Design Ice and Wind on Overhead Transmission Lines in British Columbia

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Abstract— **This paper describes BC Hydro's current design practice for determining ice and wind loads on overhead transmission lines based on the reliability-based design principles. Following important issues are discussed and clarified: selection of design reliability levels, prevention of cascading failures, determination of IceWind load case, inclusion of IceOnly load case, consideration of un-equal ice and broken wire load cases, consideration of wet snow and galloping. The BC Hydro standard practice has been developed based on the industry's best practice and BC Hydro's own successful experiences in the past. This paper may serve as a good reference for other utilities in designing their transmission lines.**

Keywords— ***Freezing rain, Galloping, Ice, Loading, Overhead Lines, Transmission, Wet snow, Wind***

I. INTRODUCTION

The province of British Columbia (BC) is prone to extreme ice and wind so that the design of overhead transmission lines (OHTL) is usually governed by them. BC Hydro (BCH) has been using reliability-based design (RBD) since 2008 as detailed in its Engineering Standard ES41B0300 [1]. This standard was developed by applying the RBD principles set up in the IEC 60826 standard [2] or CSA 60826 standard [3], considering good engineering practices and local climate and geographical conditions in BC. In this paper, the design ice and wind load as applied to overhead transmission lines is presented in detail as per the current BC Hydro standard practice.

II. RELIABILITY LEVELS

The reliability level is probably the most important parameter in the reliability-based design (RBD) of a transmission line. In principle, it shall be determined to minimize the life-cycle cost of the line, or to maximize the life-cycle benefit to the society. An OHTL's life cycle cost shall include not only the initial construction cost, but also all of the other costs that may be incurred during its life, such as routine maintenance cost, repair costs to fix any minor or major damages to the line due to any natural hazards or motor vehicle accidents, etc. In addition, the life cycle cost shall also include any impacts on local communities, environmental costs, etc. For example, a less reliable OHTL may be less expensive to build, but may end up with much greater life cycle cost due to greater maintenance cost, longer and more frequent power outages, etc. Thus, in principle, there would be an "optimum" reliability level that corresponds to the minimum life cycle cost.

BCH sets up the following four levels as the minimum acceptable target return period, T, for different transmission line voltages

- Level 1: T=50 years (69 and 138 kV lines)
- Level 2: T=100 years (230 and 287 kV lines)
- Level 3: T=200 years (360 and 500 kV lines)
- Level 4: T=400 years (critical lines).

A higher reliability level can be justified by considering the importance of the line or line section in the network. For instance, a "radial" line may be designed to a higher reliability than a "looped" one of the same voltage; a double circuit line may be designed at a high level; certain important sections (that trespass, say busy water ways, urban zones, mountainous areas) of a line may also be designed at a higher level to minimize the life cycle cost.

The basic consideration of selecting the above design return periods for various reliability levels is that the design load will be increased by approximately 15 % in overall for one level higher. This can be achieved roughly by doubling the return periods based on the historical weather data in BC [4], as shown in Table I.

TABLE I. JUSTIFYING RELIABILITY LEVELS FOR BC

Reliability Level	1	2	3	4
Return Period T (yrs)	50	100	200	400
Wind Speed Scaling Factor	1.00	1.07	1.14	1.21
Ice Thickness Scaling Factor	1.00	1.25	1.50	1.75
Wind Pressure Scaling Factor (WindOnly)	1.00	1.14	1.30	1.46
Ice Weight Scaling Factor*	1.00	1.35	1.75	2.19
Wind Load Scaling Factor (IceWind)*	1.00	1.13	1.25	1.38

*Assuming conductor diameter of 25.4 mm.

Tables II and III compare four standards: BCH [1], ASCE 74 [5], IEC 60826 [2] and CSA 60826 [3] in terms of the scaling factors of wind speed and ice thickness for various return periods. It can be observed from the tables that for wind speed, all of the four standards have almost identical scaling factors. This is presumably due to the fact that all methods adopt the classic Gumbel distribution to well fit the historical extreme wind series. On the other hand, for ice thickness, the BCH's scaling factors are very close to the ASCE 74 values [5], while both the IEC 60826 and CSA 60826 standards have comparable values. It is believed that both the IEC 60826 and CSA 60826 adopted the Gumbel distribution to fit the historical extreme ice thickness values. However, the Gumbel distribution may not perform well for ice thickness. Instead, ASCE 74 adopted the “peaks-over-threshold” method with the generalized Pareto distribution [6] and BCH adopted the modified Gumbel distribution [4]. As illustrated in Figure 1, the linear relationship between the T-year ice thickness I_T and the variable Y as assumed with the Gumbel distribution is usually not valid. Rather, only the tail portion may be assumed to be linear. Here Y is related to T by

$$Y = -\log\left[\log\left(\frac{T}{T-1}\right)\right] \quad (1)$$

TABLE II. Comparison of Scaling Factors for Wind Speed

T (yrs)	ASCE [5]	IEC [2]	CSA [3]	BCH [1]
25	0.92	--	0.95	0.93
50	1.00	1.00	1.00	1.00
100	1.07	--	1.07	1.07
150	--	1.10	1.10	1.11
200	1.14	--	1.14	1.14
400	1.20	--	1.18	1.21
500	--	1.20	1.20	1.23

