CIGRE-341 **2020 CIGRE Canada Conference**
Toronto, Ontario, October 19-22, 2020

Recommended Practice for Designing Insulation to Withstand Ice and Snow on Overhead Transmission lines in British Columbia

M. L. Lu, N. R. Tavana, S. Cherukupalli, C. Singh, D. Chakrabarti
BC Hydro Power & Authority
Canada

SUMMARY

In recent years, overhead transmission lines in British Columbia (BC), particularly those newly-built lines, have been experiencing increasing number of forced outages during winter ice or snow storms. One of the main causes appears to be the flashover across an insulator string covered with ice and/or snow. For instance, eighteen forced outages occurred on a newly built 500 kV line between BC's southern interior and the lower mainland regions since its service in 2015, all located in a 6 km section of the line having high altitude. Among them, eleven forced outages occurred in January 2020 alone.

So far icing has not been a governing factor in insulation design for overhead transmission lines in BC Hydro. Rather, insulation design is governed mainly by two factors: (1) leakage distance for power frequency voltage, and (2) dry-arc distance for switching surge voltage. Due to the generally clean and rainy environment in the province of BC, the design insulation levels of the BC Hydro's transmission lines are among the lowest in the industry. This practice has served BC Hydro reasonably well historically.

This paper is intended to review the current BC Hydro practice and make recommendations accordingly. For this purpose, extensive literature survey was conducted to collect relevant information, particularly the experimental data related to the flashover of iced insulator. This data was carefully reviewed and analysed. As a result, a simple, yet rational and practical design equation is developed for estimating withstand voltage of an iced insulator, considering icing type, degree of contamination, insulator size, and altitude. Finally, new recommendations are made for improved design insulation to withstand ice and snow in British Columbia. Similar methodology may be adopted by other utilities facing similar challenges.

KEYWORDS

Altitude, Contamination, Dry arc distance, Flashover, Ice, Insulator, Overhead line, Snow, Transmission line, Withstand voltage.

mingliang.lu@bchydro.com

INTRODUCTION

In recent years, overhead transmission lines in British Columbia, particularly those newly-built lines with relatively high elevations, have been experiencing increasing number of forced outages during winter ice or snow storms. One of the main causes appears to be the flashover across an insulator string covered with ice and/or snow. For instance, eighteen forced outages occurred on a newly built 500 kV line between BC's southern interior and the lower mainland regions (hereafter referred to as "the 500 kV line") since its service in 2015, all located in a 6 km section of the line having high altitude. Among them, eleven forced outages occurred in January 2020 alone. Figure 1 shows a structure of the 500 kV line fully covered by ice and snow in January 2020.

Figure 1. Field photo of a deadend structure of the 500 kV line taken in January, 2020.

So far icing has not been a governing factor in insulation design for overhead transmission lines in BC Hydro. Rather, insulation design is governed mainly by two factors: (1) leakage distance for power frequency voltage and (2) dry-arc distance for switching surge voltage. Due to the generally clean and rainy environment, the design insulation levels of the BC Hydro's transmission lines are among the lowest in the industry (BCH 2013). The practice has served BC Hydro reasonably well.

The issue of flashover across insulator covered with ice and snow has been well investigated and documented (CIGRE 1999, 2000; IEEE 2007a, 2007b; Farzaneh and Chisholm 2009, 2014; Farzaneh 2014). However, quite different results were often obtained by different researchers depending on test methods, test conditions, sample preparation, etc. The applicability of some of these research findings to develop practical real-life solutions has proven to be challenging.

This paper is intended to summarize the existing study results and apply them to actual line design practice in BC. For this purpose, the current BC Hydro standard practice on insulation design is examined. Recommendation is made to improve the insulation design for withstanding ice and snow based on extensive literature survey on the issue. While the study is intended mainly for BC Hydro, the result is also applicable to similar jurisdictions having issues with transmission lines heavily exposed to ice and snow in winter.

