12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP12
Vancouver, Canada, July 12-15, 2015

Vulnerability Analysis of Transmission Towers subjected to Unbalanced Ice Loads

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ABSTRACT: This paper presents a probabilistic framework for vulnerability analysis of electric transmission towers subjected to unbalanced ice loads using the concepts of statistical learning theory (SLT). Based on SLT, the implicit limit state function of each element is replaced by an approximate polynomial function that has good prediction properties. The results are presented in the form of fragility curves for 3 different unbalanced loading scenarios of longitudinal, transverse and torsional loadings. Such fragility information provides us with a better understanding of the behavior of various components of the line under different climatic conditions. It can also be used to evaluate existing transmission towers and to optimize the design of new ones. This paper further studies the effect of various design parameters such as wind speed and direction, icing rate and location of ice formation on the fragility curves of tension and suspension towers. The results show higher failure probabilities for suspension towers than tension towers. The results also indicate that for most conditions, longitudinal loads are more important than other unbalanced loading scenarios. Finally, this study concludes that wind speed, wind direction and ice accumulation rate have notable effects on the fragility curves.

1. INTRODUCTION

Previous investigations for determining the causes of transmission line failure during extreme climatic events have shown that extreme unbalanced ice loads are the primary cause of failure. Non uniform ice loads can occur either during ice accretion due to significant changes in elevation, span or exposure, or during ice shedding. The amount of ice built up on a wire is significantly dependent on wind speed and wind direction with maximum ice thickness forming on wires perpendicular to the wind direction. This can result in unbalanced ice formation of as much as 70% on adjacent spans in some cases for example where there is a change in the direction of the line (ASCE 74, 2010). In addition, concurrent winds can exacerbate the imbalance by increasing the differential tension loads in adjacent conductors or ground wires. Although some researchers have studied the effect of various factors such as structural flexibility, non-uniform ice ratio, ice position, span length and conductor properties on the resulting unbalanced longitudinal tension of transmission lines (Mozer et al, 1977, Fleming et al, 1978, Hou et al, 2012, Yang et al, 2012), no comprehensive probabilistic framework is available to develop fragility curves for different components of the transmission line considering all these effects. Such fragility information gives a better understanding of the behavior of various components of the line under different climatic conditions. Fragility curves can further help in the assessment of serviceability conditions of transmission towers and their components in the aftermath of a climatic event, and they are an essential element for risk mitigation and decision analysis.

This paper presents a probabilistic framework for vulnerability analysis of electric transmission towers subjected to unbalanced ice loads. It further studies the effect of various design parameters such as wind speed and direction, icing rate and location of ice formation on the fragility curves.

2. TRANSMISSION LINE MODEL

As indicated in Figure 1, a nine-span transmission line consisting of two sections separated by tension towers is modeled in Sap2000® and analyzed under 4 loading scenarios of uniform, longitudinal, transversal and torsional ice and accompanying wind loads. The model takes into account the effect of structural flexibility, the geometric nonlinearity and the variability of structural capacity of tower elements in calculating the conditional failure probability of towers given specific climatic conditions. A description of the towers within the line segment is presented in Table 1. And Figure 2 presents the configuration of various tower types within the line. The results are presented in the form of fragility curves for suspension tower 5 and tension tower 3.

3. THEORETICAL BACKGROUND

One challenge in the fragility analysis of complex structures such as transmission lines is the implicit nature of the limit state function for each structural component which can be expressed by equation 1.

$$G(\mathbf{x}) = C(\mathbf{x_c}) - D(\mathbf{x_d}) \tag{1}$$

where $\mathbf{x_c}$ includes the random variables related to the capacity and $\mathbf{x_d}$ includes the random variables related to the structural demand.

