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

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ABSTRACT

Climate change is anticipated to influence the reliability of overhead transmission and distribution lines through impacts on extreme weather events. Changes in the frequency and intensity of wind and ice storms may have a considerable effect on applied loads and can consequently affect 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 annual extreme wind speed and ice thickness. The methodology used for the reliability analysis of transmission lines under current and future climatic conditions is based on the concepts of statistical learning theory. The sensitivity study provides the information required to improve the capacity of transmission lines and mitigate long-term risks from the effects of a changing climate. The results indicate that climate change as predicted by many researchers can significantly affect the reliability of existing transmission line systems. Hence, relying on the historic climatic data may not be sufficient to ensure an adequate reliability of transmission line systems in the future. The specification of design loads for the evaluation of existing lines or the design of new lines should consider both future climate models and historical climate data.

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 (ASCE, 2010; CAN/CSA-C22.3, 2006; CEI/IEC 60826, 2003; EN 50341-1, 2001). 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 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 predict more intense and more frequent climatic hazards in the future (Cheng, Auld, Li, Klaassen, & Li, 2007; Cheng, Guilong, & Heather, 2011; Cheng, Li, Li, Auld, & Fu, 2012; Cheng, Lopes, Fu, & Huang, 2014; Eichelberger, Mccaa, Nijssen, & Wood, 2008; Zamuda et al., 2013) while historical events have shown to cause severe damages to transmission line networks (Bigras et al., 1998; Le Du et al., 2002; Sundell et al., 2006).

Although many studies evaluate the impacts of climate change on different infrastructures and energy sectors qualitatively (Boyle, Cunningham, & Dekens, 2013; Kezunovic, Dobson, & Dong, 2008; Peters, DiGioia, Hendrickson, & Apt, 2006; Schaeffer et al., 2012; Zamuda et al., 2013), very few studies provide quantitative assessments of the effects of climate change on the reliability of structures, specially transmission or distribution lines (Bjarnadottir, Li, Stewart, & Fang, 2014; Madsen, 2014). These studies mainly focus on effects of climate change on the reliability of single structures or specific components of a transmission or distribution line. However, this paper presents the reliability index of an overall typical transmission line system as a function of future variations in extreme climatic conditions while considering the interaction and correlation of different components of the line. The results are presented in the form of design specifications as a function of a range of plausible climate change scenarios. The information presented in this paper is useful to develop new policies,

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climate adaptation strategies and risk mitigation measures that are cost-effective for a wide range of likely climate change scenarios.

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 that are most critical for transmission lines;
(2) Considering the results of step (1), determine the corresponding random climatic variables that need to be downscaled locally from available global climate models (GCMs);
(3) Identify the consequences of climatic hazards on the 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 the focus of this study is not the local prediction of changes in the probability distribution functions of wind speed and ice built-up at specific locations from global climate change scenarios but rather a parametric study on the effect of changes in the mean and variance of the maximum annual wind and ice accumulation on the reliability of transmission lines. In other words, this study does not address step (2), and the changes in reliability levels can be linked to specific or multiple climate change scenarios at a later stage. More information about step (1) is presented in Sections 2 and 3 of this study. And, Step (3) is elaborated in Section 6.

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

Previous experience with electric transmission lines shows that one of the primary causes of structural failure of transmission lines is extreme wind and ice storms. Currently available data suggest that the intensity and frequency of extreme climatic events such as hurricanes and ice storms in various locations could increase in the future with increasing global temperatures.

A recent review by the Intergovernmental Panel on Climate Change (IPCC) (Field, 2012), presents many studies in which decreasing or increasing historical and future trends in mean or extreme wind speed are reported for various locations around the globe. This report also states that future trends in mean and extreme wind speed are difficult to predict with the currently available data and models. Cheng et al. (2012, 2014) develop a wind gust simulation model to analyze changes in the frequency of future wind gusts for different regions in Canada. The analyses are performed by downscaling data from eight GCM simulations and predict that the frequency of wind gust events could increase in the latter part of this century across Canada. The results also show a greater increase in the frequency of more severe wind gust events. For example, the authors report an increase of less than 10% in the frequency of future daily wind gust events greater than 28 km/h over the periods 2046–2065 and 2081–2100, while the increase in the frequency of daily wind gust events greater than 70 and 90 km/h are projected to be 10–20% and 20–40%, respectively. Knutson and Tuleya (1999) demonstrate that a 2.2 °C increase in sea surface temperature results in a surface wind speed increase of about 5–11% based on the analyses performed on 51 northwest Pacific storm cases.