CURRENT BC HYDRO DESIGN PRACTICE

Current BC Hydro standard practice regarding insulation design on overhead transmission lines is well documented in Engineering Standard ES41K1.3 R1 (BCH 2013). Per the standard, insulation shall meet following two requirements:

- Adequate dry arc distance to withstand switching surge voltage;
- Adequate leakage distance to withstand power frequency voltage under polluted conditions.

Most of BC Hydro's service area experiences frequent natural washing by rain, and pollution levels are low. Hence, for example, the specific leakage distance used on the 500 kV lines is one of the lowest in the industry and amounts to only about 23 mm/kV. BC Hydro standard insulation parameters for transmission lines are summarized in Table 1 for various voltage levels.

Table 1. Standard insulation parameters for BC Hydro transmission lines

Line Voltage (kV)	Insulator String Type [5]	Insulator String Number	LD [1] (mm)	DAD [2] (mm)	SLD [3] (mm/kV)	ED [4] (kV/m)
69	146x254x279	4	1116	717	25.5	61.1
138		7	1953	1155	22.3	75.9
230		12	3348	1885	22.9	77.5
287		15	4185	2323	23.0	78.5
360		19	5301	2907	23.2	78.6
500(Peace-S) [6]	146x254x318	23	7314	3530	23.0	90.0
500(Mica-S) [6]		23	7314	3530	23.0	90.0
500(Peace-D) [6]	170x280x368	20	7360	3598	23.2	88.3
500(Mica-D) [6]	156x280x381	21	8001	3501	25.2	90.7

Note: (1) LD = Leakage distance;
(2) DAD = Dry arc distance;
(3) SLD = Specific leakage distance;
(4) ED = Maximum power frequency stress per unit dry arc distance;
(5) Insulator type is defined by Length x Diameter x Leakage distance per piece.
(6) S for suspension insulator strings, and D for deadend insulator strings.

CATEGORIZATION OF ATMOSPHERIC ICING

Atmospheric icing may be classified into the following categories:

- Glaze or rime ice due to freezing rain or freezing drizzles when ambient air temperature is below 0^oC. The ice can be wet with icicles, or dry without icicles. Glaze ice is transparent with its density ranging between 700 and 900 kg/m^3. Rime ice is opaque or white with its density between 150 and 700 kg/m^3.
- In-cloud icing or hoarfrost due to moisture in cloud or air when ambient air temperature is below 0^oC. The ice is typically very dry and very loose with density less than 150 kg/m^3.
- Dry snow when ambient air temperature is below 0^oC (with density less than 100 kg/m^3); and
- Wet snow when ambient air temperature is above 0^oC (with density ranging from 150 to 700 kg/m^3).

Quite often, different icing types can be formed in a single storm. For example, freezing rain may be mixed with snow; and dry snow may be mixed with wet snow.

In BC, both dry and wet snows are very common. Freezing rains are relatively rare, and often come with snow. Hoarfrost may occasionally occur, too, but does not seem to cause concern for power lines. Typically, heavier ice and snow occur at higher altitude in BC. Thus, a power line should be located at lower elevation, avoiding such locations as top of mountain or ridges if feasible. The severity of ice and snow is also dependent heavily on the wind speed and direction. Therefore, a power line should be placed ideally at a location with minimum wind perpendicular to the line, for example, along a valley or mountain side.

FLASHOVER PERFORMANCE OF ICED INSULATOR

A long list of papers can be found in literature on this topic, quite often with different results by different researchers due to different test methods, test conditions, or sample preparation methods. The key and relevant results are summarized below for the purpose of practical application.

Mechanisms of Flashover across an Iced Insulator

The flashover mechanisms may be summarized briefly as below (Farzaneh 2014):

- For light icing (say less than 6 mm equivalent ice), the effect of ice is similar to contamination. Accordingly, flashover occurs along the surface of the ice. The flashover distance is thus very close to the leakage distance.
- For heavy icing (say greater than 10 mm equivalent ice), the ice tends to fill the gaps between the sheds, and bridge the entire length of an insulator string. Thus, flashover occurs by taking the shortest air distance among the metal parts, which is very close to the dry arc distance.
- For moderate icing (say 6-10 mm equivalent ice), flashover may take a route for which the distance is in between the leakage distance and the dry arc distance.

