A Novel Approach to the Combined Ice and Wind

Dr. M. L. Lu and Z. Kieloch, P.Eng.
Manitoba Hydro
1140 Waverley St., Winnipeg, Manitoba, Canada, R3C 2P4, mlu@hydro.mb.ca; zkieloch@hydro.mb.ca

***Abstract*—The combination of ice and wind is an important issue in designing overhead transmission lines in an ice-prone area. A novel approach is proposed in this paper to find the combination in a natural and rational fashion, based on the historical weather data. Essentially, it is proposed to estimate the wind accompanying a *T*-year ice (accreted on a circular cylinder) from examining ice accretions on both (fictitious) vertical and horizontal surfaces. The approach was used to analyze the weather data across the province of Manitoba, Canada. It was found that the wind accompanying a *T*-year ice is fairly constant regardless of the return period, *T*, and that wind invariably plays an important role in contributing to an extreme ice accretion. The case of an extreme ice without wind does not appear to be realistic, at least for the province of Manitoba.**

I. Introduction

WIND invariably exists during an ice storm, adding horizontal load to a transmission line overhead conductor vertically loaded with ice. This is reflected in the current practice of transmission line design [1, 2]. For example, the combination of 12.7 mm (½”) ice and 385 Pa (8 psf) wind is typically adopted in Manitoba Hydro for designing most transmission lines in the province of Manitoba. This load case often generates the highest horizontal loading.

The current, common practice of deriving the combined ice and wind on transmission line conductors is that, first, ice and ice-on wind are statistically analyzed separately, and then the resulting extreme ice and extreme wind are combined together [1, 3]. There, wind may either refer to wind speed [1] or wind load [3]. This approach tends to overestimate the wind accompanying an extreme ice since it is unlikely that both extreme wind and the extreme ice occur at the same time, even during icing periods. In practice, the ice-on wind is assumed to be a certain percentage of the corresponding extreme wind that covers all seasons. For example, CSA proposed to combine a *T*-year ice (i.e. an ice with a return period of *T* years) with 60% of the *T*-year wind speed [2].

In this paper, a novel approach is described to find a combined ice and wind in a more rational fashion. The approach essentially involves estimating the wind accompanying a *T*-year ice (accreted on a circular cylinder) from examining ice accretions on both (fictitious) vertical and horizontal surfaces. The approach might still tend to overestimate the wind load, but will likely be less conservative than the existing method mentioned above.

This new approach is being used in Manitoba Hydro in reviewing its design practice related to the combined ice and wind. The historical weather data from 12 stations across the province of Manitoba is used to derive the combined ice and wind. Chaine’s model [4] was adopted in the data analysis for the consistency with previous studies. The preliminary study results are reported here.

II. Methodology

The proposed approach is described next.

First, historical weather data is collected and sorted so that ice storm related data is ready in a storm-by-storm manner.

Second, a particular icing model (say, Chaine’s model [4]) is used to estimate amounts of ice accreted on a vertical, a horizontal, as well as a cylindrical surface, storm by storm.

Third, the ice accretion amounts obtained in the previous step are statistically analyzed separately to find their corresponding extreme values for different return periods.

Finally, a *T*-year radial ice thickness on a conductor is found as being the *T*-year radial ice thickness on a circular cylinder, and the wind accompanying this *T*-year ice is derived from the ratio of the *T*-year, horizontal ice accretion to the *T*-year, vertical ice accretion.

To illustrate the last step, the vertical and horizontal ice accretion can generally be defined as [5]

$$A_h = P_v t = \frac{W V_d t}{\rho_w} \quad (1)$$

$$A_v = P_h t = \frac{W V_w t}{\rho_w} \quad (2)$$

where A_h and A_v are the amount of ice accreted on a horizontal and vertical surface, respectively (A_h and A_v may alternatively be called the vertical and horizontal ice accretion, respectively); P_v and P_h are the vertical and horizontal precipitation rates, respectively; t is the duration of the ice accretion; W is the liquid water content; ρ_w is the mass density of water; V_d and V_w are the vertical speed of water droplets and the wind speed, respectively.