TABLE III. Comparison of Scaling Factors for Ice Thickness

T (yrs)	ASCE [5]	IEC [2]	CSA [3]	BCH [1]
5	--	--	--	0.50
10	--	--	--	0.65
25	0.80	--	0.95	0.80
50	1.00	1.00	1.00	1.00
100	1.25	--	1.10	1.25
150	--	1.20	1.15	--
200	1.50	--	1.20	1.50
400	1.85	--	1.25	1.75
500	--	1.45	1.30	--

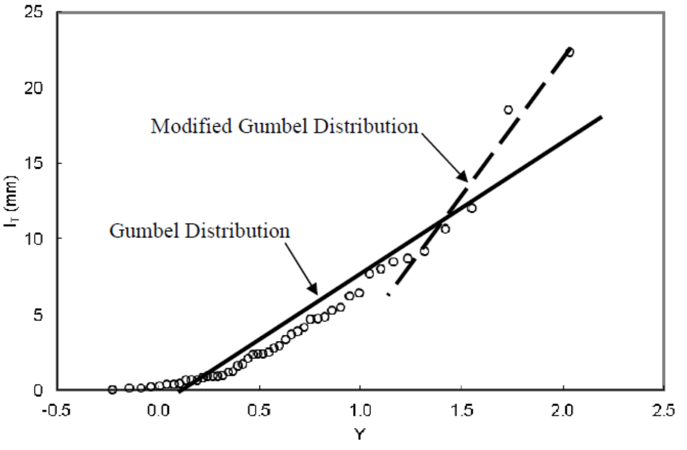

Figure 1. Illustrating the relationship between I_T and Y [4].

III. Prevention of Cascading Failures

Per the traditional deterministic-based design (DBD), both loads and strengths are assumed to be constants without variation. Thus, an OHTL is considered to be “safe” with certainty if the design strength exceeds the design load. However, according to RBD, both loads and strengths are considered as “random variables” so that there is always a likelihood of failure regardless of how reliable an OHTL may be designed. Therefore, a two-tiered design philosophy shall be adopted in RBD:

- An OHTL shall be intact without any (initial) damage or failure if the actual load is below the design load.
- Proper design measures shall be taken to minimize the consequences of any initial damage or failure in case the design load is exceeded.

TABLE IV. Strength Factors for Various Line Components [1]

Component	Reliability	Security	Safety
Tangent Structure	0.90	N/A	0.50
Angle Structure	0.80	N/A	0.50
Strain Structure	0.75	N/A	0.50
Deadend Structure	0.75	0.75	0.50
Conductor	0.60	0.60	0.50
Hardware	0.50	0.50	0.50
Insulator	0.50	0.50	0.50
Guy Wire	0.85*	0.85*	0.50
Foundation	0.90*	0.90*	0.50
Soil/Rock Capacity	0.85*	0.85*	0.50

*Additional factor to be applied on the strength factor of a given structure.

The latter is implemented by preventing cascading failure. More specifically, following measures are adopted in BCH to prevent cascading failure:

- Implement strength coordination among various components of an OHTL by applying different strength factors on different components while keeping the unity load factor. In principle, a component with higher importance or lower cost shall be designed to higher reliability. Thus, for example, angle structures shall be stronger than tangent structures; strain structures shall be stronger than angle structures; and deadend structures shall be stronger than strain structures. In this way, in case a tangent structure fails, its adjacent angle structure or strain structure may likely contain the failure. As the last resort, the adjacent deadend structure will certainly stop the cascading failure, as a deadend structure is defined in BCH as the cascading stopping structure by ensuring that the structure is able to withstand any broken wire (conductor or skywire) conditions under all the design extreme loads (for the given design return period). See Table IV for the various strength factors for different components for the purpose of strength coordination.

- As a minimum requirement, deadend structures shall be installed one per every 10 km or N structures, whichever governs. Here, N shall be 25, 30, 35, or 40 for 500/360 kV, 230/287 kV, 138 kV, or 69 kV transmission lines, respectively. For important line sections (such as important river crossings) deadend structures should be placed closer (e.g. deadend – suspension – suspension – deadend, or even deadend – deadend). Usually, deadend structures are placed at line angles.