For practical purpose, it is assumed in this paper (and many others) that flashover on an iced insulator will take a route equivalent to the dry arc distance. The assumption is always conservative. Therefore, an iced insulator's withstand capability will be measured by withstand voltage per unit length of dry arc distance. In addition, power frequency voltage is always assumed throughout this paper because it is unlikely that switching operations or lightning events occur during an ice storm.

Effect of Icing Types

The effect of icing type on an insulator's withstand voltage per dry arc distance was well summarized by Farzaneh and Chisholm (2014) as in Figure 2, where the icing stress product (ISP) is defined as the product of the ice weight *w* (g per cm of dry arc distance) and the conductivity of the melted ice C (μS/cm) at 20°C (Chisholm et al. 2000).

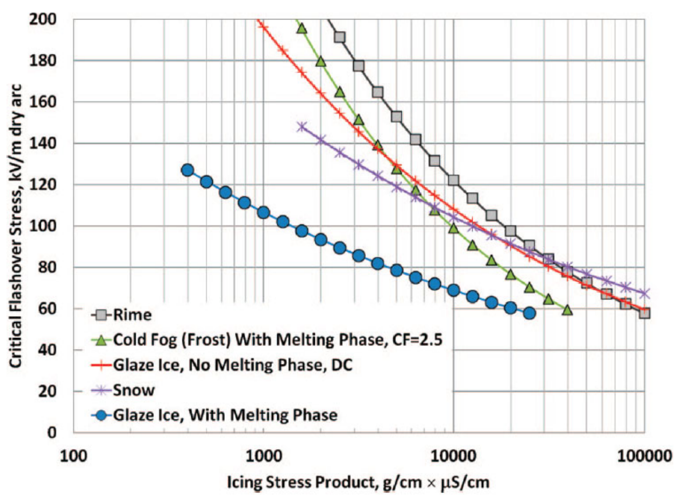

Figure 2. Flashover stress for five typical icing types (courtesy of Farzaneh and Chisholm 2014).

The data in Figure 2 may be interpreted as following:

- The glaze ice with long icicles fully bridging the entire length of an insulator string constitutes the worst case scenario and accordingly leads to the lowest withstand voltage for the same ISP and the same insulator.
- The rime ice has the highest withstand voltage, presumably because it is the driest among the five icing types.
- The melting frost, non-melting glaze, and snow seem to have comparable withstand voltage, presumably because they have comparable wetness level.
- In conclusion, it seems that, for a given ISP and insulator type, the withstand voltage depends mainly on the wetness level of the icing, regardless of the icing types.

Effect of Contamination Level

The contamination level of icing is represented by the conductivity, C (μS/cm), of the water melted from ice at 20°C as it appears in ISP. Its effects are summarized in Figure 3 for both ice and snow.

Figure 3(a) may be curve-fitted nicely by the following equation

$$E_{ws} = 178\ C^{-0.2} \tag{1}$$

Where Ews is the withstand voltage per unit dry arc distance (kV/m).

Similarly, Figure 3(b) may be curve-fitted nicely by the following equation

$$E_{ws} = 32.8\ C^{-0.2} \tag{2}$$

It is important to note that both equations produce the same exponent value of 0.2 approximately, regardless of ice or snow.