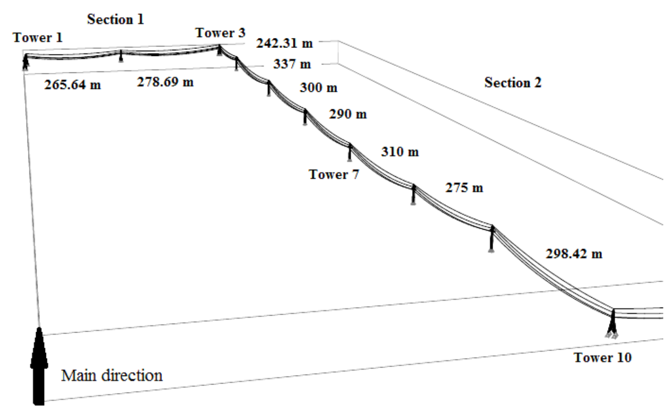

Figure 1: Nine span segment of the transmission line under study

Table 1:Descriptin of towers within the studied line segment.

Tower Number	*Tower Height (m)*	*Tower Type*
1	*30.5*	*TM*
2	*28.75*	*TA*
3	*27.5*	*TM*
4	*33.25*	*TB*
5	*33.25*	*TB*
6	*30.25*	*TB*
7	*30.25*	*TB*
8	*28.75*	*TB*
9	*33.25*	*TB*
10	*27.5*	*TM*

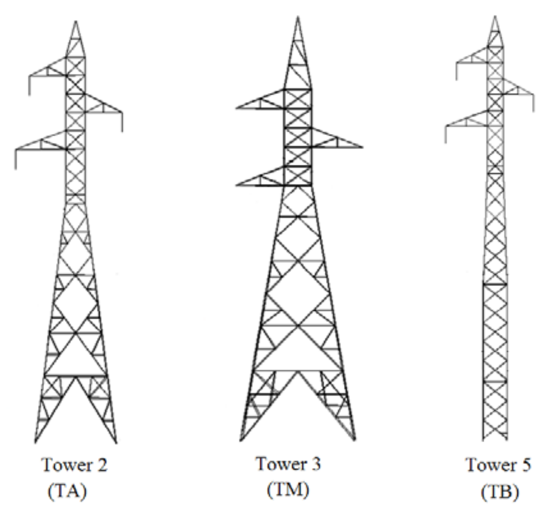

Figure 2: The configuration of tower types within the line

This issue has traditionally been dealt with by means of the Response Surface Method (RSM) (Bucher and Bourgund, 1990, Rajashekhar and Ellingwood, 1993). However RSM is based on the Empirical Risk Minimization (ERM) principle which can result in overfitting due to the rigid and non-adaptive nature of the selected model (Guan and Melchers, 2001, Hurtado, 2004). In order to overcome this problem, this paper adopts the concepts of Statistical Learning Theory (SLT) and the Structural Risk Minimization (SRM) inductive principle to substitute D($\mathbf{x_d}$) with a surrogate model that has good generalization (prediction) properties. Unlike ERM base methods, SRM does not impose strict assumptions over the class of approximating functions and prevents high bias produced by the discrepancy between the assumed functions and the actual governing functions. In this study, for each structural element, the best model which has the lowest prediction error is selected from the class of polynomial functions. In order to estimate the final unbiased prediction error of the selected model, a 3 fold cross-validation technique is applied. The selected model is validated by calculating the adjusted coefficient of multiple determination ($\bar{R}^2$) and the prediction coefficient of multiple determination ($\bar{R}_p^2$) using equations 2 and 3. A good model will have $\bar{R}^2$ and $\bar{R}_p^2$ values near 1.

$$\bar{R}^2 = 1 - \frac{MSE}{MST} = 1 - \left(\frac{n-1}{n-p}\right)(1 - R^2) \quad (2)$$

$$R_p^2 = 1 - \frac{\sum_{i=1}^{n_{te}}(y_{ite} - \hat{y}_{itr})^2}{\sum_{i=1}^{n_{te}}(y_{ite} - \bar{y}_{te})^2} \quad (3)$$

In equation 2, *MSE*, *MST*, *n* and *p* are the error mean square, the total mean square of variation in observations, the total number of samples and the number of model variables, respectively. n_{te} and $\bar{y}_{te}$ in equation 3 represent the number and mean of the observed responses (y_{ite}) in the test fold, respectively. and $\hat{y}_{itr}$ is the predicted response of the observations in the test fold using the fitted model to the training fold samples.

