Analysis of the effect of climate change on the reliability of overhead transmission lines

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Abstract

Climate change is anticipated to have an impact on the operation of overhead transmission and distribution lines through impacts of extreme weather events. The changes in the frequency and intensity of wind and ice storms may have a considerable effect on the applied loads and can consequently change the probability of structural failure of different components of the line. This study examines the reliability of transmission lines under a range of assumed changes in the mean and standard deviation of climatic variables affecting transmission lines such as wind speed and ice thickness. This sensitivity study provides useful information required to improve the capacity of transmission lines and mitigate the long-term risks from the effects of a changing climate.

Keywords: Structural reliability analysis, Transmission lines, climate change

Résumé

Les changements climatiques ont un impact potentiel sur la performance du réseau de transport d'électricité si ceux-ci impliquent une augmentation des événements climatiques extrêmes. Les effets climatiques peuvent affecter la fréquence des événements ainsi que la distribution conjointe de leurs effets (e.g. vent et verglas) et affecter la fiabilité du réseau. Un modèle détaillé d'une ligne existante est développé afin d'analyser la robustesse du réseau en fonction d'une changement de la moyenne et de l'écart-type des distributions pour les vents et les accumulation extrêmes de verglas pour différents scénarios de changements climatiques. Ces résultats sont utiles afin d'évaluer les meilleures stratégies de renforcement du réseau en anticipation des impacts reliés aux changements climatiques.

Mots clés : Analyse de fiabilité des structures, lignes de transport, changements climatiques.

1. Introduction

Decisions relating to the design, maintenance, replacement or updating of transmission line systems come with a long-term commitment. Although these decisions and the associated investments need to consider future climate conditions, current transmission line guidelines and standards are developed on the basis of historical climate data and do not take into account a probable change in the frequency and intensity of climatic hazards [1,2,3,4]. In order to respond to climate change, it is required to determine the impacts of various climate change scenarios on the reliability of these complex structural systems. The results of such study can be used to improve the robustness of transmission lines and mitigate the long-term risks from the effects of a changing climate. This is particularly important considering that many researchers project more intense and more frequent climatic hazards in the future [5,6,7,8,9,10] while previous events have shown that extreme weather events can cause severe damages to the transmission line network [11,12,13].

Although many studies explain the impacts of climate change on different infrastructures and energy sectors qualitatively [5,14,15,16,17], only a few studies are available which attempt to make quantitative assessments of the effects of climate change on the reliability of structures, specially transmission or distribution lines [18,19].

In order to perform a comprehensive risk analysis and provide a quantitative assessment of climate change impacts on transmission lines, the following steps need to be completed.

(1) Identify the primary adverse climate impacts which are considered to be critical for transmission lines.

(2) Considering the results of step (1), determine the corresponding random climate variables that need to be projected at the local scale from available Global Climate Models (GCMs).

(3) Identify the types of consequences that the considered climatic hazards can impose on the studied structural system.

The main objective of this study is to quantify the impact of future changes in the frequency and intensity of climatic hazards such as wind and ice storms on the structural reliability of transmission line systems using the concepts of statistical learning theory (SLT). It should be noted that this study does not attempt to project the potential changes in the probability distribution functions of wind speed and ice built-up at a specific location from available climate change scenarios, however it performs a sensitivity analysis by examining the reliability of transmission lines under a range of assumed changes in the mean and standard deviation of extreme wind speeds and ice thicknesses. The sensitivity analysis conducted at this stage helps to gain insight about future reliability of transmission lines due to possible frequency and intensity changes of severe climatic hazards. Such information could be incorporated into policies, climate adaption strategies and disaster-risk-reduction measures.

2. Effect of climate change on climatic variables that affect transmission lines

Our previous experience with electric transmission lines has indicated that one of the primary reasons of structural failure in transmission lines is extreme wind and ice storms. Currently available data suggest that the intensity and frequency of hurricanes and ice storms will increase in a future with increasing temperatures.

Cheng et al [9,10] developed a wind gust simulation model in order to project the changes in the frequency of future wind gust events in different regions of Canada. They downscaled eight GCM simulations and predicted that the frequency of wind gust events could increase late this century over Canada. The results also showed greater projected percentage increase in the frequency of more severe wind gust events. For example, the authors reported an increase of less than 10% in the frequency of future daily wind gust events greater than 28 km/hr over the periods 2046-2065 and 2081-2100, while the increase in the frequency of daily wind gust events greater than 70 km/hr and 90 km/hr are projected to be 10%-20% and 20%-40%, respectively. Knutson and Tuleya [20] demonstrated that a 2.2°C increase in sea surface temperature results in a surface wind speed increase of about 5%-11%.