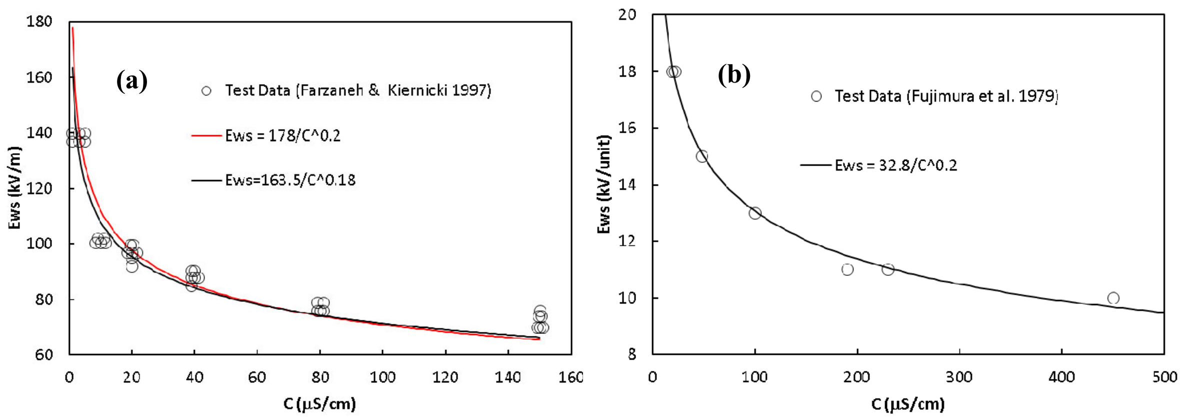

Figure 3. Variation of the withstand voltage of the insulators as a function of the conductivity C of water melted from ice for **(a)** wet ice (Farzaneh and Kiernicki 1997); and **(b)** snow (Fujimura et al. 1979), for the same conditions otherwise.

Effect of Icing Mass

The effect of both icing mass and density is represented by the ice mass m per unit dry arc distance as it appears in ISP. Its effects are summarized in Figure 4 for both ice and snow.

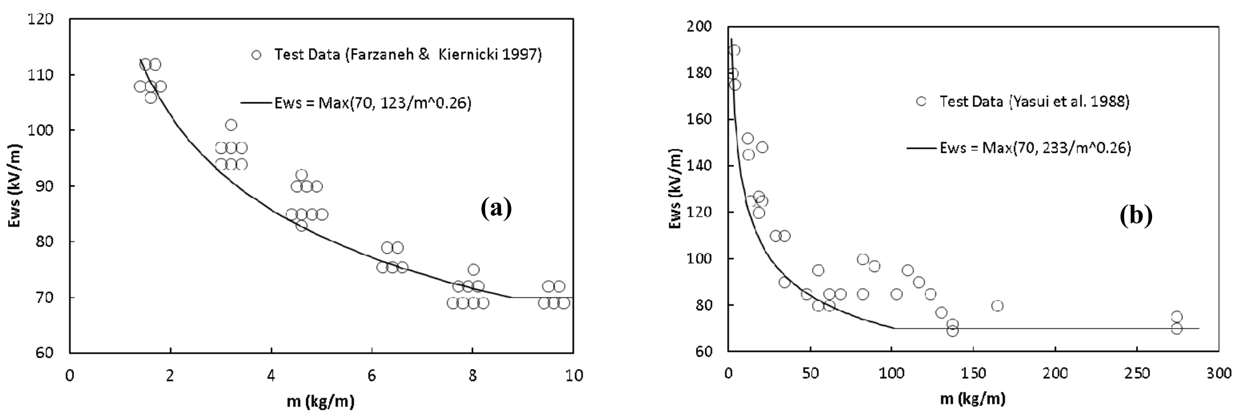

Figure 4. Variation of the withstand voltage of the insulators E_{ws} as a function of the icing mass m for **(a)** wet ice having conductivity C of 80μS/cm (Farzaneh and Kiernicki 1997); and **(b)** snow having conductivity C of 75μS/cm (Yasui et al. 1988).

Figure 3(a) may be curve-fitted nicely by the following equation

$$E_{ws} = \text{Max}\ (70,\ 123/m^{0.26}) \tag{3}$$

Where E_{ws} is the withstand voltage per unit dry arc distance (kV/m), and m is the icing mass per unit insulator length (kg/m).

Similarly, Figure 3(b) may be curve-fitted nicely by the following equation

$$E_{ws} = (70,\ 233/m^{0.26}) \tag{4}$$

It is important to note that both equations produce the same exponent value of 0.26 approximately, regardless of ice or snow.

Icing mass m (kg/m) is related to the equivalent radial ice thickness b (m) by the following semi-empirical equation:

$$m = \rho\, \pi\, b\, (b + k_D\, D) \tag{5}$$

where ρ is the density of ice (or snow) (kg/m^3). D is the diameter of an insulator's shed (m). k_D is an empirical factor and takes the value of 0.45 for regular ceramic insulators.

