using 3-dimensional structural analysis software) revealed that the tower was not as strong as originally assumed, V = 57 m/s, but instead would reach code capacity at V = 45 m/s. Case 104L includes tower-specific local topographic effects, and shows a 52.6% chance of failure for this tower. Case 105L also assumes V = 45 m/s, but with lower wind speeds assumed, and shows this tower has a 26.8% chance of failure; Case 105 also shows three other highly loaded towers, but these did not collapse, in part because the local orientation of the line suggests that the prevailing wind loads were more nearly parallel to the circuit for these towers.

CASE STUDY 3. 345 kV Transmission Line, Ice and Wind Loading

A 345 kV circuit transmission line in New Brunswick failed due to ice loads, see [3, 4] for details. A storm with sleet, freezing rain and light winds occurred from April 2 to April 3 1993 in southern New Brunswick. This resulted in heavy ice loading on transmission and distribution circuits in the area. At 10:04 am on April 3 1993, the 345 kV line failed. The failure included 15 transmission towers, of which one was a heavy angle tower, and 14 were suspension tangent-type towers (Figure 8). Arguably 13 (maybe 14) of the failures were due to cascading effects, and at most 1 (maybe 2) were due to overloads.

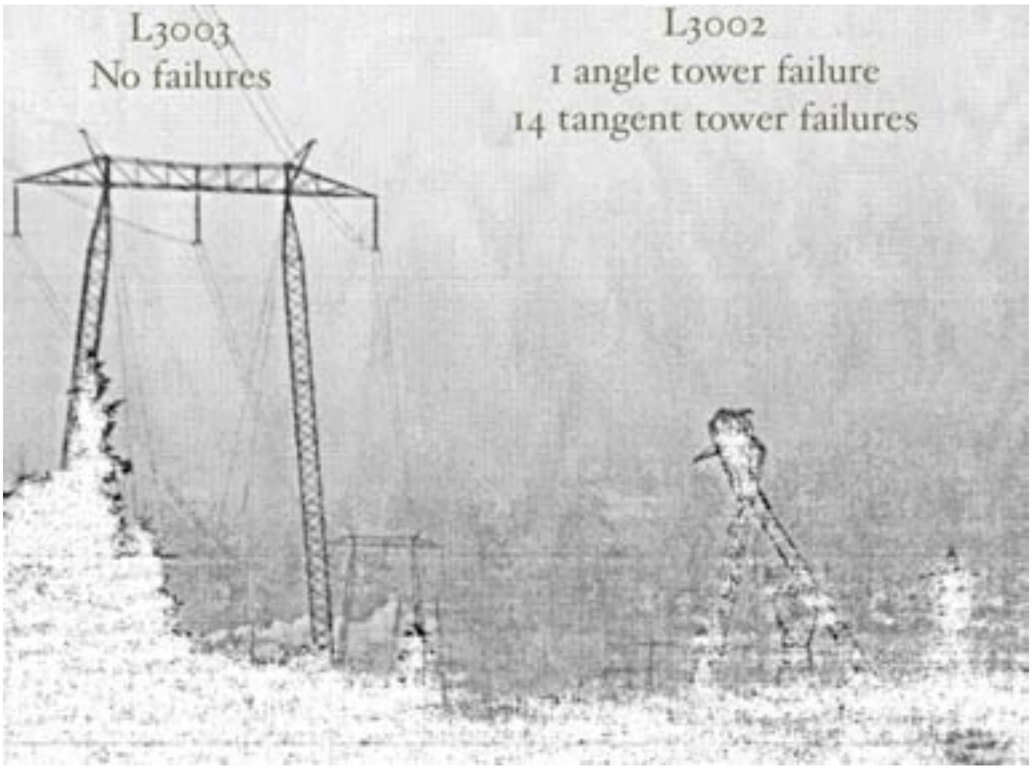

Figure 8. Case Study 3. Collapsed Tower Due to Ice Load

Due to heavy unbalanced ice loading, coupled with light winds, a guy wire failed at a tangent suspension tower, number "294". This caused the adjacent angle-type structure to collapse. These two failures resulted in cascading of 3 towers towards the north and 10 towers towards the south.

Ice build up on the conductors varied in thickness and configuration, depending on location along the line. The equivalent of 25 mm of radial ice was observed on some of the conductors, and nearly 50 mm on one face of the conductor at one location. Calculations for the first structure that failed suggested that at 25 mm of ice and no wind, the structure was at 75% of its strength capacity. At the time the line failed, nearby weather station CYSJ reported winds at 5 m/s, winds from the NNE. Light freezing rain and light freezing drizzle was reported continuously from 12:24 am to 11:31 am April 3. Winds were generally 2 to 3 m/s during the accumulation of freezing drizzle from 2:40 am through 9:00 am on April 3, but then picked up to about 5 m/s between 10:00 am and 10:12 am.