Cheng et al. (2007, 2011) investigate impacts of climate change on future freezing rain events for eastern and southern-central parts of Canada. The results are expressed in terms of the frequency of future daily freezing rain events. The results indicate that eastern Canada could experience more frequent freezing rain events towards the end of the century (2081–2100) especially during the coldest months (December–February) in comparison to the average historical frequency (1958–2007), while fewer events are expected during the warmer months (November, March, April). General circulating models also predict that for locations above 30 °N, extreme winter storms will become more frequent and severe if the amount of environmental CO_2 doubles (Lambert, 1995).

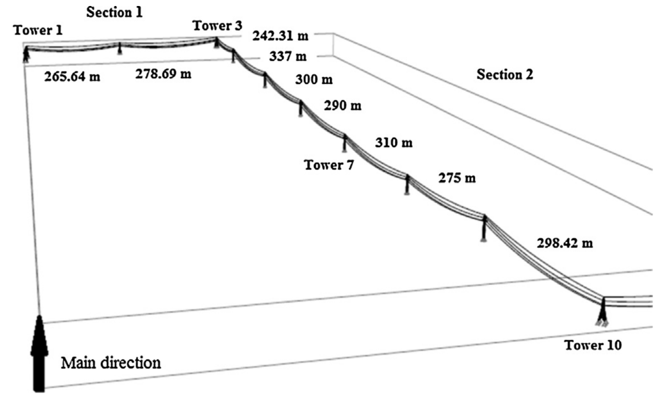

Fig. 1. Nine span segment of the transmission line under study.

3. Possible effects of climate change on transmission lines

The anticipated increase in the frequency and severity of extreme weather events are anticipated to have an impact on the reliability of transmission lines since they increase 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 which is the high-amplitude, low-frequency wind induced vibration of overhead conductors 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

The analysis is performed for a line segment that is representative of typical transmission lines with components, layout and spatial scale that are of interest for realistic reliability assessments. As indicated in Fig. 1, the nine-span segment of the studied 120 kV transmission line consists of two sections separated by tension towers and is modelled with Sap2000®. The diameter and weight per unit length of conductors are 27.78 mm and 15.26 N/m, respectively, and the diameter and weight per unit length of ground wires are 12.57 mm and 7.44 N/m, respectively. Fig. 2 presents the configurations of tower types for the line while Table 1 provides detailed information on the towers. It is noted that three families of towers are used in this line segment which include light suspension towers (LS), heavy suspension towers (HS) and angled towers (STR). In this study, ten towers are included in the system reliability analysis due to the limited spatial extension of climatic hazards. According to CEI/IEC 60826 (2003) and CAN/CSA-C22.3 (2006), in a flat to rolling terrain and based on a span of 400 m, 1–5 towers are usually

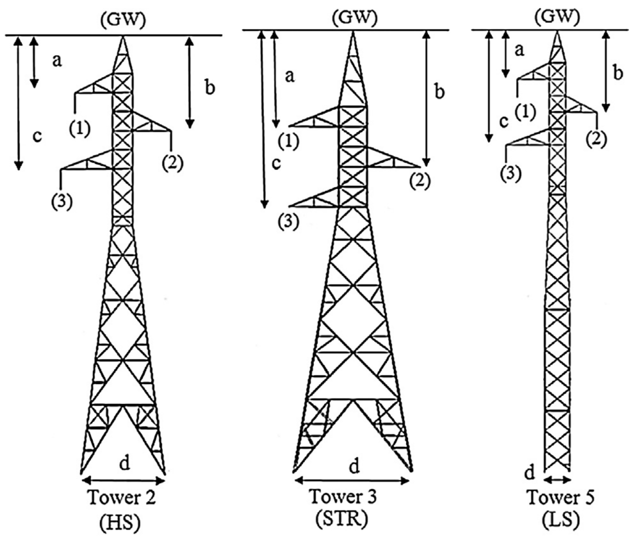

Fig. 2. The configuration of tower types within the line.