In two separate studies [7,8], Cheng et al investigated possible impacts of climate change on future freezing rain events for eastern and southern-central parts of Canada. These studies focused on projections of changes in frequency and intensity of future daily freezing rain events in terms of daily duration of the each event. The results indicated that eastern Canada could experience more freezing rain events towards the end of the century (2081-2100) especially during the coldest months (December-February) with respect to the average historical conditions (1958-2007), while less freezing rain events are expected during the warmer months. General circulating models predict that at locations north of 30 degrees North, winter storms will become more frequent and severe if the amount of environmental CO_2 doubles [21].

3. Possible effects of climate change on transmission lines

The changes in the frequency and severity of extreme weather events are anticipated to have an impact on the reliability of transmission lines. Increasing intensity of storm events increases the risk of structural damage to electric transmission and distribution lines.

Heavy snowfalls or freezing rain events can cause failure in different components of a line and consequently trigger a cascading failure incident. In addition, concurrent winds during or after winter storms can increase the failure probability of ice covered structural components.

It is noted that this study does not consider failure scenarios caused by dynamic effects of wind such as galloping or vibration in the reliability analysis. Determining the contribution of these failure scenarios to the overall failure probability of components and their sensitivity to climate change can be the subject of future studies.

4. Description of the studied transmission line section

As indicated in Figure 1, a nine-span transmission line consisting of two sections separated by tension towers is modelled in Sap2000®. Figure 2 presents the configuration of various tower types within the line and Table 1 provides a description of the towers within the line segment. The modelled structures are analyzed for various combinations of wind speed, wind direction and ice thickness. The results obtained at this level are further used to train a demand function for each component as explained in section 5.

The model takes into account the effect of structural flexibility, the geometric nonlinearity and the variability of structural capacity of each transmission line component in calculating component and system failure probabilities. The model also considers the effects of wind direction and exposure on ice accumulation. It is noted that 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 effect 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 [3]. This study applies the Simple model proposed by Jones [22] to determine the amount of ice accumulation from available meteorological data as indicated in equation 1.

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

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/cm3), the density of glaze ice (0.9 gr/cm3), the wire direction and the wind direction, respectively. V_j is the wind speed (m/s) and ω_j=0.067$P_j^{0.846}$ [23] is the liquid water content (gr/m3) of the rain-filled air in the jth hour.

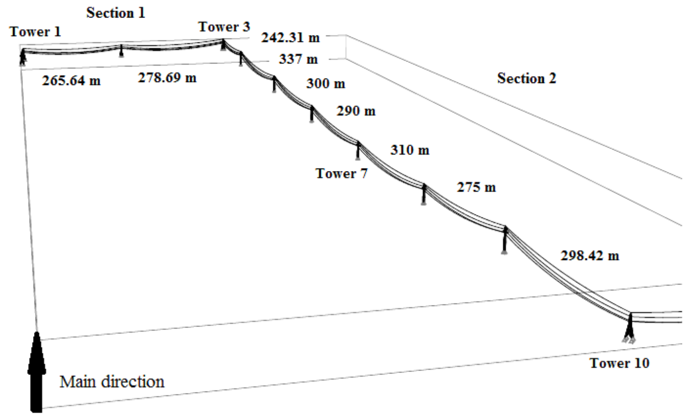

Figure 1. Nine span segment of the transmission line under study.

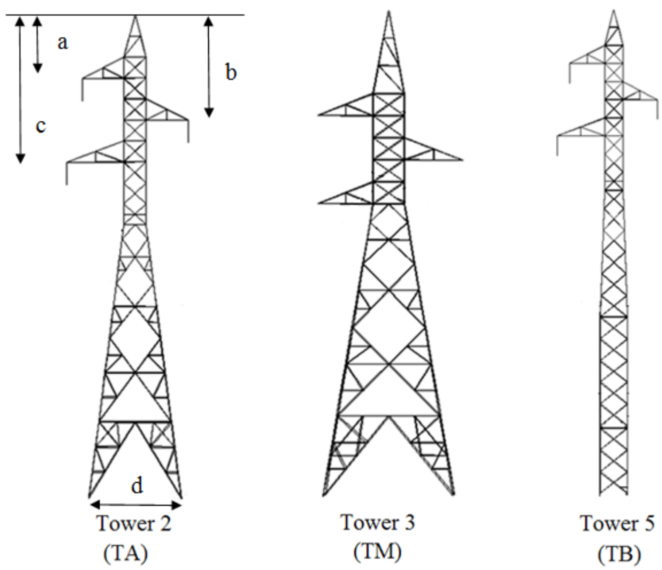

Figure 2. The configuration of tower types within the line.

