Design Winds During Ice Storm as a Function of Direction For Transmission Lines

L. Chouinard[1] ,N. Feknous[2], and G. Sabourin[3]

[1]McGill University, Montreal, Luc.chouinard@mcgill.ca
2SNC-Lavalin, Montreal, Nadia.feknous@*SNC-Lavalin.com*
[3]Hydro Quebec, Montreal, Gilles.sabourin@hydro.qc.ca

Abstract— **Current design codes define the reference wind speed as the expected wind speed for a given return period without considering wind direction. This is appropriate for axisymmetric structures such as telecommunication towers but is very conservative for directional structures such as transmission lines. A procedure was developed for the estimation of the probability distribution function of maximum wind speed as a function of direction. The procedure was applied to the sample of annual maximum wind speeds under the assumption that the Gumbel distribution applies. The proposed procedure is general and could be easily applied to other distributions and to event-based models. The procedure was used to estimate the maximum wind speed as a function of direction for the sample of maximum annual wind speeds and of maximum annual wind speeds during ice storms at 22 locations in the province of Quebec. Results are presented in the form of a ratio relative to the reference wind speed at for each location. These indicate that significant reductions could be obtained at many strategic locations for both the maximum annual wind speed and for the maximum wind speed during ice storms when line orientation is accounted for in the evaluation of line vulnerability.**

I. INTRODUCTION

Transmission lines are structures that are very sensitive to the direction of the applied loads, in particular from wind. Wind load directionality effects are combined effects resulting from atmospheric flow patterns, local exposure, and aerodynamic pressure coefficients. Accounting for wind directionality effects can be economically desirable in regions where directionality effects are important either for maximum annual winds or for extreme winds during glaze icing events.

A local directionality factor must combine two effects, the event directionality, and the siting or local exposure directionality. The first effect is a function of large-scale climatic conditions and is estimated from data in open terrain. It is usually assumed that the effects of local exposure on wind climate directionality can be eliminated for sites located at commercial airports (open terrain). Only the first directionality effect is considered in the present article. The objective of this article is to review and propose procedures for the estimation of design directional winds and to apply them at different sites across Quebec.

II. METHODOLOGY

Wind direction obtained from meteorological stations is recorded in 10 degrees sectors. This data set is used to obtain the maximum wind speed for each year in each of 36 sectors. One procedure is to fit an extreme value distribution to the sample of extreme values for each of the 36 sectors. However, typical samples are usually small for winds during glaze ice events and some sectors may have calm winds for several years. Fitting a distribution to each sector usually results in distribution parameters with large variability from sector to sector. The distribution is then a conditional on wind direction.

$$f_{V|\theta}(v \mid \theta) \qquad [1]$$

An option to increase sample size is to lump sectors; however, in most cases this does not increase significantly sample size in quadrants other those of dominant winds. Another option is to assume that extreme distribution for non-directional winds is common to all directions during a season or period, and that the sample of all winds can be used to define the probability distribution function of wind direction. The joint probability distribution function is then obtained from the following expression

$$f_{V,\theta}(v,\theta) = f_V(v \mid \theta) \cdot f_\theta(\theta) \qquad [2]$$

Further assuming independence between wind speed and wind direction during a storm pattern,

$$f_{V,\theta}(v,\theta) = f_V(v) \cdot f_\theta(\theta) \qquad [3]$$

Both of these methods are used to characterize of the wind both in terms of direction and severity at a given location. Structural effects are obtained by integrating the joint probability distribution function with design equations, for example, the distribution can be used to analyze the maximum loads applied on conductors and supporting structures and to specify the design loads for different recurrence periods. In this case, the wind-induced load on conductors can be estimated with the following relationship,

$$F = \rho \cdot V_\perp^2 \cdot (D + 2H) \cdot C_d + \varepsilon \qquad [4]$$

where ρ is the air density, V⊥ is the wind speed (perpendicular to the conductor), D is the diameter of the conductor, H is the radial equivalent accumulation of ice, C_d is the drag coefficient, and ε represents model uncertainty (usually a normally distributed random variable with zero mean and standard deviation σ_ε). In this expression, the drag coefficient is a function of the total ice accumulation, wind speed, wind direction, and temperature during accumulation. The cumulative distribution function of wind-induced loads can be derived from the joint probability distribution function of wind and ice using the following expression