Table 1
Description of towers of the 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	STR
2	28.75	3.75	6.25	8.75	5.26	HS
3	27.5	6	8.5	11	7.08	STR
4	33.25	3.75	6.25	8.75	1.9	LS
5	33.25	3.75	6.25	8.75	1.9	LS
6	30.25	3.75	6.25	8.75	1.9	LS
7	30.25	3.75	6.25	8.75	1.9	LS
8	28.75	3.75	6.25	8.75	1.9	LS
9	33.25	3.75	6.25	8.75	1.9	LS
10	27.5	6	8.5	11	7.08	STR

subjected to maximum wind and maximum ice and wind loads while 10–20 towers are usually subjected to maximum ice loads.

The modelled transmission line is analyzed for various combinations of wind speed, wind direction and ice accumulation. The results obtained from these analyses are used to train a surrogate demand function, $D(\mathbf{x_d})$, for each component of the line which relates component demands to climatic variables and can substitute the time consuming finite element solver of the line as described in Section 5.

The model accounts for the effects of structural flexibilities, component interactions, geometric nonlinearities and uncertainty on the capacity of transmission line components for calculating component and system failure probabilities. Parametric uncertainties of wind and ice loads are also considered in the probabilistic model. However, it is noted that model uncertainties such as uncertainties in determining wind and ice loads applied on towers and conductors given a specific wind speed and ice thickness and structural model uncertainties resulting from variations in the dimension and stiffness of structural elements, are not taken into account in this paper and further study is needed to quantify model uncertainties and incorporate them into the proposed probabilistic framework. 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 (ASCE, 2010). This study applies the Simple Model proposed by Jones (1998) to determine the amount of ice accumulation from available meteorological data as indicated in Eq. (1).

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

where P_j, ρ_0, ρ_i, θ and $\emptyset$ are the precipitation rate (mm in the jth hour), the density of water (1 g/cm^3), the density of glaze ice (0.9 g/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, 1950) is the liquid water content (g/m^3) of the rain-filled air in the jth hour.

5. Methodology used for reliability assessment of transmission lines

Fig. 3 presents the flowchart of the steps involved in the reliability assessment of the studied line under current and future climatic conditions. Each step is further explained in Sections 4–6.

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 Eq. (2).

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

where $D(\mathbf{x_d})$ is the demand function, $C(\mathbf{x_c})$ is the capacity function, $\mathbf{x_c}$ is the random vector of variables related to the capacity and $\mathbf{x_d}$ is the random vector of 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 (Mahadevan & Haldar, 2000; Zhao & Ono, 1999) which require to estimate the gradient of the performance function, and of the simulation based methods (Karamchandani, 1987; Melchers, 1999) 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 (Bucher & Bourgund, 1990; Rajashekhar & Ellingwood, 1993). Since RSM is based on the empirical risk minimization (ERM) principle and can result in overfitting due to the rigid and non-adaptive nature of the selected model (Guan & Melchers, 2001; Hurtado, 2004), this paper adopts the concepts of SLT to substitute $D(\mathbf{x_d})$ with a surrogate model that has good generalization (prediction) properties. This surrogate model replaces 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 (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 Eq. (3) (Cherkassky, Shao, Mulier, & Vapnik, 1999; Vapnik, 2000).