4. MODEL SELECTION USING SLT

In a study presented by Cherkassky and Mulier (2007), it is stated that SLT or Vapnik–Chervonenkis (VC) theory is the best currently available theory for flexible statistical estimation from finite samples. The theory presents an analytical generalization bound for model selection as shown in equation 4 (Cherkassky et al., 1999, Vapnik, 1995).

$$R(\omega) = R_{emp}(\omega).\left(1 - \sqrt{p - p\ln p + \frac{\ln n}{2n}}\right)_+^{-1} \quad (4)$$

Where $R(\omega)$ is the unknown prediction error, $R_{emp}(\omega)$ is the known empirical error, n is the number of training samples and p is the ratio of VC dimension (h) to the sample size. VC dimension is a characteristic of a set of functions which equals the maximum number of samples for which all possible binary labelings can be induced without error. It is noted that in the case of linear real-valued functions, h is the number of free parameters.

In this study, based on the SRM principle, the class of polynomial functions are divided into nested subsets (S_k) according to their degree of complexity. Then from the functions in subset S_k, SRM finds the function with lowest empirical risk over the training sample. Using equation 4, the prediction error can be calculated for each subset S_k. The best model with the optimal complexity is the one with the lowest prediction error. Figure 3 and 4 present the calculated $\bar{R}^2$ and $\bar{R}_p^2$ respectively for all members of tower 3. The adjusted coefficient of multiple determination expresses the quality of fit between the regression model and the training samples while preventing overfitting by penalizing the analyst for adding terms to the model. The prediction coefficient of multiple determination shows the ability of the selected model to predict future samples. The results show the adequacy of the selected model.

5. DEVELOPING FRAGILITY CURVES AND PARAMETRIC STUDY

Once the approximating function is selected to describe the demand in each element of the transmission line, the conditional failure probability of that element for a given climatic condition is calculated by comparing its demand with the distribution of its capacity.

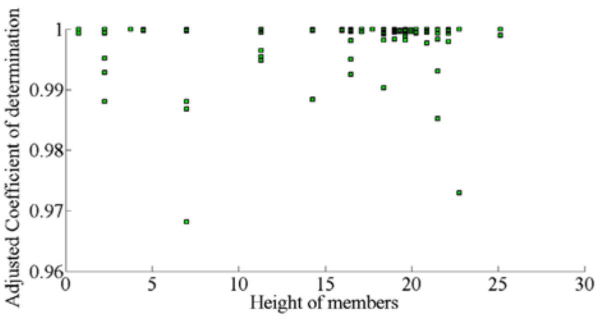

Figure 3: Adjusted coefficient of determination for all members of tower 3

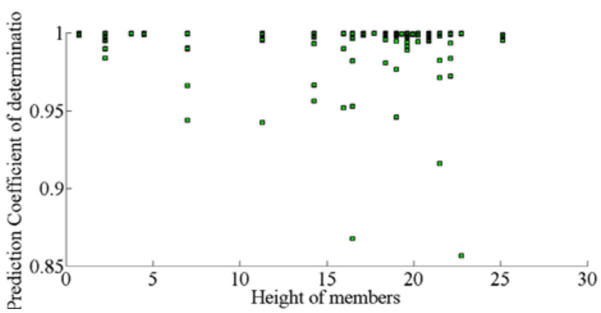

Figure 4: Prediction coefficient of determination for all members of tower 3

The capacity of each tower member is calculated based on ASCE10-97 (2003). It is assumed that the capacity of overhead tower components have a lognormal distribution with a coefficient of variation of 10% (CAN/CSA-C22.3, 2006).

The fragility curve for each tower is developed by assuming that the tower is represented by a series system. It should be noted that this assumption is conservative and implies that the tower fails once any one of its members fails. The other assumption used in this study is that the correlation between failure events of different tower members is only due to the same climatic conditions and the capacity of members are independent. It should be mentioned that developing fragility curves for other components of the line such as the wire system and foundations is beyond the scope of this paper, and further studies are required to determine and use these information to develop system fragility curves for transmission lines.

