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Consideration of Wind Direction on the Reliability of Transmission Tower Systems

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Abstract: The application of probabilistic methods and reliability theory to the design and analysis of electric transmission lines has gained recognition among the professionals as it offers a methodology to systematically study the probability of non-performance of these complex structural systems considering the uncertainty associated with all the variables involved in the definition of limit states. Operational experience with transmission lines highlights climatic hazards as one of the principal causes of overhead tower failures. The inherent randomness of climatic variables such as wind direction and speed and of the structural capacities of components has a major effect on the failure probability of transmission towers. The objective of this paper is to develop a reliability model using response surface method to assess the structural reliability of typical overhead towers, considering the randomness of these climatic variables and of the resistance of structural elements. The Response surface method is applied to implicitly determine the limit state function for each component of the tower through repeated structural analysis of the overhead tower under various combinations of climatic events. Therefore, a Visual Basic code is developed to prepare a three dimensional model of a two span transmission line section in the structural analysis software SAP2000. As the approximate limit state function is determined, Monte Carlo simulation can be used efficiently to assess the component and system reliability of the overhead tower since the evaluation of the response surface function requires very little computational effort.

1 Introduction

Conducting studies on the reliability evaluation of transmission lines has become increasingly important due to the strategic and enormous importance of electric transmission networks. During the last decades many organizations such as IEC(International Electrical Commission), IEEE, ASCE and CIGRE adopted the reliability/probability based design concepts to the transmission lines design. The movement resulted in the development of many reliability based guidelines such as the North-American Standard ASCE 74 (2010) , the European Standard EN 50341 (2001), CEI/IEC 60826 (2003) and CAN/CSA-C22.3 (2006). Although the main objective of these standards is to provide a framework for the design of new lines, they introduce many probabilistic concepts which can be used to perform the reliability analysis of existing overhead lines.

Structural systems reliability analysis is concerned with the assessment of structural safety in terms of probability since the analysis of engineering components or systems requires consideration of the uncertainties associated with all the variables intervening in the performance criteria or definition of limit states. One of the main probabilistic aspects that should be considered in studying the behaviour of transmission lines is the randomness associated with the climatic loads. Foschi (2004) applied reliability concepts to calculate the reliability of Lattice transmission towers and wood poles assuming a linear structural behaviour under wind and ice loads. Li et al (2006) calculated the reliability of wood poles at 15 locations across Canada based on linear and non-linear analysis and actual climatic data of the region. Haldar (2006) estimated the system reliability of a transmission line considering the variability of ice thickness and of the capacity of components.

Unfortunately, not much attention is given to reliability assessment of electric overhead towers considering the randomness associated with wind direction, and current design procedures are based on established wind speed maps which do not consider the randomness of this variable. It should be noted that using the wind data from all directions as being perpendicular to the line results in conservative estimates of tower systems reliabilities.

The objective of this paper is to develop a reliability model using response surface method to assess the structural reliability of typical overhead towers, considering the randomness of climatic variables such as wind direction and speed and of the resistance of structural elements. Such reliability models are essential to develop simplified reliability procedures that can be used in early stages of design, and to assess upgrading strategies to increase line capacity. The model is used to calculate the failure probability of a typical suspension lattice steel tower in a two span line section. Figure 1 shows the studied two-span line section comprised of one BBA tangent tower bounded by two BBM dead-end towers.