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

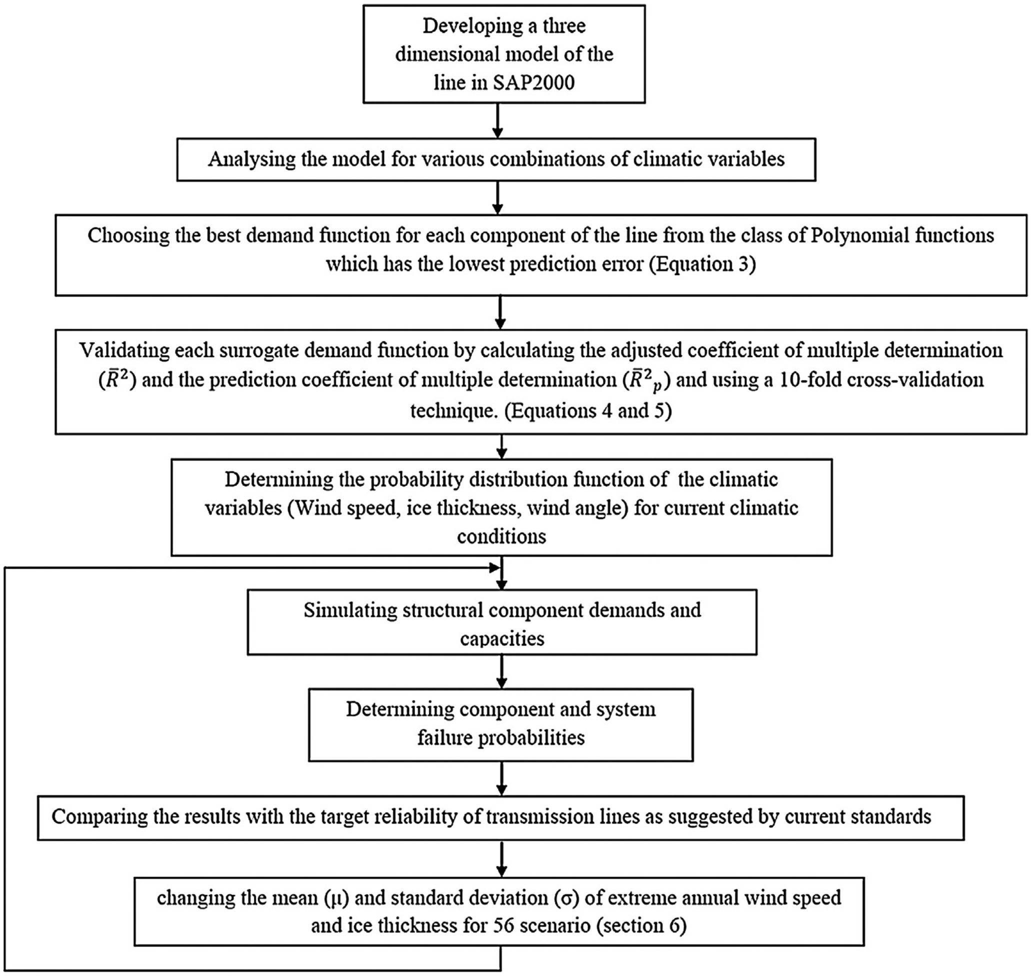

Fig. 3. Flowchart of the steps involved in the reliability assessment of the studied line under current and future climatic conditions.

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 Eq. (3), 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 ($\bar{R}_p^2$) using Eqs. (4) and (5). A good model will have $\bar{R}^2$ and $\bar{R}_p^2$ values near 1.

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

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

In Eq. (4), MSE, MST, n and p are the mean square error, the total mean square of variation in observations, the total number of samples and the number of model variables, respectively. In Eq. (5), n_{te} and $\bar{y}_{te}$ 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 ith observation in the test fold using the fitted model.

Fig. 4 presents $\bar{R}^2$ and $\bar{R}_p^2$ 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 shown demonstrate the adequacy of the selected model and validate its application for determining the failure probability of components.

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 each component. The analysis is performed for an hypothetical line and for the purposes of the analyses, distributions for wind speed and ice accumulation are derived to be consistent with CAN/CSA-C22.3 (2006). Note that for an actual line, site specific data on wind speed and ice accumulation could be used to obtain more accurate