5.1. Fragility curves for various loading scenarios

Current design guidelines such as the European Standard EN 50341 (2001), CEI/IEC 60826 (2003) and CAN/CSA-C22.3 (2006) suggest that in addition to uniform ice loads, adequate reliability of transmission lines should be investigated for unbalanced ice loads that generate torsion, longitudinal or transversal bending on the tower. They suggest to apply non-uniform ice loads on up to 3 consecutive spans. In this study 6 loading scenarios are considered: uniform, transverse, 2 longitudinal and 2 torsion. Figure 5 shows how loads are applied on the wire system for each scenario. The solid line represents the wires that are loaded more, while the dash line represents the wires which are loaded less.

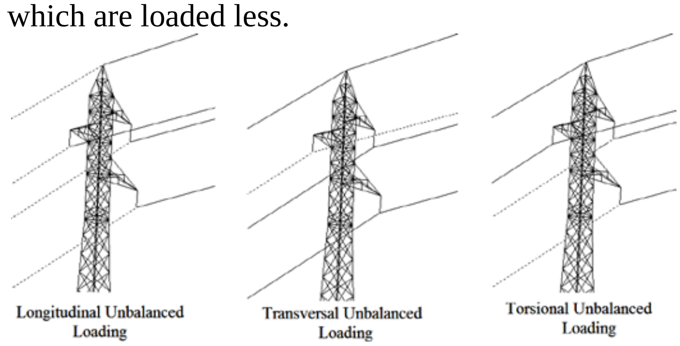

Figure 5: Non uniform loading conditions

Figure 6 and 7 present the resulting fragility curves for tension tower 3 and suspension tower 5 respectively. It is assumed that the air temperature is -5°C and there is no wind. In these figures, L, TR and TO represent Longitudinal bending, TRansverse bending and TOrsion, respectively. Indices 1 and 2 correspond to unbalanced loading of three spans before and after the studied tower respectively.

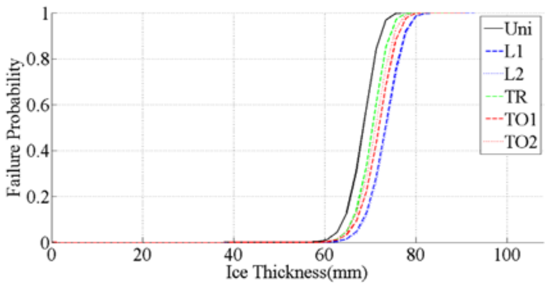

Figure 6:Fragility curves for tension tower 3 under different scenarios of ice loading with no wind

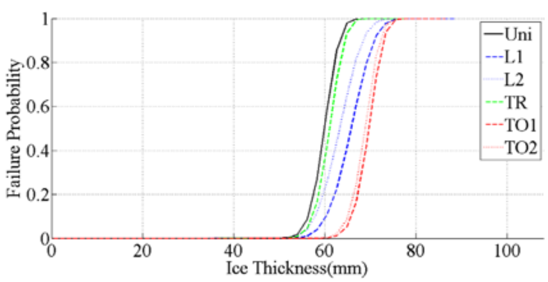

Figure 7:Fragility curves for suspension tower 5 under different scenarios of ice loading with no wind

It is inferred from Figures 6 and 7 that suspension tower 5 is more vulnerable than tension tower 3 for all loading scenarios. This is due to the fact that current design procedures tend to design suspension towers as the weakest link in the transmission line systems. Figure 6 also indicates that when no wind is blowing the governing ice load scenario for angle towers is the one that puts the tower under the highest amount of ice loads. In addition, Figure 7 shows that unbalanced loading of case 2 (ice shedding from 3 spans after the studied tower) results in higher failure probabilities compared to case 1 (ice shedding from 3 spans before the studied tower). This is due to the fact that the effect of unbalanced loads applied on the spans after the tower can be reduced by the longitudinal displacement of several suspension insulators. However, this is not the case when loading the spans near an angle tower where the insulators are in series with the conductor.