Eq.(5) is derived by matching the following empirical equation (Farzaneh 2014):

$$m = 1500\,D\,b \tag{6}$$

See Figure 5 for the comparison of the two equations.

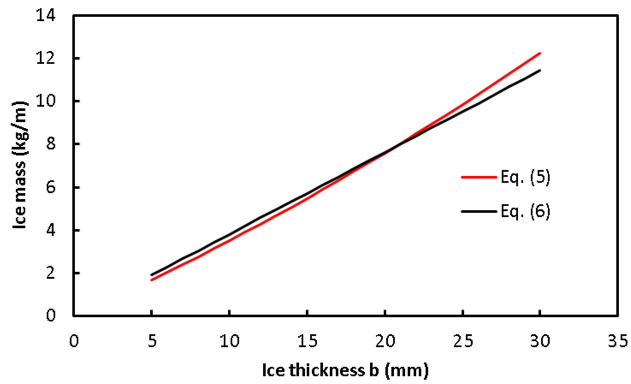

Figure 5. Comparison of the two equations the correlate ice mass with ice thickness (assuming D = 254mm, and $\rho = 900 kg/m^3$).

Effect of Altitude

The effect of altitude on the flashover performance of an iced insulator may be represented by the following equation (Farzaneh et al. 2006)

$$E_{ws}/E_{ws0} = (P/P_0)^{\alpha} \tag{7}$$

Where E_{ws} and E_{ws0} are the withstand voltage per unit dry arc distance (kV/m) under the air pressure P (kPa) and the standard air pressure P_0 = 101.3 kPa, respectively. It is recommended that the empirical exponent α take the value of 0.45. Tests indicate that α may vary from 0.40 to 0.53 (Farzaneh et al. 2006; Hu et al. 2007).

On the other hand, the air pressure P is related to the altitude z by (Jacob 1999):

$$P/P_0 = e^{(-z/zr)} \tag{8}$$

where z is the altitude (km), and zr is the reference altitude of 8.5 km.

Inserting Eq. (8) into Eq. (7) leads to

$$E_{ws}/E_{ws0} = e^{(-0.45z/zr)} \tag{9}$$

Table 2 is created from Eq. (9) to illustrate the altitude effect.

Table 2. Effect of Altitude on the withstand voltage of insulator.

z (km)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
P/P_0	1	0.943	0.889	0.838	0.790	0.745	0.703	0.662	0.625	0.589	0.555
E_{ws}/E_{ws0}	1	0.974	0.948	0.924	0.900	0.876	0.853	0.831	0.809	0.788	0.767

Effect of Insulator Diameters

The effect has been investigated experimentally by Farzaneh et al. (2006). It was concluded there that the flashover withstand voltage of an insulator is inversely proportional to the 0.19 exponent of its shed diameter, or

$$E_{ws} \propto D^{-0.19} \tag{10}$$

A similar result can be obtained by inserting Eq. (6) into Eq. (3) or Eq. (4) so that

$$E_{ws} \propto D^{-0.26} \tag{11}$$

Both Eqs. (10) and (11) indicate that, for the same conditions otherwise, an insulator with smaller diameter tends to have greater flashover withstand capacity, mainly due to the smaller ice mass it will collect. These results confirm, from another perspective, that the flashover along an iced insulator is governed practically by the dry arc distance, not the leakage distance.

Effect of Insulator Types

Following observations can be made from the literature survey:

- Polymer insulators seem to perform better than porcelain or glass insulators (Farzaneh & Drapeau 1995; Jiang, et al. 2014). This may be explained partly by the factor that polymer insulators are typically much smaller in diameter than porcelain or glass insulators.
- Anti-fog type insulators seem to perform better than standard ones for relatively light icing due to longer leakage distance but may not perform better for heavy icing (Farzaneh 2014; Farzaneh & Drapeau 1995; IEEE 2007b).
- Insulators with alternating diameters or booster sheds seem to perform better than regular ones having same shed diameter (IEEE 2007b, CIGRE 1999, Yin et al. 2015).