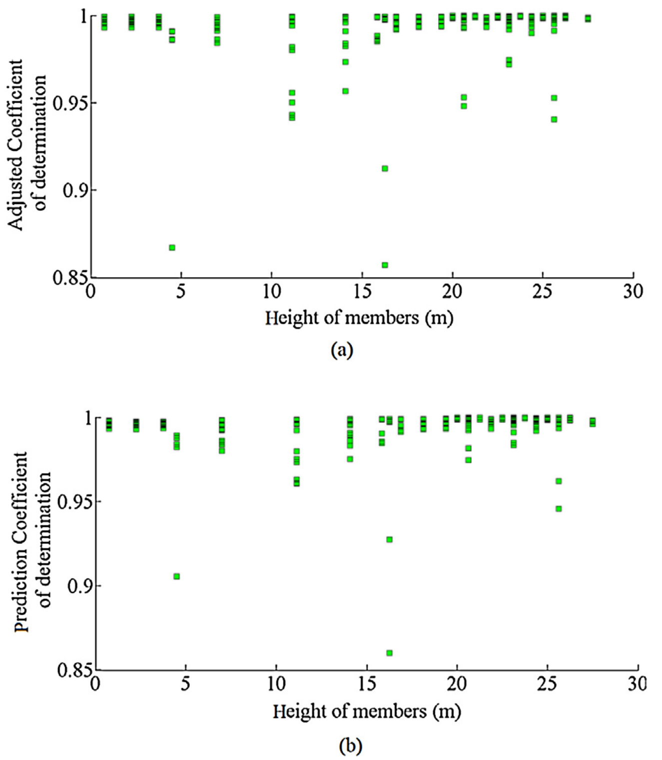

Fig. 4. (a) Adjusted coefficient of determination and (b) prediction coefficient of determination for all members of tower 2.

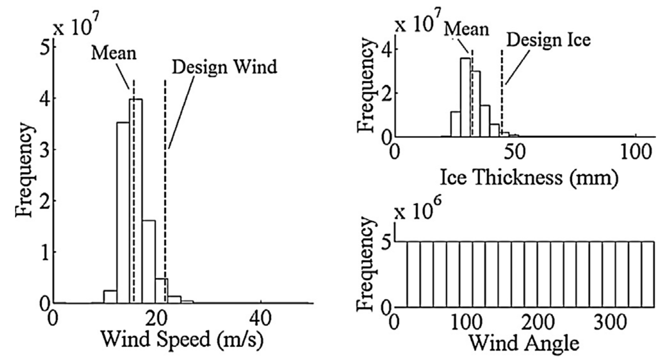

Fig. 5. Histograms of simulated climatic variables.

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

and less conservative estimates of atmospheric hazards in comparison to code derived distributions (Chouinard, Elfashny, Nguyen, & Laflamme, 1998). 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 (CAN/CSA-C22.3, 2006). It is noted that, following CAN/CSA-C22.3 (2006), the 50 year return period extreme concurrent wind speed is assumed as 70% of the 50 year return period extreme wind speed which is 31.17 m/s for the location of the line. Therefore, in this study, the annual extreme concurrent wind speed is assumed to have a Gumbel distribution with a mean and standard deviation of 15.64 (m/s) and 2 (m/s), respectively (CAN/CSA-C22.3, 2006). The statistical parameters of the probability distribution of extreme annual ice thickness and extreme annual concurrent wind speed are estimated from the climatic coefficients proposed by CAN/CSA-C22.3 (2006) to derive the 25, 100, 150, 200, 400, and 500 year ice thickness and wind speed variables based on their 50 year design values using the regression technique. The likelihood of wind blowing from different directions is assumed to be uniform. 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. Fig. 5 indicates the histograms of the simulated climatic variables of wind speeds, ice thicknesses and wind angles using Monte Carlo simulation for 10^8 events.

The capacity for each member of the overhead towers is calculated based on ASCE10-97 (2003). It is assumed that the capacity of overhead tower components has a lognormal distribution with a coefficient of variation of 10% (CAN/CSA-C22.3, 2006). The nominal rated tensile strength of conductors and ground wires are 141.7 and 139 kN, respectively. They are assumed to have a lognormal distribution with a coefficient of variation of 3% (CAN/CSA-C22.3, 2006). 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 has a lognormal distribution with a coefficient of variation of 5% (CAN/CSA-C22.3, 2006). In addition, following CEI/IEC 60826 (2003), it is assumed that the probability of each element of the line not having its nominal strength is 10%.