Table 1. Description of towers within the studied line segment.

Tower Number	*Tower Height (m)*	*a (m)*	*b (m)*	*c (m)*	*d (m)*	*Tower Type*
1	*30.5*	*6*	*8.5*	*11*	*8.06*	*TM*
2	*28.75*	*3.75*	*6.25*	*8.75*	*5.26*	*TA*
3	*27.5*	*6*	*8.5*	*11*	*7.08*	*TM*
4	*33.25*	*3.75*	*6.25*	*8.75*	*1.9*	*TB*
5	*33.25*	*3.75*	*6.25*	*8.75*	*1.9*	*TB*
6	*30.25*	*3.75*	*6.25*	*8.75*	*1.9*	*TB*
7	*30.25*	*3.75*	*6.25*	*8.75*	*1.9*	*TB*
8	*28.75*	*3.75*	*6.25*	*8.75*	*1.9*	*TB*
9	*33.25*	*3.75*	*6.25*	*8.75*	*1.9*	*TB*
10	*27.5*	*6*	*8.5*	*11*	*7.08*	*TM*

5. Methodology used for reliability assessment of transmission lines

5.1 Defining and validating the limit state function for each component based on the concepts of Statistical Learning Theory (SLT)

One challenge in determining the reliability of complex structural systems such as transmission lines is the implicit nature of the limit state function for each structural component or for the whole system. The general form of a limit state function is indicated in equation 2.

$$G(\mathbf{x}) = C(\mathbf{x_c}) - D(\mathbf{x_d}) \tag{2}$$

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.

It is noted that the implicit nature of the limit state function limits the application of the gradient based reliability analysis methods [24,25] which require to estimate the gradient of the performance function, and the simulation based methods [26,27] due to the vast computational effort needed for repeated calls on the finite element solver of the structure. Many researchers have traditionally used the Response Surface Method (RSM) to explicitly define the unknown limit state function [28,29]. Since RSM is based on the Empirical Risk Minimization (ERM) principle and can result in over-fitting due to the rigid and non-adaptive nature of the selected model [30,31], this paper adopts the concepts of SLT to substitute D(**xd**) with a surrogate model that has good generalization (prediction) properties. This surrogate model allows to replace the finite element solver of the model and reduces the time and computational effort required to perform a Monte Carlo simulation. SLT is based on the Structural Risk Minimization (SRM) inductive principle and unlike ERM based methods, it does not impose strict assumptions over the class of approximating functions. Therefore, it can prevent the high bias produced by the discrepancy between the assumed function and the actual governing function.

In a study presented by Cherkassky and Mulier [32], 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 3 [33,34].

$$R(\omega) = R_{emp}(\omega).\left(1 - \sqrt{p - p\ln p + \frac{\ln n}{2n}}\right)_+^{-1} \tag{3}$$

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 labellings 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, for each structural element, the best model which has the lowest prediction error is selected from the class of polynomial functions. To achieve this goal, 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.

In order to estimate the final unbiased prediction error of the selected model, a 10-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 ($\bar{R}^2{}_p$) using equations 4 and 5. A good model will have $\bar{R}^2$and $\bar{R}^2{}_p$ values near 1.

$$\bar{R}^2 = 1 - \frac{MSE}{MST} = 1 - \left(\frac{n-1}{n-p}\right)(1 - R^2) \tag{4}$$

$$R_p^2 = 1 - \frac{\sum_{i=1}^{n_{te}} (y_{ite} - \hat{y}_{itr})^2}{\sum_{i=1}^{n_{te}} (y_{ite} - \bar{y}_{te})^2} \tag{5}$$

In equation 4, 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 5 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.

Figures 3 presents the calculated $\bar{R}^2$and $\bar{R}^2{}_p$ respectively for all members of suspension tower 2. The adjusted coefficient of multiple determination expresses the quality of the 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 and validate its application in determining the failure probability of components.