Notice that the ice-on wind information is contained in the horizontal ice accretion (i.e. the ice accreted on a vertical surface). Thus, the wind speed corresponding to the given ice accretion can be derived from the horizontal and vertical ice accretions by

$$V_w = \frac{A_v}{A_h} V_d \,. \tag{3}$$

Here, the droplet speed, V_d, can be conservatively taken as 4 m/s, which corresponds approximately to the droplets of 1 mm diameter [6].

When Eq. (3) is used to find the wind speed accompanying a *T*-year ice accreted on a circular cylinder, the corresponding *T*-year, vertical and horizontal ice accretion should be used in the calculation. Thus, the resulting wind speed should correlate well to the *T*-year extreme ice. In contrast, the *T*-year, ice-on, wind speed or wind load does not necessarily correlate well to the *T*-year ice, as an extreme wind speed or wind load will unlikely encounter an extreme ice during icing periods.

It can be deduced from the individual methodologies that, among the three methods: the ones based on statistics of ice-on wind speed [1], ice-on wind load [3], and ice accretions as proposed in this paper, the present method should predict the lowest wind to accompany a *T*-year ice, if no artificial reduction is made on the resulting wind in the other two methods. Regardless, the present method still likely tends to overestimate the wind, because a *T*-year, horizontal ice accretion is still not necessarily coexistent with a *T*-year, vertical ice accretion, although the chances of such coexistence should be higher than in the coexistence of a *T*-year, ice-on wind and a *T*-year ice as in the other two methods. Therefore, the present method appears to be more rational, yet it remains likely to be conservative.

TABLE I
WEATHER STATIONS, THEIR PERIODS OF RECORDS, AND THE TOTAL NUMBER OF ICING EVENTS

No.	Station	Period of Record			Total
		Start	End	Years	Events
1	Brandon	1958	1999	42	245
2	Churchill	1953	1999	47	418
3	Dauphin	1953	1998	46	216
4	Gimli	1953	1991	39	237
5	Island Lake	1971	1999	29	161
6	Lynn Lake	1968	1999	32	179
7	Norway House	1973	1999	27	213
8	Portage Southport	1953	1992	40	232
9	Rivers	1953	1970	18	107
10	The Pas	1953	1999	47	251
11	Thompson	1967	1999	33	252
12	Winnipeg	1953	1999	47	287

III. APPLICATION

The proposed approach is now used to find the combined ice and wind for the province of Manitoba, Canada, by using the available historical weather data at 12 weather stations across the province (see Table I). Chaine's model is adopted here to be consistent with the previous study [7], although Goodwin's model [8] was found to correlate much better to freezing rain experiments [5, 9]. The preliminary results are presented next.

A. Wind speed associated with ice events

For each ice event, an average wind speed over this event can be estimated from the accumulated A_v and A_h by Eq. (3) with V_d being 4 m/s. Thus, for all the yearly maximum icing events across the province of Manitoba, the estimated wind speeds averaged over those individual events are plotted against the corresponding accumulated ice thicknesses, as shown in Fig. 1. Notice that each point in the figure stands for one icing event.

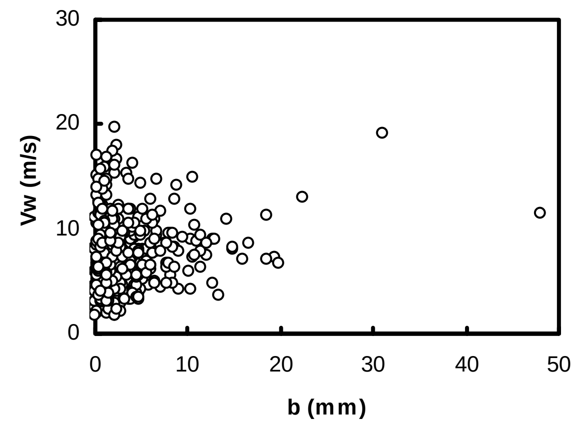

Fig. 1. Estimated average wind speeds, V_w, of yearly maximum ice events in Manitoba. Here, *b* is the radial ice thickness accreted over an ice storm.