The failure probability of each component of the line is estimated as 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 both 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 the modelled 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 and may be considered in future studies when experimental data becomes available. Table 2 shows the estimates of the failure probabilities and the corresponding reliability indices for different components of the line and the whole 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 to minimize the impact of a potential failure (CEI/IEC 60826, 2003).

5.3. Target reliability of transmission lines

The target reliability level of a structure is the reliability level that minimizes the total working-life cost of the structure and maintains a balance between performance and life-cycle cost of the structure. Therefore, in order to determine the acceptable level of reliability for a given structure, an optimization problem between the consequences of failure and the costs of safety measures needs to be solved. The parameters that should be considered in solving this optimization problem include (1) the consequence and nature of failure, (2) the economic losses, (3) the social inconvenience and (4) the amount of expense and effort required to reduce the probability of failure (Cherkassky & Mulier, 2007).

For transmission lines, based on their strategic function within the supply network, three reliability levels are proposed (CAN/CSA-C22.3, 2006; CEI/IEC 60826, 2003).

1) All lines should at least have a reliability level characterized by setting the 50 year return period loads equal to the strengths with an exclusion limit of 10% (level 1).
2) Lines below 230 kV which constitute the principal source of electric supply to a region or lines above 230 kV should be designed for a reliability level characterized by setting the 150 year return period loads equal to the strengths with an exclusion limit of 10% (level 2).
3) Lines above 230 kV which constitute the principal source of electric supply to a region or lines should be designed for a reliability level characterized by setting a 500 year return period loads equal to the strengths with an exclusion limit of 10% (level 3).

These reliability levels result in an almost constant yearly failure probability between $1/2T$ and $1/T$, independent of the shape of the system load and strength curves and the coefficients of variation of each variable (CAN/CSA-C22.3, 2006; CEI/IEC 60826, 2003). Where, T is the return period of climatic events. It is noted that, following CEI/IEC 60826 (2003) and CAN/CSA-C22.3 (2006), the studied 120 kV transmission line should have a level 1 reliability with an expected annual system failure probability between 0.01 and 0.02. As indicated in Table 2, the estimated annual failure probability of the line is 0.0145 for current climatic conditions. This shows that the model provides failure probabilities which are in line with the design standards for current climatic conditions.

6. Impact of climate change on the reliability of transmission lines

Estimating and quantifying changes in climate conditions and extreme events is a challenging task. For this purpose, various methodologies based on extreme value theory or general circulation models have been used by scientist (García-Cueto & Santillán-Soto, 2012). The World Meteorological Organization (WMO) suggests extreme value analysis in which the same statistical distributions are used over time while the parameters in the statistical models vary over time to describe the temporal evolution of the extremes (Data, 2009). The same assumption can be found in the works of Huntingford et al. (2003), Beniston et al. (2007) and Pryor and Barthelmie (2010). In this study, climatic variables for current and future climate conditions are assumed to follow Gumbel distribution in accordance with CAN/CSA-C22.3 (2006). 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 (μ) and standard deviation (σ) of extreme annual wind speed and ice thickness for 56 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 (μ, σ) of extreme wind speed and ice thickness individually. A change in the mean value is related to a change in the severity of an event while an increase in the standard deviation corresponds to an increase in the variability of climate related events.

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. However, comparing the effect of these two variables, the mean value has more effect on the reliability of the line since an increase of 20% in the mean value of extreme wind speed can reduce the reliability index of the system by more than 30%, while an increase of 20% in the standard deviation of extreme wind speed can reduce the system reliability index by less than 8%. Therefore, as indicated in Table 3, a mild reduction of 5% in the mean value of the wind speed will increase the structural reliability even if there is a 10% increase in the standard deviation. Similarly, it is inferred from Table 4 that the mean value of extreme ice thickness has more effect on system reliability index of the transmission line compared to the standard deviation of extreme ice thickness.

Comparing the results from Tables 3 and 4 demonstrates that changes in the distribution for 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 extreme ice thickness can reduce the reliability index of the system by more than 17%. It is noted that an increase of 20% in the mean value of extreme annual wind speed and extreme annual ice thickness approximately represents current climatic conditions at the most exposed hazardous regions near the location of the line.