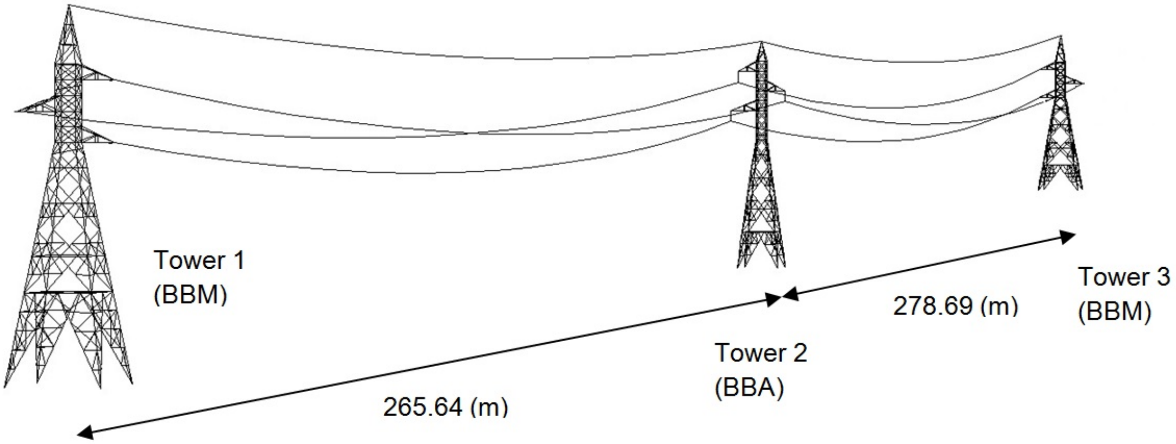


Figure 1: The studied two-span line section

2 Reliability Assessment

2.1 Basic Reliability Concepts

The reliability of an electric transmission tower is the probability that it will perform as required in the given conditions within the specified period of time. In general, the performance of an engineering structure can be described by a performance or limit state function, G(x) which is normally a function of several random variables such as the component capacities, wind speed and wind direction and can be written as Equation 1.

[1] $\mathrm{G}(\mathrm{x}) = \mathrm{G}(\mathrm{x}_1, \mathrm{x}_2, \cdots, \mathrm{x}_\mathrm{n})$

Where x_1, x_2, ...,x_n are the random variables. Some of these may affect the applied loads denoted by D, while the others may influence the load carrying capacity, denoted by C. The performance function can be rewritten as Equation 2.

[2] $\mathrm{G}(\mathrm{x}) = \mathrm{C}(\mathrm{x}_\mathrm{c}) - \mathrm{D}(\mathrm{x}_\mathrm{d})$

Where x_c include all those random variables related to the capacity and x_d include all those random variables related to the demand. Non-performance correspond to combinations such that D > C or G < 0, Thus, estimating the probability of non-performance is equivalent to estimating the probability of the event G < 0. Conversely, the combination of the random variables resulting in G > 0 will make the system perform as required, i.e. it will survive and the corresponding probability (P(G(x) > 0)) is termed reliability. The situation G = 0 is a limit state between failure and survival.

2.2 Performance Functions

To calculate the performance function, a computational model describing the problem of interest is required. It is noted that in this study the limit state function is not known explicitly due to the complexity of the structure and structural response of components. In order to define the limit state function implicitly, a point-by-point discovery procedure is applied through repeated structural analysis of the line under different climatic loads using the software SAP2000. Further, the Response Surface method is applied to fit a differentiable performance function such as a polynomial to the demands obtained for each component from a limited number of discrete structural analysis of the line.(Melchers, R.E., 1999). Table 1 shows the range of wind speeds and wind angles with respect to the line direction which are used for the full factorial design of weather combinations. It is assumed that no ice exists during these weather conditions and the corresponding temperature is equal to -10 °C.

Table 1: The corresponding values of climatic variables to develop a full factorial design of climatic combinations under which the line section is analysed by SAP2000

Climatic Variable	Wind Speed (m/s)	Wind angle (Degree)
Start Value	0	0
End Value	50	360
Step	5	30

A stepwise regression analysis is performed on the results obtained from SAP2000 for each component of the overhead tower. During the analysis the contribution of each regressor variable is investigated to determine which regressor variables should be included in the model. The developed response function which is a function of wind speed and wind angle with respect to the line direction can substitute $D(x_d)$ in Equation 2 and provide the limit state function for each component of the tower. As the approximate limit state function is determined, Monte Carlo simulation can be used efficiently to assess the component and system failure probability of the overhead tower since the evaluation of the response surface function requires very little computational effort.

2.3 Weather Statistics

The wind speed statistical parameters used in the reliability analysis were determined by assuming that the average 10 minute wind speed without ice with a 50 year return period is 30.92 (m/s). Using the coefficients proposed by CSA to derive the corresponding values of climatic variables for 25, 100, 150, 200, 400, and 500 years and performing a regression analysis the mean value and standard deviation of the annual extreme wind speed are calculated and equal to 22.35 (m/sec) and 2.86 (m/sec) respectively. It is assumed that wind speed and wind angle variables have Gumbel and Uniform distributions respectively. Figure 2 indicates the histograms of the simulated wind speeds and wind angles using Monte Carlo simulation.