It can be observed from Fig. 1 that, for major ice storms in Manitoba, a moderate wind of 4 to 19 m/s invariably exists. (A major ice storm is loosely defined here as one with ice thickness of 6 mm, or 1/4 inch, and above.) In particular, no major ice storm has an accompanying wind less than 4 m/s, indicating that the Ice-Only case is not realistic at least for Manitoba.

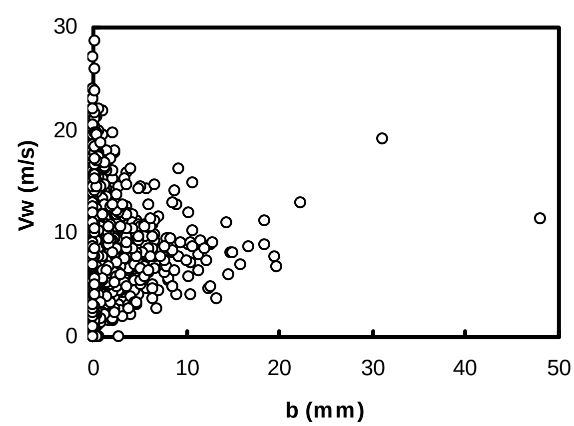

Fig. 2. Estimated average wind speeds, V_w, of all ice events in Manitoba. Here, *b* is the radial ice thickness accreted over an ice storm.

For comparison, the average wind speeds of all icing events are plotted in Fig. 2. It can be seen that Fig. 2 is quite similar to Fig. 1, particularly for major ice events (i.e. those with 6 mm or thicker ice). Therefore the previous conclusion remains valid as only major ice storms are practically of interest.

B. Relative contribution of wind to ice accretion

According to Chaine's model, the equivalent radial ice thickness, *b*, is expressed as [4]

$$b = \sqrt{\frac{RK}{2}\sqrt{A_h^2 + A_v^2} + R^2} - R \qquad (4)$$

where *R* is the radius of a circular cylinder (or conductor), and *K* is an empirical factor.

Eq. (4) shows that radial ice accretion is dependant on two main components: A_h and A_v, which represent amount of ice accreted on a horizontal and vertical surface, respectively. Eqs. (1) and (2) indicate that A_h and A_v come from the freezing precipitation and the wind, respectively. Thus, the relative contribution of wind to ice accretion with respect to that of precipitation can be measured by the ratio of A_v to A_h. If the A_v to A_h ratio is unity, wind and precipitation contribute equally to the ice accretion. If the ratio is greater than unity, wind contributes more than precipitation. Fig. 3 shows the ratios for all the yearly maximum events. Clearly, the ratio is invariably greater than 1 for all the major icing events, and can be up to a factor of 5. Thus, for all the major icing events, wind seems to play a more important role than precipitation itself in the process of ice accretion.

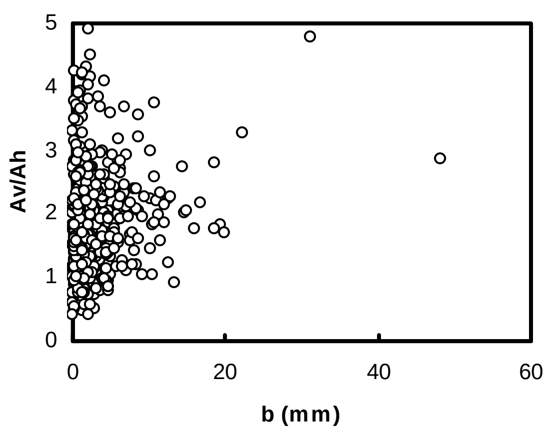

Fig. 3. Ratios of A_v to A_h for all the yearly maximum icing events in Manitoba. Here, b is the radial ice thickness accreted over an ice storm.