It is noted that in Tables 3 and 4, the values in bold font show the percentage change in the reliability index of the transmission line system and a negative value represents a reduction in the reliability index while a positive value represents an increase in the system reliability index.

In order to get a better understanding of Tables 3 and 4, the results are also presented in Figs. 6 and 7, respectively.

In Fig. 6, the lower horizontal axis is the percentage change in the mean value of extreme wind speed and the upper horizontal axis is the corresponding mean value of extreme wind speed (m/s). The left and right vertical axes are the percentage change in the standard deviation of extreme wind speed and the corresponding value of the standard deviation of extreme wind speed (m/s), respectively. The solid contour lines show the system reliability index, while the dashed contour lines show the 50 year return period wind speed (m/s) which is the design wind speed

Table 3
Percentage change in the transmission line system reliability index as a function of mean and standard deviation of the extreme wind speed distribution.

% of change in σ_{wind}	σ_{wind}	% of change in μ_{wind}			
		−5	0	10	20
		μ_{wind} (m/s)			
		21.23	22.35	24.58	26.82
−20	2.28	17.04	9.71	−6.50	−24.67
−10	2.57	12.07	4.89	−10.70	−27.58
0	2.86	6.54	0.00	−14.40	−30.37
10	3.14	2.51	−3.86	−18.01	−32.95
20	3.43	−1.56	−7.58	−20.81	−35.34

Table 4
Percentage change in the transmission line system reliability index as a function of mean and standard deviation of the ice thickness distribution.

% of change in σ_{Ice}	σ_{Ice}	% of change in μ_{Ice}				
		−20	−10	0	10	20
		μ_{Ice} (mm)				
		25.76	28.98	32.20	35.42	38.64
−20	3.30	17.97	10.96	2.51	−5.56	−14.72
−10	3.70	17.04	9.51	1.42	−6.96	−15.99
0	4.10	15.32	8.53	0.00	−8.45	−17.19
10	4.50	14.01	6.72	−1.56	−9.68	−18.68
20	4.90	12.07	5.05	−2.80	−11.23	−20.50

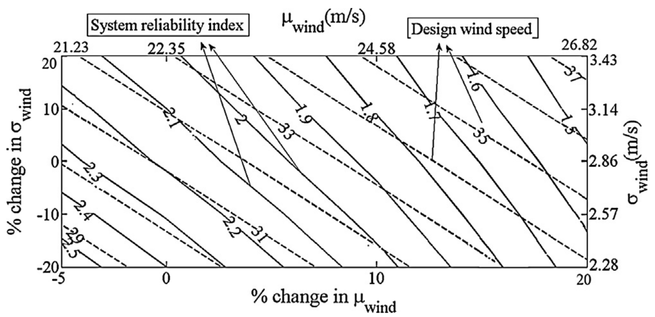

Fig. 6. The effect of changing the mean and standard deviation of extreme wind speed distribution on the system reliability index and design wind speed.

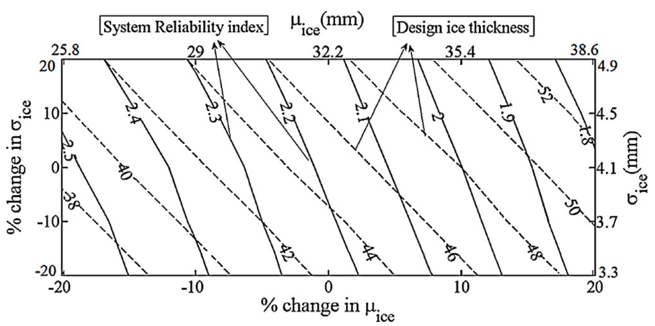

Fig. 7. The effect of changing the mean and standard deviation of extreme ice thickness distribution on the system reliability index and design ice thickness.

for this line. It is inferred from this figure that if the mean value of extreme wind speed increases by 10% from 22.35 to 24.58 m/s while the standard deviation is unchanged, the reliability of the line is reduced from 2.18 to 1.87. In order to maintain the same reliability index, the transmission line should be upgraded for a design wind speed of 33.4 m/s instead of its current design value of 31 m/s. It is noted that, in order to propose an upgrading strategy, the following questions should be answered: (1) which components contribute more to the system failure, (2) which components have higher improvement potential for the entire system, (3) which upgrading strategy results in a desirable strength coordination between line components and consequently minimizes the impacts of a potential failure. Determining the best upgrading strategy and estimating the reliability of the improved line using the statistical learning theory is the subject of a future study.