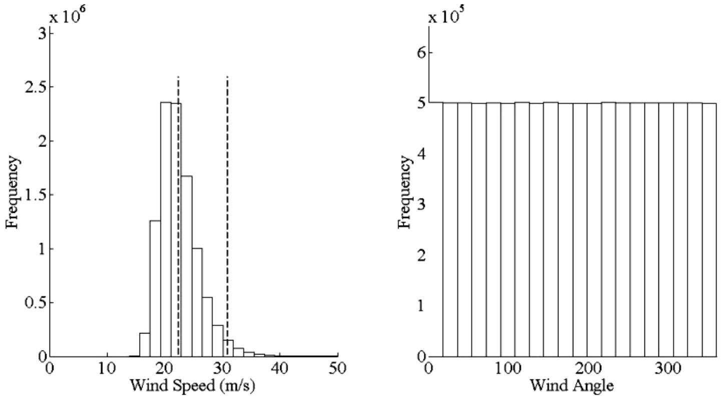


Figure 2: Histograms of simulated climatic variables

2.4 Simulation of Component Demands and Capacities

Component demands are simulated by randomly sampling from the distributions for the climatic variables and substituting into the developed response function for each component of the tower. Component capacities are calculated based on ASCE10-97 (2003). The capacity of tension members is equal to the minimum of the bearing capacity of the connection, the shear capacity of the bolts and the tension capacity of the member, and the capacity of the compression members is equal to the minimum of the bearing capacity of the connection, the shear capacity of the bolts and the compression capacity of the member. In addition, a lognormal distribution is considered for structural component capacities with a Coefficient of Variation of 10%. The histogram of the simulated capacity and the histogram of demands for the critical component (Component 124 - Group: SF) is shown in Figure 3.

2.5 Calculation of Component Failure Probabilities

In Monte Carlo simulation, the number of failures is determined by counting the number of events for which the demand exceeds the capacity. The probability of failure of each component is equal to the ratio of the number of the failure events to the total number of simulated events. The result changes with the chosen number of simulations, and converges to the exact probability with the greater number of simulations. In this study due to the small value of the failure probability of components 10^7 events are simulated for the failure probability calculations. The probability of failure of the most critical components of the mid-span tower and their location are provided in Table 2 and Figure 4 respectively.

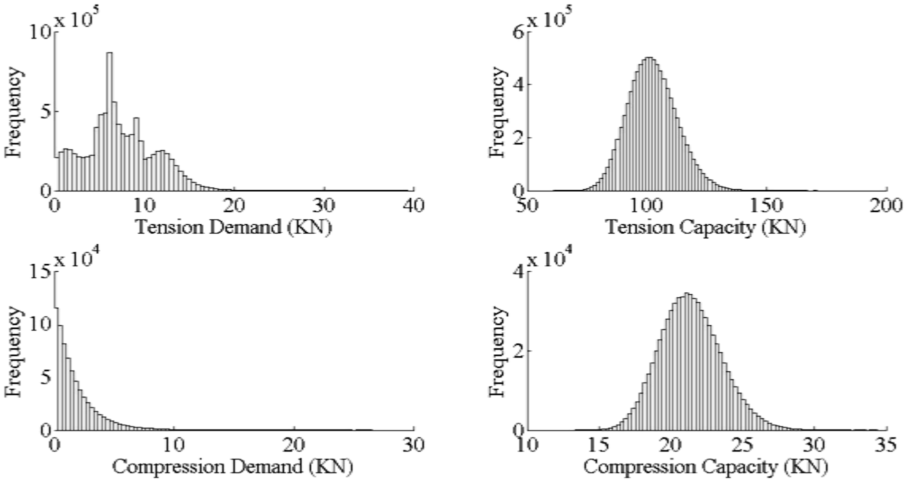


Figure 3: Histograms of simulated demands and capacities in component 124 Group: SF

Table 2: Probability of failure of the most critical components of the mid-span tower