$$F_F(f) = 1 - \iiint_{\Omega_{\underline{X}}} f_{\underline{X}}(\underline{x})\, d\underline{x} =$$

$$1 - \iiint_{\Omega_{\underline{X}}} f_{C_d}(c_d) \cdot f_{V_\perp}(v_\perp) \cdot f_H(h)\, d_{c_d}\ dv_\perp\ dh \quad [5]$$

where $\Omega_{\underline{X}}$ is the region in the space of the vector of the random variables $\underline{X}$:{C_d, V,θ, H} such that the load F is larger than f. For design purposes, a wind-induced load can be selected from the cumulative distribution function for any given return period.

In the presence of smaller samples and structures that have a well-defined weaker axis, such as transmission lines, it is usually preferable to proceed with the sample of extreme winds acting perpendicular to the weak axis of the structure. This procedure is similar to the concept of an equivalent wind speed used by Huang and Twisdale (1981), Rossowsky (2000) and by Simiu and Heckert (1998) and avoids the step of characterization of the extreme distribution of directional winds. Note that it is possible that one particular event results in the m-year maximum wind speed in more that one direction.

Directional characteristics of the wind are most important in the design of direction sensitive structures, such as transmission lines. In the extreme case, it can be assumed that such structures are sensitive only to the speed of a component of the wind perpendicular to the transmission line. For such structures, the design wind is based on the absolute value of the maximum component of the wind in the given direction. The mean upcrossing rate is then calculated as the sum over all classes and directions of the upcrossing rate of he component of the wind in the desired direction of level v;

$$\nu_s(v) = \lambda \int_0^{2\pi} f(\theta)\left(1 - F\left(\frac{v}{\sin\theta^*}\right)\right) d\theta \qquad [6]$$

where λ is the recurrence rate of ice storms, f(θ) is the probability density function for wind direction, and θ^* is the angle of incidence of the wind with the transmission line.

III. ANALYSIS AND RESULTS

The proposed procedure was applied to 22 sites across the province of Quebec. Only the results for Quebec City are presented in this article (Figure 1). The meteorological data set was provided by Environment Canada while the data set on glaze ice accumulation was provided by Hydro-Québec. A common concern with wind data during glaze ice events is the effect of ice accumulation on wind speed measurements. This effect, if present, does not appear to be very significant for the data set that was analyzed since very few events are associated with large amounts of ice accumulation that could interfere with readings. The data set for the annual maximum wind speed covers a period of 30 years is based on measurements of wind speed at 10 m above level and correspond to the average wind measured over a two minute period before each hour. The data set on glaze ice accumulation covers a period of 25 years.

Figure 1 Québec City and surrounding area.

Figure 2 shows the wind rose for Quebec City during glaze ice events. This figure clearly indicates a dominant pattern for winds that are oriented along the St-Laurent River Valley.

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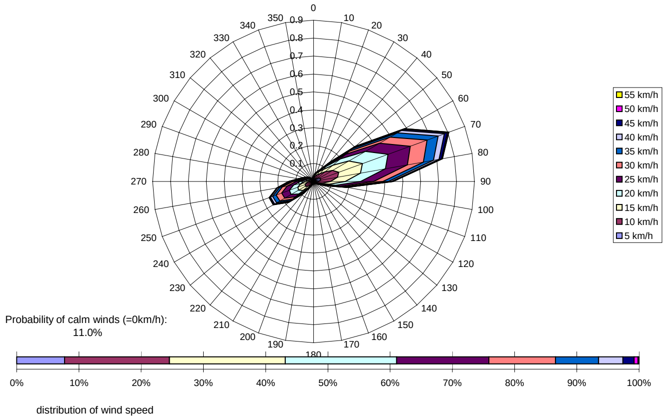

Figure 2 Wind rose for Quebec City during glaze ice events

This distribution of winds translates in ice accumulations and transverse loads that are more severe for transmission lines that cross the St-Laurent River at that location (Figure 3). The red and blue contour lines in the figure correspond respectively to the mean and median ice accumulation ratios. The green and yellow contour lines correspond respectively to the 95% confidence intervals and indicative of the degree of variability of the accumulation ratios. These ratios are defined relative to the maximum ice accumulation, which is based on the assumption that winds remain perpendicular to a transmission line during ice accumulation. The results indicate that a reduction factor of up to 25% can be achieved on ice accumulations in the most favorable case when the line is directed parallel to dominant winds. Note that these results are dependent on assumptions relative to the vertical droplet velocity and assume a cylindrical and uniform ice accumulation around the conductor. The reduced ice accumulation reduces both the magnitude of the vertical loads as well as the projected area of the iced conductor in the calculation of the transverse wind load (Chouinard et al. 2002).