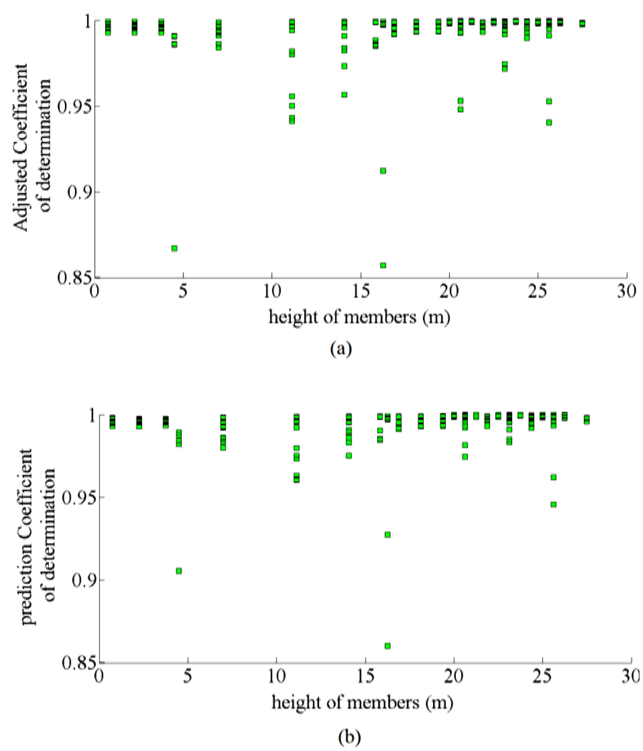

Figure 3. (a) Adjusted coefficient of determination and (b) Prediction coefficient of determination for all members of tower 2

5.2 Determining the component and system failure probabilities for current climatic conditions

After determining the performance function for each structural component of the transmission line, structural demands are simulated by randomly sampling from the distributions for the climatic variables and substituting into the selected response function for that component. The annual extreme ice thickness is assumed to have a Gumbel distribution with a mean and standard deviation of 32.2 (mm) and 4.1 (mm), respectively. And the annual extreme concurrent wind speed is assumed to have a Gumbel distribution with a mean and standard deviation of 15.64 (m/sec) and 2 (m/sec), respectively [2]. The likelihood of wind blowing from different directions is assumed to be equal. Since the effect of temperature on the failure probability of tower elements is small and failure due to excessive sag of conductors is not considered in this study, temperature is assumed to be deterministic and equal to -5 °C. Figure 4 indicates the histograms of the simulated current climatic variables of wind speeds, ice thicknesses and wind angles using Monte Carlo simulation for 10^8 events.

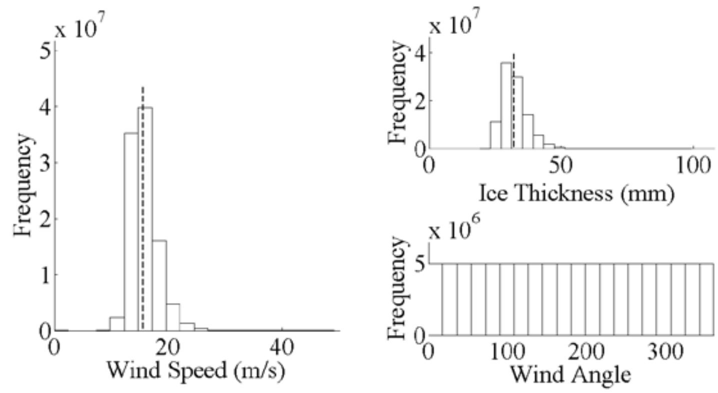

Figure 4. Histograms of simulated climatic variables

The capacity for each member of the overhead towers is calculated based on [35]. It is assumed that the capacity of overhead tower components have a lognormal distribution with a coefficient of variation of 10% [2].The nominal rated tensile strength of conductors and ground wires are 141.7 KN and 139 KN, respectively. They are assumed to have a lognormal distribution with a coefficient of variation of 3% [2]. Three groups of insulators with nominal capacities of 70, 140 and 240 KN are used in the studied line section. It is assumed that the capacity of insulators have a lognormal distribution with a coefficient of variation of 5% [2].

The failure probability of each component of the line is equal to the ratio of the number of events for which the structural demand exceeds the structural capacity to the total number of simulations. In order to calculate the failure probability of each tower and the whole line, they are represented as series systems. It should be noted that this assumption is conservative and implies that the tower/transmission line fails once any one of its structural components fails. The other assumption used in this study is that the correlation between failure events of different components is only due to the same climatic conditions and the capacity of members are independent. Also, it should be mentioned that the failure probability of foundations are not considered when estimating the system failure probability. Table 2 shows the estimated failure probabilities and the corresponding reliability indices for different components of the line and the system under current climatic conditions. The results indicate that suspension towers have higher failure probabilities/lower reliability indices compared to other components of the line.