5.2. The effect of wind velocity and direction

Ice accretion has two effects on the transmission line. It imposes additional vertical loads on the structural system and intensifies the applied wind loads by increasing the projected area of the structural elements exposed to the wind.

The amount of ice accretion is dependent on the amount of wind-blown raindrops and can vary significantly depending on the wind speed and direction. Since there is little data available on equivalent uniform ice thickness from natural ice accretion on transmission lines, many researchers have developed mathematical models to simulate the ice built up from available meteorological information (Jones 1996, 1998, Jones et. al, 2002, Chaine and Castonguay, 1974, MRI, 1977). In this paper, in order to study the effect of wind speed and direction on ice accumulation, the Simple model proposed by Jones (1998) is used. This model is described by available meteorological data as indicated in equation 5.

$$R_{eq} = \sum_{j=1}^{N} \frac{1}{\rho_i \pi} \{(P_j \rho_0)^2 + (3.6 V_j \omega_j \sin[\theta - \emptyset])^2\}^{1/2} \quad (5)$$

where P_j , ρ_0 , ρ_i , θ and $\emptyset$ are the precipitation rate (mm in the jth hour), the density of water (1 gr/cm^3), the density of glaze ice (0.9 gr/cm^3), the wire direction and the wind direction, respectively. V_j is the wind speed (m/s) and $\omega_j = 0.067 P_j^{0.846}$ (Best, 1949) is the liquid water content (gr/m^3) of the rain-filled air in the jth hour.

In order to illustrate the effect of wind direction on the vulnerability of towers, fragility curves are developed for two wind angles of 0 and 90 degrees with respect to the main direction as indicated in Figure 1. Figure 8 presents the fragility curves for suspension tower 5 when 20 m/s wind is blowing at 90 degrees. It is noted that for the same tower, fragility curves for all loading scenarios are equal to zero when wind angle is 0 degrees. This is due to the fact that based on the simple model for a 20 m/s wind speed the amount of ice built up on line section 2 when wind angle is 0 degrees can be as much as 70% less than the amount of ice built up when wind angle is 90 degrees. In addition, at 0 degrees no wind load is imposed on line section 2.

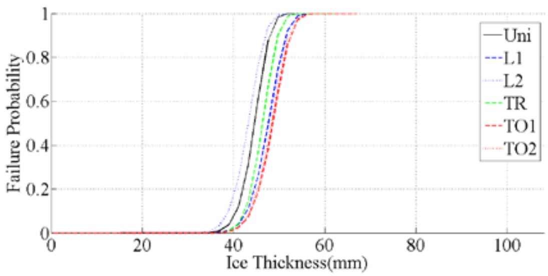

Figure 8: Fragility curves for suspension tower 5 under different scenarios of ice loading with 20 m/s of wind blowing at 90 degrees

Figure 9 and Figure 10 present the fragility curves for tension tower 3 when the wind angle is 0 and 90 degrees, respectively. They highlight the effect of wind direction on the importance of different loading scenarios. For example, it is inferred that due to the location of ice shedding, L2 is more critical than L1 and TO2 is more critical than TO1 when wind angle is 0 degree, while L1 is more critical than L2 and TO1 is more critical than TO2 when the wind angle is 90 degrees. This is due to the fact that when the wind angle is 0 degree with respect to the main direction of the line, low amounts of ice accumulate on the spans after the studied tower which are parallel to the wind direction and ice shedding from these spans does not affect the fragility curves significantly. However, this is not the case when the spans before the tower that are perpendicular to the wind direction shed their ice (L1 is the least critical scenario). The same concept applies for the case where wind angle is 90 degrees with respect to the main direction of the line.