The actual failure mechanism appears to have been a high longitudinal load on tower "294"; and this initiated the subsequent zippering. Since the failure likely had some contribution from both ice and wind, three constraints were adopted for the design strength criterion, assuming an original design span of 457 m:

- When the actual radial ice thickness is 27 mm, the tower reaches its nominal strength limit.
- When the actual radial ice is 19 mm and there is a concurrent wind speed of 25 m/s.
- When the wind speed, with no ice, is 45 m/s.

Reliability results are in Table 3. For Case 201, it was assumed that the wind along the circuit varied from 7 m/s (southern end of the circuit at coast) to 2 m/s (northern terminus of the circuit). It was assumed that the ice along the circuit varied from 0 mm (northern end of line, inland) to 25 mm (southern terminus of the circuit). In the vicinity of the tower failures, the ice thickness was assumed to vary from 23 mm to 24 mm. A "design" strength of 45 m/s wind (no ice) or 27 mm radial glaze ice (no wind), and all towers have a design span of 457 m. Case 201 shows a total number of tower failure initiations of 1.41. The maximum chance of failure of any tower along the alignment is 9.0%.

Case 202 begins with Case 201, with somewhat reduced average wind speeds to range from 5 m/s (coast) to 2 m/s (inland). For towers 294 and 293 specifically, as they are on hills, Case 202 considers topographic effects to increase their wind speed to about 6 m/s.

Case 203 begins with Case 202, and then assumes a strength defect on Tower 294 guy wire splice, such that the splice is 75% of the rated guy wire capacity. This increases the chance of failure for Tower "294" from 2.7% to 16.5%. Case 204 begins with Case 203, and then increases D/C from 0.50 to 0.60; this reduces the total number of tower failure initiations to 0.63. Case 205 begins with Case 204, and then sets the actual ice loading for all towers southwards to the coast at 25 mm. This increases the total number of tower failure initiations to 1.04, and the chance of failure of Tower "294" at 24%.

Table 3. Case 3 Parameter Study, Cases 201 through 205

Case	Wind Speed m/s T, S - N	Ice mm S - N	Beta Total	Tower Local Strength	D/C Cutoff	Tower Failures (initiations)	Towers with p(fail) > 1%	Towers with p(fail) > 5%	Tower "294" p(fail)
201	7 - 2	25 - 0	0.30	1.00	0.50	1.41	46	7	0.029
202	6, 5 – 2	25 - 0	0.30	1.00	0.50	1.28	45	5	0.027
203	6, 5 – 2	25 - 0	0.30	0.75	0.50	1.41	45	6	0.165
204	6, 5 – 5	25 - 0	0.30	0.75	0.60	0.63	9	6	0.165
205	6, 5 – 5	25 - 0	0.30	0.75	0.60	1.04	12	12	0.237

Note: T, S – N, T = Specific to selected towers, S – N = South and North of transmission line section studied

Observations: lacking the knowledge of a pre-existing construction defect in the guy wire, the models can provide reasonable forecasts for emergency planning purposes, but cannot identify specific towers for retrofit in any cost effective way.

BPA APPLICATION

The reliability models described herein were extended to address the 700+ transmission circuits in the BPA system, including more than 80,000 transmission towers. The models factor in 11 types of wind and ice storms, including code-type "50-year" wind events as well as scenario based extreme events (like the 1962 Columbus Day storm that impacted Oregon with wind speeds over 63 m/s (140 mph). The SERA simulation model is used to evaluate the entire BPA system. For more details, see [4].

CONCLUSIONS

If one wishes to use this type of reliability model for emergency planning purposes (i.e., will there be one or more tower failures along an entire transmission line, given a certain type of storm), the model is easy to use and reasonably accurate. Calibration of the model for purposes of trying to identify specific towers that might fail, and thus cost-effective tower-specific mitigation, requires an extra level of effort (perhaps a few days or even weeks of effort per transmission line), and should address topographic effects and tower-specific weaknesses.

Upgrade / retrofit strategies for existing transmission towers should not be isolated to individual towers; instead, upgrades should be applied to small groups of "highest at risk" towers along an individual circuit. This reflects that randomness, uncertainties and the effort needed to collect tower-specific information all act to limit the ability to readily identify the single "bad actor" tower along an entire transmission line.

ACKNOWLEDGEMENT

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