Component	Group	Probability of Failure (1E-5)
124	SF	0.79
126	SF	0.74
207	PMBA	0.06
204	PMBA	0.06
206	PMBA	0.02
114	SBD	0.01

2.6 Calculation of System Failure Probability

A climatic event resulting in failure of at least one component in the structure is assumed to correspond to failure of the structure (i.e. a weakest link model). This assumption is conservative and assumes that the truss is statistically determinate. The failure probability for the structure is equal to the ratio of the number of failure events, which are the combinations of climatic variables that result in failure of at least one member of the overhead tower, to the sample size which is 10^7 in this study. The estimated failure probability for the structure is equal to 1.15E-5.

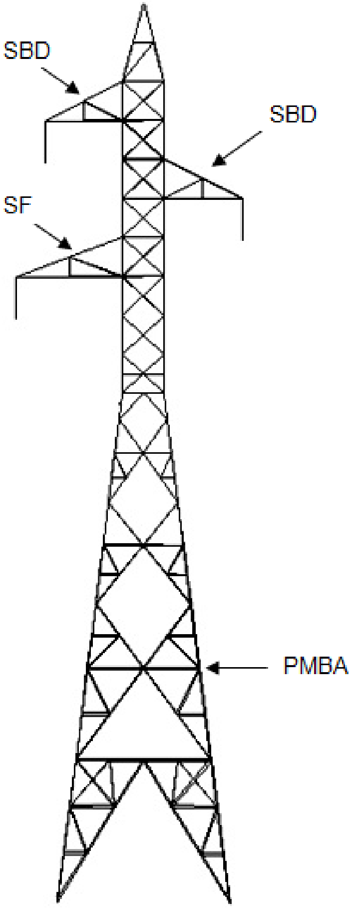


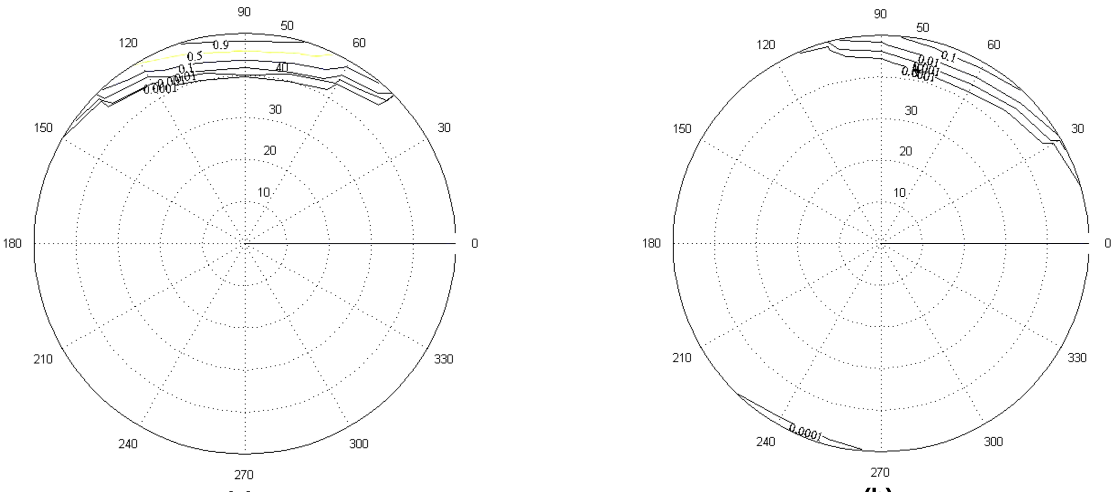
Figure 4: Location of the most critical components in Tower BBA

2.7 Developing Fragility Curves and Determining the Design Point

A component fragility curve is the conditional probability of failure of the component given a specific climatic condition and is obtained from Equation 3. Wind direction and speed are considered as Intensity Measures (IM) to develop fragility curves.

$$[3] \quad \mathrm{P(Failure \mid IM) = P(Failure \cap IM)/P(IM)}$$

In order to develop the fragility curves, probability of failure is calculated at a set of given IM values. Each given value of IM results in a deterministic demand value which is compared with the distribution of component capacity to get the conditional probabilities of failure. The developed fragility curves for the two most critical component groups of the mid-span tower (Component 124- Group: SF and Component 207-Group: PMBA) are shown in Figure 5. It is inferred that the critical wind angle which results in the highest probability of failure may differ for different members of the tower based on their orientation, and the assumption of wind always blowing perpendicular to the line may result in inaccurate failure probabilities.