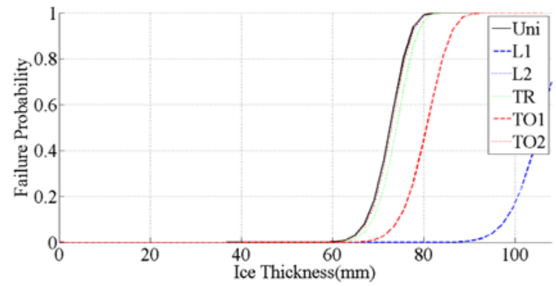

Figure 9: Fragility curves for tension tower 3 under different scenarios of ice loading with 20 m/s of wind blowing at 0 degrees

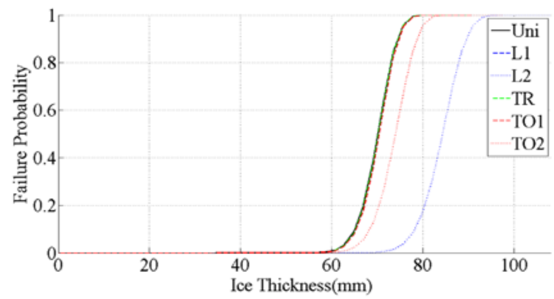

Figure 10: Fragility curves for tension tower 3 under different scenarios of ice loading with 20 m/s of wind blowing at 90 degrees

5.3. The effect of icing rate

Current design guidelines propose different icing rates when considering unbalanced ice loading scenarios. The icing rate suggested by CAN/CSA-C22.3 (2006) is 70% and 28% of the reference design ice load on two adjacent spans. In this study, fragility curves are developed for different icing rates of 100/10, 100/30, 100/50 and 70/28 on adjacent spans. Figure 11 shows the effect of ice rating on fragility curves of suspension tower 5 for L2 which is the most critical unbalanced loading scenario in the presence of wind. These fragility curves correspond to a 20 m/s wind with an angle of 90 degrees.

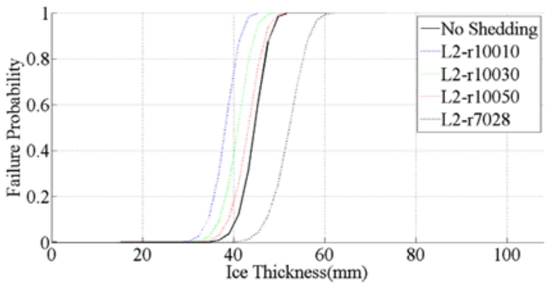

Figure 11:the effect of ice rating on fragility curves of suspension tower 5 for loading scenario L1

It is indicated that tower 5 becomes more vulnerable under L2 loading scenario as the difference between the applied ice loads on adjacent spans increases. It is also inferred that the icing rate of 70/28 proposed by CAN/CSA-C22.3 is not necessarily the most critical icing rate and caution should be exercised when designing transmission towers for unbalanced ice loads.

6. CONCLUSIONS

This paper presents a probabilistic framework based on the concepts of SLT to develop fragility curves for suspension and tension transmission towers under various unbalanced icing scenarios.

The results indicate that SLT selects a model that has good prediction properties and can be used for developing fragility curves. In addition, the effect of wind speed and direction, icing rate and location of ice formation is investigated on the developed fragility curves. A summary of the highlights of this study is presented in the following.

- Suspension towers are more vulnerable than tension towers for all loading scenarios.
- For most cases, longitudinal loads are more critical than other unbalanced loading scenarios.
- Ice shedding from the spans far from a tension tower will result in higher failure probabilities for nearby towers due to lower available movement freedom of conductor attachment points with tension towers.
- Wind speed and direction significantly affect both wind and ice loads applied to transmission lines and consequently fragility curves can change remarkably based on these parameters.
- Icing rate notably influences the unbalanced fragility curves of towers. In addition, the results indicate that the icing rate of 70/28 proposed by CAN/CSA-C22.3 is not necessarily the most critical icing rate. This signifies the necessity of further studies on determining the appropriate design point based on available climatic data of the structure location.

The results from this paper can further be used to develop fragility curves for transmission lines as a system.

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