C. Comparison of ice accretion with and without wind

Another way to examine the effect of wind on ice accretion is to compare ice thickness *b* (with wind effect incorporated) to the thickness *b'* due purely to freezing precipitation (with the assumption that no wind exists for the duration of the ice storm).

Thus, Fig. 4 is prepared to show the comparison for all the yearly maximum icing events in Manitoba. It can be observed from Fig. 4 that a reduction factor of 0.3 to 0.8 would apply for the ice thickness if wind is assumed to be absent during a major icing events (b > 6 mm). The reduction factor would become 0.4 to 0.6 for more severe ice storms (b > 12.7 mm). That is, a "calm" ice storm appears to produce only about half of the ice thickness of otherwise the same, but "windy" ice storm, as far as severe ice storms (b > 12.7 mm) are concerned.

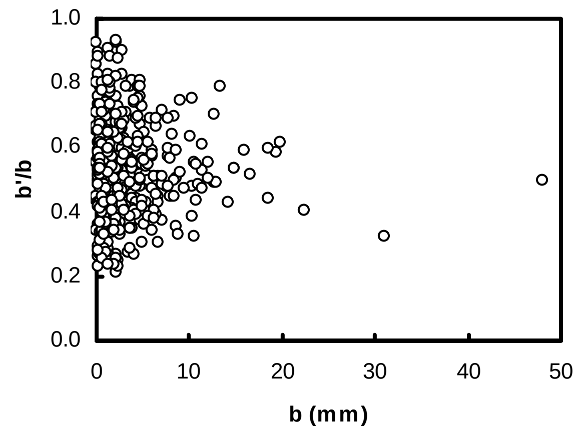

Fig. 4. Comparing ice thicknesses with and without wind for all the yearly maximum icing events in Manitoba. Here, b' is the ice thickness without considering wind effect, and b is the ice thickness considering wind effect.

D. Frequency analysis results

Frequency analysis was made to find the distribution of extreme values related to icing across the province of Manitoba as described elsewhere [6]. The results are summarized here in Table II.

Then the *T*-year ice, x_T, can be calculated from the mean, *m*, and the standard deviation, *s*, of the parameter *x*, by [10]

$$x_T = m - s\frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\ln\left(\frac{T}{T-1}\right)\right] \qquad (5)$$

where *T* is the return period, and the parameter *x* can be A_v, A_h, or *b*.

TABLE II
SUMMARY OF STATISTICAL RESULTS ON ICE ACCRETION IN MANITOBA

Station No.	A_h (mm)		A_v (mm)		*b* (mm)	
	m	*s*	*m*	*s*	*m*	*s*
1	2.365	2.920	4.346	5.634	3.106	3.450
2	3.516	4.932	8.665	13.701	6.103	8.737
3	2.089	2.229	3.798	4.636	2.856	3.240
4	2.696	3.320	4.555	5.174	3.429	3.672
5	2.287	3.138	3.955	5.574	2.931	4.098
6	2.180	3.269	2.470	3.148	2.234	2.732
7	2.233	2.402	3.419	4.325	2.743	3.012
8	2.336	2.331	4.488	4.699	3.431	3.266
9	1.755	1.589	3.113	2.566	2.571	2.162
10	1.586	1.684	2.312	2.725	2.035	2.102
11	2.532	2.856	4.277	5.983	2.888	3.266
12	2.468	2.760	5.759	7.508	4.038	4.682

Note: m and s refer to the mean and the standard deviation of a particular parameter.

Table III shows the results of A_v, A_h and b for the return period of 50 years, commonly used in designing transmission lines. Also given in Table III is the average wind speed that may accompany a 50-year ice thickness, as estimated by using Eq. (3).