Effect of Insulator Orientation

Following observations can be made from the literature survey:

- For an insulator covered with wet ice, a vertical arrangement seems to be the worst, and a horizontal one seems to be the best (CIGRE 1999. This is because icicles could easily bridge the sheds for a vertical insulator, while such a bridging is difficult for a horizontal one.
- For snow (particularly dry snow), a vertical arrangement seems to be the best, and a horizontal one seems to be the worst (CIGRE 2000). This is because it is difficult for snow to accumulate on a vertical insulator, but is much easier on a horizontal one.
- Overall, an orientation of about 45 degrees or a V-type arrangement seems to be the best (CIGRE 1999; IEEE 2007b), considering that both ice and snow could occur.

Effect of Dry Arc Distance

An insulator's performance for withstanding ice/snow induced flashover depends for the most part on the length of dry arc distance (IEEE 2007b; Farzaneh 2014). In fact, increased insulation length (or dry arc distance) remains the most reliable way to improve performance (IEEE 2007b). it has been demonstrated experimentally that the flashover withstand voltage of an iced insulator is approximately proportional to its dry arc distance, regardless of ice (Farzaneh 2014; Jiang et al. 2007) or snow (Yasui et al. 1988; Fujimura et al. 1979). This justifies the use of withstand voltage per unit dry arc distance for measuring the performance of an insulator for the purpose of ice/snow induced flashover.

RECOMMENDED DESIGN PRACTICE

Based on above studies, it is recommended that following equation be used for practical design purpose:

$$E_{ws} = \max[70, A/m^{0.26}]\,(C_0/C)^{0.2}\,e^{-0.45z/zr} \tag{12}$$

Where E_{ws} is again the withstand voltage per unit dry arc distance (kV/m). *m* is the ice/snow mass per unit length (kg/m). C_0 is the reference conductivity of melted water from ice/snow, and takes the value of 75 μS/cm. C (μS/cm) is the conductivity of melted water from ice/snow under concern. z (km) is the altitude/elevation where the insulator is located. zr is the reference elevation and takes the value of 8.5 km. In addition, A is an empirical parameter and should take the value of 123 or 233 for wet ice or dry snow, respectively, as shown in Eqs. (3) and (4).

In practice, both ice and snow can occur, either separately or in combination. Both ice and snow can be wet or dry. Therefore, for practical purpose, the value of 123 defines the lower bound (which is the scenario of wet ice), and the value of 233 defines the upper bound (which is the scenario of snow). Depending on the local weather conditions and design conservativeness, the design *A* value could range between the lower and upper bounds. Accordingly, following three design levels are recommended:

- *Level 1:* *A* takes the mean value of 178. This may apply to any regions where snows prevail and freezing rain is infrequent.
- *Level 2:* *A* takes the lower quartile of 150. This may apply to any regions where both snow and freezing rain prevail and freezing rain does not tend to produce wet ice with long icicles.
- *Level 3:* *A* takes the lower bound value of 123. This may apply only to any regions where freezing rain prevails and often produces very wet ice with long icicles.

The above three design levels as well as the upper bound curve are plotted in Figure 6 for C = 75µS/cm at sea level (z = 0 km).

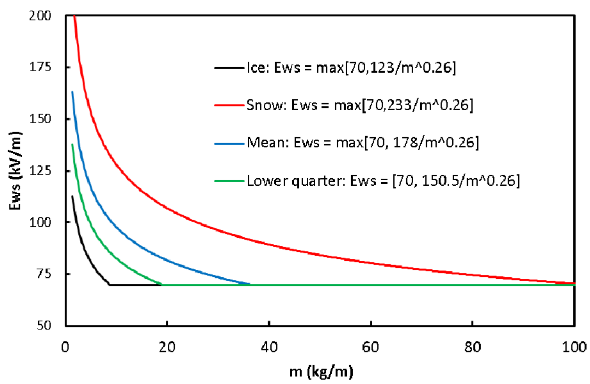

Figure 6. Illustrating the different design levels for iced insulators (C = 75 µS/cm, z = 0 km).