This is due to the fact that current design procedures are based on a specific strength coordination in which the suspension towers are considered as the weakest link in the transmission line system [1].

Table 2. Failure probabilities and reliability indices of components and the system under current climate.

	Failure Probability	*Reliability Index*
Tower 1	5.70×10^{-5}	*3.86*
Tower 2	1.80×10^{-3}	*2.91*
Tower 3	1.40×10^{-5}	*4.19*
Tower 4	7.80×10^{-3}	*2.42*
Tower 5	8.60×10^{-3}	*2.38*
Tower 6	3.80×10^{-3}	*2.67*
Tower 7	3.50×10^{-3}	*2.70*
Tower 8	4.50×10^{-3}	*2.61*
Tower 9	4.80×10^{-3}	*2.59*
Tower 10	4.60×10^{-5}	*3.91*
Wire system	2.30×10^{-5}	*4.08*
Transmission line	1.45×10^{-2}	*2.18*

6. Impact of climate change on reliability of transmission lines

In this study, it is assumed that climate change will not change the distribution type of climatic variables and they will still follow the Gumbel distribution. In order to investigate the effect of climate change on the reliability of transmission lines and their components, a sensitivity analysis is performed by changing the mean and standard deviation of wind speed and ice thickness individually and simultaneously using 27 scenarios. Tables 3 and 4 present the percentage change in the reliability index of the studied transmission line system as the result of changing the distribution parameters of wind speed and ice thickness individually.

Table 3. Sensitivity of the transmission line system reliability index on wind speed

Scenario	*Parameter*	*% of change*	*% of change in the system reliability index*
1	μ_{wind}	*-5*	*6.54*
2		*10*	*-14.40*
3		*20*	*-30.37*
4	σ_{wind}	*-20*	*9.71*
5		*-10*	*4.89*
6		*10*	*-3.86*
7		*20*	*-7.58*

It is inferred from Table 3 that both mean value and standard deviation of the wind speed have significant influence on the reliability index of transmission line systems and a change of 20% in the mean value of the wind speed can reduce the reliability index of the system by more than 30%.

Table 4. Sensitivity of the transmission line system reliability index on ice thickness

Scenario	*Parameter*	*% of change*	*% of change in the system reliability index*
8	μ_{Ice}	*-20*	*15.32*
9		*-10*	*8.53*
10		*10*	*-8.45*
11		*20*	*-17.19*
12	σ_{Ice}	*-20*	*2.51*
13		*-10*	*1.42*
14		*10*	*-1.56*
15		*20*	*-2.80*

Comparing the results from Tables 3 and 4 demonstrates that ice thickness has less effect on the reliability of transmission line systems compared to the wind speed. However, this influence is still significant and a change of 20% in the mean value of ice thickness can reduce the reliability index of the system by more than 17%.

Table 5 presents the percentage change in the reliability index of the studied transmission line system as the result of changing the mean value of wind speed and ice thickness simultaneously.

Table 5. Sensitivity of the transmission line system reliability index on wind speed and ice thickness

		% of change in μ_{wind}			
		-5	*0*	*10*	*20*
% of change in μ_{Ice}	*-20*	*21.46*	*15.32*	*2.23*	*-12.48*
	-10	*15.32*	*8.53*	*-6.22*	*-21.47*
	0	*6.54*	*0*	*-14.40*	*-30.37*
	10	*-1.44*	*-8.45*	*-23.40*	*-39.76*
	20	*-10.39*	*-17.19*	*-32.55*	*-49.25*

It is inferred from Table 5 that a simultaneous change in the mean value of concurrent wind speed and ice thickness intensifies their effect on the reliability of transmission lines. This can be explained by the nonlinear nature of the applied wind loads on ice covered components. In other words, ice thickness amplifies the applied wind loads by increasing the projected area of the structural elements exposed to the wind. In addition, it imposes additional vertical loads on the components.

7. Conclusions

In this study, the sensitivity of the reliability of a typical transmission line system to climate change is investigated and it is shown that a change in the mean value or standard deviation of extreme wind and ice events can significantly alter the reliability index of existing transmission line systems. It is demonstrated that a 20% change in the mean value of wind speed and ice thickness can reduce the reliability index of the studied transmission line system by more than 30% and 17%, respectively. This effect is even more significant when the increase in wind speed and ice thickness is concurrent due to the applied wind loads on ice covered components. Hence, considering the increasing environmental CO_2, relying on the historic climatic data may not be sufficient to ensure an adequate reliability of transmission line systems in the future.

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