TABLE III
50-YEAR RADIAL ICE THICKNESSES AND ACCOMPANYING WIND SPEED IN MANITOBA

Station No.	A_h (mm)	A_v (mm)	V_w (m/s)	b (mm)
1	9.9	19.0	7.6	12.0
2	16.3	44.2	10.8	28.8
3	7.9	15.8	8.0	11.3
4	11.3	18.0	6.4	12.9
5	10.4	18.4	7.1	13.6
6	10.7	10.6	4.0	9.3
7	8.5	14.6	6.9	10.6
8	8.4	16.7	8.0	11.9
9	5.9	9.8	6.6	8.2
10	6.0	9.4	6.3	7.5
11	9.9	19.8	8.0	11.4
12	9.6	25.2	10.5	16.2

For a given return period of T years, either the T-year ice thickness, b_T, or its accompanying wind speed, V_T, can be viewed as a random variable that is applicable to the entire province of Manitoba. Thus, the mean, m_T, and standard deviation, s_T, of b_T or V_T can be found by

$$m_T = \frac{\sum_{i=1}^{n} x_{T,i}}{n} \qquad (6)$$

and

$$s_T = \sqrt{\frac{n\sum_{i=1}^{n} x_{T,i}^2 - \left(\sum_{i=1}^{n} x_{T,i}\right)^2}{n(n-1)}} \qquad (7)$$

where, x is either b or V_w. $x_{T,i}$ is the T-year b or V_w for the ith station.

The m_T and s_T values are given in Table IV for different return periods, T.

Assuming that both b_T and V_T follow a normal distribution, then the b_T and V_T with 85% or 95% confidence level (i.e., 15% or 5% in terms of exclusion limit) over the entire province can be found respectively by

$$x_{T,85\%} = m_T + 1.036 s_T \qquad (8)$$

and

$$x_{T,95\%} = m_T + 1.645 s_T\,. \qquad (9)$$

Here, again, x can be either ice thickness, b, or its accompanying wind speed, V_w. Physically, $b_{T,85\%}$, for example, is the T-year ice thickness that will exceed 85% of the T-year ice thicknesses all over the province.

The values of $b_{T,85\%}$, $b_{T,95\%}$, $V_{T,85\%}$ and $V_{T,95\%}$ are presented also in Table IV.

TABLE IV
STATISTICAL RESULTS ON T-YEAR RADIAL ICE THICKNESS b_T AND ACCOMPANYING WIND V_T

T (yrs)	b_T (mm)		V_T (m/s)		b_T (mm)		V_T (m/s)	
	m_T	s_T	m_T	s_T	85%	95%	85%	95%
5	5.86	2.30	7.36	1.67	8.2	9.6	9.1	10.1
10	8.03	3.31	7.44	1.75	11.5	13.5	9.3	10.3
20	10.10	4.29	7.48	1.80	14.6	17.2	9.4	10.4
30	11.30	4.85	7.50	1.82	16.3	19.3	9.4	10.5
40	12.14	5.25	7.51	1.83	17.6	20.8	9.4	10.5
50	12.79	5.55	7.52	1.84	18.6	21.9	9.4	10.5
70	13.77	6.01	7.53	1.85	20.0	23.7	9.4	10.6
100	14.81	6.50	7.54	1.86	21.5	25.5	9.5	10.6

So far, the wind speed is the hourly averaged one. However, it is the peak wind speed (i.e. gust wind speed) that will produce highest wind pressure and thus control a design. The gust wind speed can be estimated from the hourly wind speed by [11]

$$V_G = 1.29V + 2.6 \qquad (10)$$

where V refers to an hourly wind speed (m/s), and V_G is the corresponding gust wind speed (m/s).

The gust speeds of $V_{T,85\%}$ and $V_{T,95\%}$ are listed in the 2nd and 3rd columns in Table V, after applying an additional factor of 1.5, a value chosen somewhat arbitrarily. Here this factor is used to account for the variation of hourly wind speed during an ice storm. In other words, it is assumed here that the maximum hourly wind speed of an ice storm is 50% higher than the hourly wind speed averaged over the storm's duration.