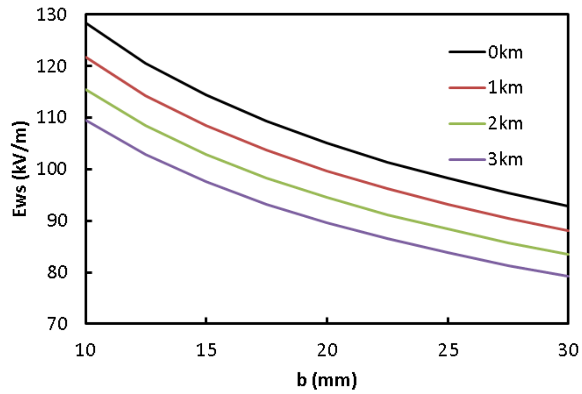

Figure 7. Illustrating Level 1 design for D = 254mm and C = 75 µS/cm.

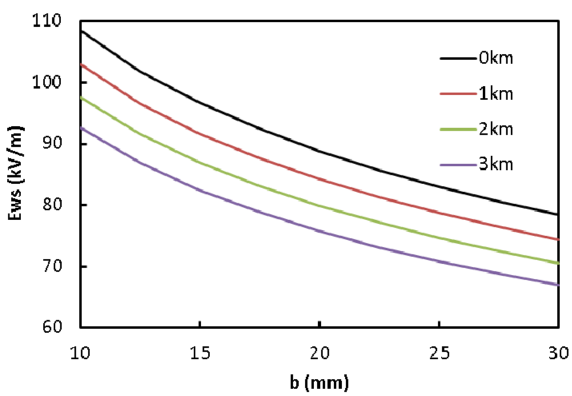

Figure 8. Illustrating Level 2 design for D = 254mm and C = 75 µS/cm.

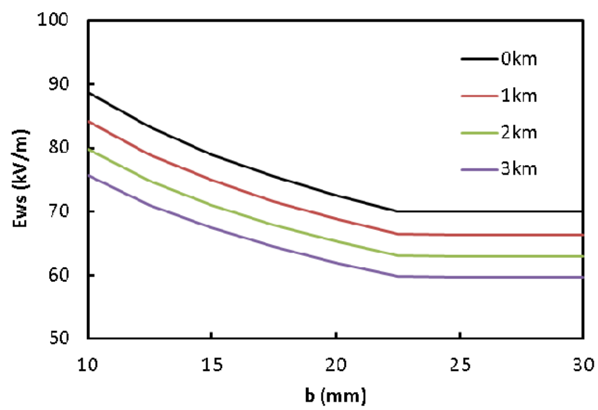

Figure 9. Illustrating Level 3 design for D = 254mm and C = 75 µS/cm.

In British Columbia, snow storms are more common than freezing rainstorms, particularly wet snow prevails. Wet glaze ice with long icicles due to freezing rainstorms is rare. Thus, either Level 1 or Level 2 may apply to BC depending on local weather conditions. In addition, the contamination level is generally low in BC. Thus, use of the reference C value of 75 µS/cm seems to be reasonably conservative. Accordingly the minimum required withstand voltage per unit dry arc distance is recommended for BC as a function of both the equivalent ice thickness *b* and the altitude *z*. in Figures 6, 7, and 8 for Levels 1, 2, and 3, respectively. Here *b* is the thickness of equivalent circular glaze ice having the density of 900 kg/m^3. It is recommended that *b* should have a design return period of 50 years.

CONCLUSION

Based on extensive literature review and study, a simple, practical yet comprehensive equation has been established for designing insulation to withstand flashover due to ice deposition on insulators. The equation is able to consider many important factors, such as icing type, insulator diameter, ice mass and density, altitude, contamination level. Accordingly, three different design levels are defined and recommended. While the recommendations are intended for British Columbia, the methodology could be applicable for any cold regions facing similar challenges with regional adjustments.