In Fig. 7, the lower horizontal axis is the percentage change in the mean value of extreme ice thickness and the upper horizontal axis is the corresponding mean value of extreme ice thickness (mm). The left and right vertical axes are the percentage change in the standard deviation of extreme ice thickness and the corresponding value of standard deviation of extreme ice thickness (mm), respectively. The solid contour lines show the system reliability index, while the dashed contour lines show the 50 year return period ice thickness (mm) which is the design ice thickness for this line. It is inferred from this figure that if the mean value of extreme ice thickness increases by 10% from 32.2 to 35.42 mm, while the standard deviation remains constant, the reliability index is reduced from 2.18 to 2.0. In order to maintain the same reliability index, the transmission line should be upgraded for a design ice thickness of 48 mm instead of its current design value of 45 mm.

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 extreme wind speed and ice thickness distributions simultaneously. Fig. 8 shows the effect of changing the mean value of the extreme wind speed and ice thickness distributions on the system reliability index and design wind and ice loads.

Table 5
Percentage change in the transmission line system reliability index as a function of the mean value of extreme wind speed and ice thickness distributions.

% of change in μ_{Ice}	μ_{Ice} (mm)	Ice_{50} (mm)	% of change in μ_{wind}			
			−5	0	10	20
			μ_{wind} (m/s)			
			21.23	22.35	24.58	26.82
			Wind_{50} (m/s)			
			30.05	31.17	33.40	35.64
−20	25.76	38.50	21.46	15.32	2.23	−12.48
−10	28.98	41.70	15.32	8.53	−6.22	−21.47
0	32.2	45.00	6.54	0.00	−14.40	−30.37
10	35.42	48.00	−1.44	−8.45	−23.40	−39.76
20	38.64	51.40	−10.39	−17.19	−32.55	−49.25

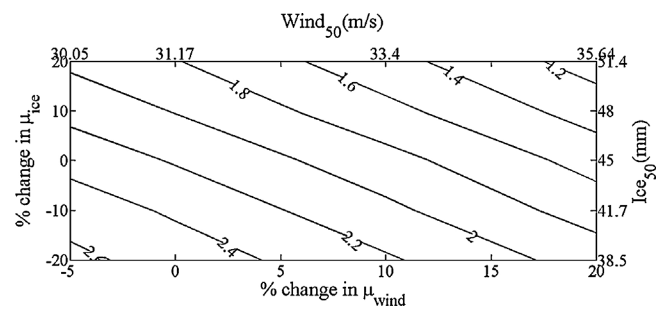

Fig. 8. The effect of changing the mean value of extreme wind speed and ice thickness distributions on the system reliability index and design wind and ice loads.

It is inferred from Table 5 and Fig. 8 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. The analysis of wind statistical characteristics for various sites across Canada indicates that the coefficient of variation is relatively constant which shows a strong correlation between the mean and standard deviation (Ye, 2013). If a similar relation is observed for future climates, an increase in mean severity will also be accompanied by a corresponding increase in the standard deviation which may further reduce the reliability index of existing lines.

7. Conclusion

In this study, the sensitivity of the reliability of a typical transmission line system to climate change is investigated using the statistical learning theory 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. The reliability of transmission lines is shown to be more sensitive to an increase in the intensity of extreme wind speed than to an increase in the intensity of extreme ice thickness. For example, it is demonstrated that a 20% change in the mean value of extreme wind speed and extreme 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. In other words, a climate change as predicted by many researchers can significantly reduce the reliability of existing transmission line systems. 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. The specification of design loads for the evaluation of existing lines or the design of new lines should consider both future climate models and historical climate data.

Future research remains to be done on projecting the potential changes in the probability distribution functions of wind speed and ice built-up from available climate change scenarios and integrating these results into the proposed probabilistic framework.

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