Finally, the gust speeds obtained in the previous step are converted to wind pressure for the given return period by the following equation:

$$p_T = 0.719 V_{G,T}^2 \qquad (11)$$

where, p_T is in Pa, and $V_{G,T}$ is in m/s.

Eq. (11) is derived from Ref [12] by assuming drag coefficient to be 2.0 [6, 13] instead of 1.0, the value valid for a circular cylinder and often used for iced conductor, too [1, 2].

The T-year wind pressures with 85% and 95% confidence level are given in the 4th and 5th columns in Table V.

TABLE V
STATISTICAL RESULTS ON T-YEAR RADIAL ICE THICKNESS AND ACCOMPANYING GUST WIND

T (Yrs)	Gust Wind (m/s)		Wind Pressure (Pa)		Ice Thickness (mm)	
	85%	95%	85%	95%	85%	95%
5	21.5	23.5	332	395	8.3	9.6
10	21.8	23.9	342	409	11.5	13.5
20	22.0	24.1	347	417	14.6	17.2
30	22.0	24.2	350	421	16.3	19.3
40	22.1	24.2	351	423	17.6	20.8

50	22.1	24.3	352	424	18.6	21.9
70	22.2	24.3	353	426	20.0	23.7
100	22.2	24.4	354	427	21.5	25.5

E. Discussion

The following observations can be made from the results shown in Tables IV and V.

(1) Wind speed is almost constant regardless of the return period. More specifically, at an 85% confidence level, the hourly wind speed averaged over an ice storm for any return period is about 9 m/s. The maximum gust wind speed is about 22 m/s. In terms of wind pressure, the value is about 350 Pa, which is quite close to the current criterion of 385 Pa (8 psf) wind used by Manitoba Hydro.

(2) Ice thickness increases with return period. For the return period of 50 years, the average ice thickness is 12.79 mm, which is close to the current criterion of 12.7 mm (½ inch) ice. At the 85% confidence level, the ice thickness is 18.55 mm, which is close to 19.05 mm (¾ inch).

(3) If 100 years are used for return period, at the 85% confidence level, the ice is 21.54 mm thick, in combination with 354 Pa wind.

(4) As an extreme ice is invariably accompanied by an almost constant wind of about 350 Pa, the current Ice-Only criterion (25.4 mm or 1" ice without wind) is clearly not realistic, and therefore not necessary to exist.

IV. Conclusion

A novel approach was described in above context to deal with the combined ice and wind on overhead transmission lines. This approach was applied to investigate the ice loading across the province of Manitoba by using the available weather data at 12 weather stations in Manitoba.

The following conclusions can be made from this investigation.

(1) Wind produces not only wind pressure, but it also has important contribution to ice accretion on an overhead line. In fact, wind has invariably a greater contribution to a severe ice accretion (b > 6 mm) than freezing precipitation itself, in Manitoba.

(2) A "calm" ice storm invariably produces less ice accretion than a "windy" ice storm given the same condition otherwise. In particular, for severe ice storms (b > 12.7mm), a "calm" icing would only create about half of the ice thickness that the corresponding "windy" icing could produce.

(3) Therefore, the Ice-Only loading case is unnecessary to consider in designing an overhead power line. It is the Wind-on-Ice loading case that should only be considered because it not only causes wind pressure, but also produces invariably heavier ice than the Ice-Only loading.

(4) An extreme ice is invariably accompanied by almost constant wind speed, regardless of the return periods, at least for the province of Manitoba.

(5) For the Wind-on Ice criterion, the currently used 12.7 mm (½") ice is found to be approximately a 50-year ice thickness averaged over the province of Manitoba. If an 85% confidence level is required, the value should be raised to 19.1 mm (¾"). On the other hand, the currently used 385 Pa (8psf) wind is found to be reasonably acceptable with an 85% confidence level for the province of Manitoba.

V. References

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