BIBLIOGRAPHY

BCH (2013): “Insulation and Electrical Clearances for Conductors to Supporting Structures.” Transmission Engineering Standard ES41K 1.3 (R0), BC Hydro.

CIGRE (1999): “Influence of Ice and Snow on the Flashover Performance of Outdoor Insulators: Part I: Effects of Ice.” No. 187, Electra.

CIGRE (2000): “Influence of Ice and Snow on the Flashover Performance of Outdoor Insulators: Part II: Effects of Snow.” No. 187, Electra.

IEEE (2007a): “Selection of Line Insulators With Respect to Ice and Snow – Part I: Context and Stresses.” IEEE Task Force on Icing Performance of Line Insulators. IEEE Trans. Power Delivery, Vol.22, No.4.

IEEE (2007b): “Selection of Line Insulators With Respect to Ice and Snow – Part II: Selection Methods and Mitigation Options.” IEEE Task Force on Icing Performance of Line Insulators. IEEE Trans. Power Delivery, Vol.22, No.4.

Farzaneh, M. (2014): “Insulator Flashover under Icing Conditions.” IEEE Trans. Dielectrics & Electrical Insulation, Vol.21, No.5.

Farzaneh, M., Drapcau, J. F. (1995): “AC Flashover Performance of Insulators Covered with Artificial Ice.” IEEE Trans. Power Delivery. Vol. 10, No. 2.

Farzaneh, M., Kiernicki, J. (1997): “Flashover Performance of IEEE Standard Insulators Under Ice Conditions.” IEEE Trans. Power Delivery, Vol.12, No.4.

Farzaneh, M., Zhang, J. and Volat, C. (2006): “Effect of Insulator Diameter on AC Flashover Voltage of an Ice-covered Insulator String.” IEEE Trans. Dielectrics & Electrical Insulation. Vol.13, No.2.

Farzaneh, M., Zhang, J., Frechette, M., Sakakibara, T., and Da Silva, E. (2006): “Effects of High Altitude and Atmospheric Icing on the Performance of Outdoor Insulators.” IEEE/PES Trans. & Dist. Conf. & Exposition: Latin America.

Hu, J., Sun, C., Jiang, X., Zhang, Z., and Shu, L. (2007): “Flashover Performance of Pre-contaminated and Ice-covered Composite Insulators to be Used in 1000kV UHV AC Transmission Lines.” IEEE Trans. Dielectrics & Electrical Insulation. Vol. 14, No. 6.

Yasui, M., Naito, K., Hasegawa, Y. (1988): “AC Withstand Voltage Characteristics of Insulator String Covered with Snow.” IEEE Trans. Power Delivery, Vol.3, No.2.

Matsuda, H., Komuro, H., Takasu, K. (1991): “Withstand Voltage Characteristics of Insulator String Covered with Snow and Ice.” IEEE Trans. Power Delivery, Vol.6, No.3.

Farzaneh, M, and Chisholm, W. A. (2009): “Insulators for Icing and Polluted Environments.” New York, USA. IEEE/Wiley.

Farzaneh, M., Chisholm, W. A. (2014): “50 Years in Icing Performance of Outdoor Insulators.” IEEE Electrical Insulation Magazine, Vol.30, No.1.

Chisholm, W. A., Kuffel, K., Farzaneh, M. (2000): “The Icing Stress Product, a Measure for Testing and Design of Outdoor Insulators in Freezing Conditions.” Proc. 2nd Int. Workshop on High Voltage Engineering. Tottori, Japan.

Jacob, D. J. (1999): “Introduction to Atmospheric Chemistry.” Princeton University Press, USA.

Jiang, X., Xiang, Z., Zhang, Z., Hu, J., Hu, Q., and Shu, L. (2014): “Comparison on AC Icing Flashover Performance of Porcelain, Glass, and Composite Insulators.” Cold Regions Science & Technology. No. 100.

Yin, F., Jiang, X., Farzaneh, M., and Hu, J. (2015): “Electrical Performance of 330-kV Composite Insulators with Different Shed Configurations under Icing Conditions.” IEEE Trans. Dielectrics & Electrical Insulation. Vol. 22, No. 6.