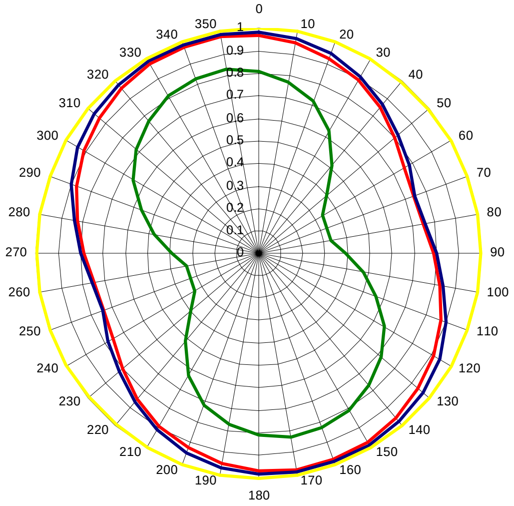

Figure 3 Glaze ice accumulation as a function of line orientation - Quebec City.

Figure 4 shows the results of the extreme directional winds for Quebec City during glaze ice events as well as for maximum annual winds. The blue line corresponds to the 50-year maximum annual wind speed and the purple line shows the 50-year wind speed during ice storms. Both are normalized relative to the reference wind, defined as the 50-year maximum wind speed to define the directionality factor,

$$\frac{V(\theta)}{V_R} \qquad [7]$$

In the non-directional method, the time series of maximum wind speeds in all directions (i.e. direction independent) is fitted with the Gumbel distribution and the reference wind speed V_R for a return period T_R is obtained from,

$$V_R = F_V^{-1}\left(\frac{1}{T_R}\right) \qquad [8]$$

where F_V is the cumulative distribution function for the Gumbel distribution. Note that the directionality factor is by definition smaller than or equal to 1 because the 50-year wind is by definition less than or equal to the reference 50-year wind. This definition of directionality factor offers some advantages. Normalizing the directional wind by the reference wind (i.e. code values), the results from the present study can be readily applied in design. The blue and red circles correspond respectively to the observations used for fitting the extreme value distributions for each direction and can be used to provide a visual assessment of the goodness-of-fit of the model. In this example, it is shown that there is a significant decrease in design winds as a function of direction both for the annual maximum wind and the wind during ice storms. For the annual maximum winds the reduction in wind velocity can be as high as 65% while winds during ice storms can vary from 35to 65% of the reference wind. This is a significant reduction considering that wind pressure is proportional to the square of the wind velocity. Further research is required before incorporating these findings in design specifications for transmission lines.

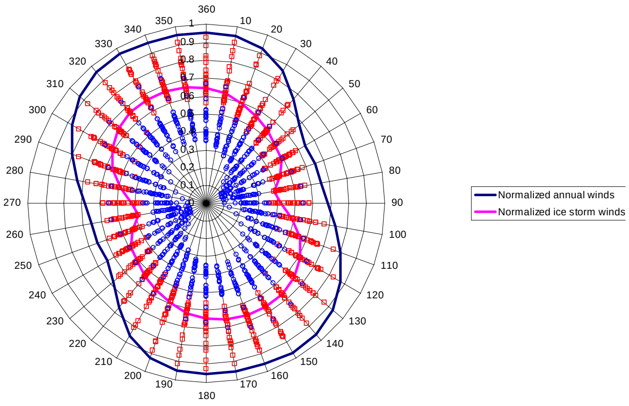

Figure 4 Extreme annual winds and extreme winds during glaze ice events as a function of line orientation at Quebec City.

IV. CONCLUSION

Wind directionality effects are very important for the design of structures such as electric transmission lines. A better characterization of extreme winds as a function of direction can represent significant savings for the design and for upgrading existing lines. A method has been proposed and demonstrated for a given site in open terrain conditions. Future developments of the procedure will address issues related to regional criteria and local adjustments for topographical features.

VI. REFERENCES

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