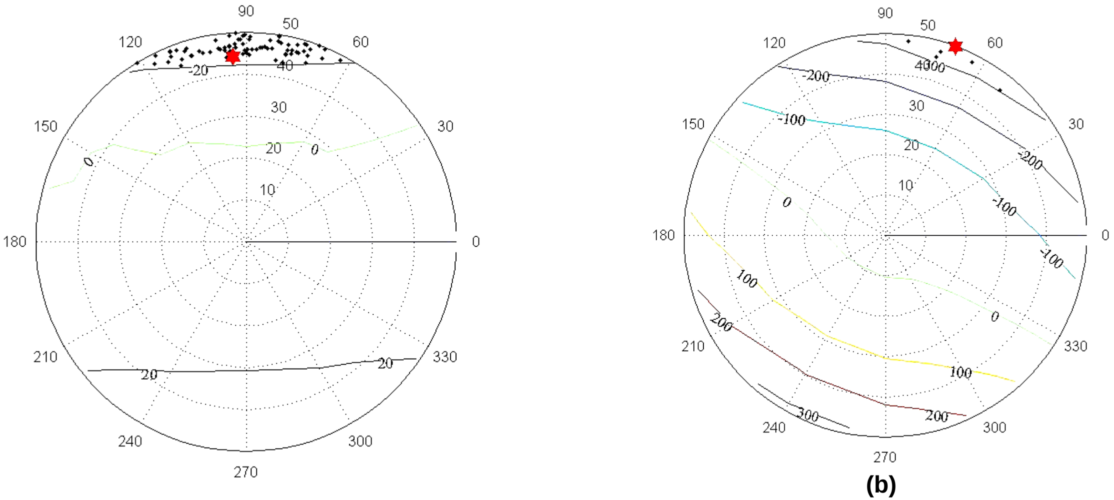


(a) (b)

Figure 5: Fragility curve for (a) Component 124- Group: SF and (b) Component 207- Group: PMBA as a function of the wind speed and wind angle

Figure 6 indicates the climatic combinations that result in failure in the two most critical component groups of the mid-span tower (Component 124- Group: SF and Component 207-Group: PMBA) and their corresponding load levels. In this figure the red dot represents the design point which is the combination of wind speed and wind angle that results in the failure of the component and has the highest likelihood. In order to obtain the design point, all the combinations of climatic variables that result in the failure of the studied component are investigated to determine which has the highest value of the joint probability density function of wind speed, wind angle and capacity. Assuming that all these variables are independent, the joint probability density function can be calculated from equation 4.

[4] $$f_{W_sW_aR}(w_s, w_a, r) = f_{W_s}(w_s).f_{W_a}(w_a).f_R(r)$$



(a) (b)

Figure 6: The climatic combinations that result in failure of (a) Component 124- Group: SF and (b) Component 207- Group: PMBA (black dots) and their corresponding load levels and the design point (red star)

3 Conclusions and Future Works

This study has developed a reliability model using response surface method to assess the structural reliability of typical overhead towers, considering the randomness of climatic variables such as wind direction and speed and of the resistance of structural elements. The limit state function for each component of the tower is determined by fitting a polynomial function to the component demands obtained from repeated structural analysis of the overhead tower under various combinations of climatic events using SAP2000. As the approximate limit state function is determined, Monte Carlo simulation is applied to assess the component and system failure probability of the overhead tower since the evaluation of the response surface function requires very little computational effort. The design point and the fragility curve is provided for the most critical component of the studied tower. It is inferred that the critical wind angle which results in the highest probability of failure may differ for different members of the tower based on their orientation, and the assumption of wind always blowing perpendicular to the line may result in inaccurate failure probabilities.

The forthcoming reliability analysis of the overhead lattice towers considering other climatic variables such as ice thickness and temperature as well as wind speed and angle will provide a better understanding of the transmission towers reliability under different climatic events.

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