In Table IV, the reliability load cases contain all the load cases related to intact lines, including the un-equal ice load cases. The security load cases normally refer to all of the broken wire load cases under the extreme ice and/or wind conditions for the design T-year return period. On the other hand, the safety load cases correspond to all the load cases related to construction, maintenance, and general public safety. It is worth mentioning that the strength factors as given in Table IV for security load cases include the dynamic load factors due to broken wire conditions. A unity strength factor may be used for a security load case if the dynamic load factor is considered explicitly.

IV. COMBINED ICE AND WIND

The combined ice and wind load case (or IceWind for brevity) is the basic one for all ice related load cases. It consists of T-year extreme ice I_T plus a representative maximum wind during extreme ice storms W_I at the representative ambient air temperature of -5 °C. In principle, IceWind shall be determined based on statistical analysis of local historical weather data. However, the resulting IceWind shall meet the minimum requirements shown in Table V.

TABLE V. MINIMUM REQUIRED ICEWIND LOAD [1]

Reliability Level	1	2	3	4
Return Period T (yrs)	50	100	200	400
Ice Thickness I_T (mm)	12.5	15.0	17.5	20.0
Wind Pressure W_I (Pa)	200			300

It is recommended that the accompanying wind pressure W_I for "IceWind" be estimated by the following equation:

$$W_I = 0.5\tau\rho(K_R K_T V_{rB})^2 C_{I-S} G_C G_L \qquad (2)$$

where, ρ is the standard air density of 1.225 kg/m^3 at 15°C and seal level; τ is the temperature correction factor for air density, and may take the value of 1.05; K_R is the terrain roughness factor as defined in IEC 60826 [2] for the four terrain categories A, B, C and D; K_T is the scaling factor for wind speed from 50-year to weekly maximum and may take the value of 0.5; V_{rB} (m/s) is the 50-year wind averaged over 10 minutes at the standard height of 10m on Terrain B ground; C_{I-S} is a combined factor that includes the drag coefficient of the iced conductor and the glaze-to-snow conversion factor, and shall take the value of 2.0. G_C is the combined gusting and height factor for conductors as defined in IEC 60826 [2]. G_L is the span factor and may take the value per the following German standard equation [7]

$$G_L = \min\,[1, (0.6 + 80/L)] \qquad (3)$$

where L is the span length (m).

Table VI compares span factors from three methods: IEC 60826 [2], ASCE 74 [5], and the German one [7]. Here, ASCE-C and ASCE-B refer to the span factors for Terrain C and B per ASCE 74 [5]. The ASCE's Terrain C and B are equivalent to IEC's Terrain B and C, respectively. It can be seen from the table that the German equation produces a result same as IEC 60826 for short spans (<200 m) and similar to ASCE 74 for relatively long spans. The German equation has been selected by BCH due to its simplicity.

TABLE VI. COMPARISON OF SPAN FACTORS FROM VARIOUS METHODS

Span Length (m)	200	300	400	500	600
IEC 60826 [2]	1.00	0.98	0.95	0.92	0.89
ASCE-C [5]	0.89	0.85	0.82	0.79	0.78
ASCE-B [5]	0.84	0.80	0.78	0.75	0.72
German [7]	1.00	0.87	0.80	0.76	0.73

In BC, wet snow prevails often, particularly in mountainous areas with high elevations. Thus, both I_T and W_I shall be viewed as being equivalent to the wet snow effect as captured by C_{I-S} that includes the glaze-to-snow conversion factor of 1.5.

Eq. (2) represents essentially the weekly maximum, gusting wind pressure. This is justified somewhat by the fact that an ice storm hardly last more than a week. In addition, Eq. (2) shows that W_I is independent of the return period T, as demonstrated previously [8].

This IceWind load is intended to replace the traditional DBD load of CSA C22.3-1 Severe, Heavy, Medium A, or Medium B [9].

As per IEC 60826 [2], there are two IceWind load cases: IceWind1 for T-year ice in combination with the average of yearly maximum wind during ice presence, and IceWind2 for average ice in combination with the T-year wind during ice presence. The BCH's IceWind corresponds approximately to IceWind1. IceWind2 may not be necessary, as it is located somewhere between the two extreme cases: IceWind and WindOnly (i.e. the T-year extreme wind without ice).

V. ICE ONLY WITHOUT WIND

Traditionally, in some Canadian utilities, such as BC Hydro, an IceOnly load case was considered in addition to the CSA IceWind load case. Clearly, an IceOnly load case is a hypothetical load case because there is always wind during any ice storm, albeit how small the wind could be. However, this tradition is kept in the current BCH practice by considering IceOnly as derived from the IceWind load case. More specifically, the hypothetical T-year IceOnly thickness

I_{TO} is defined as 1.5 times the true T-year ice thickness I_T but neglecting wind, while the ambient air temperature remains at -5 °C. Generally, the addition of IceOnly load case will not affect the design significantly but will provide the benefit of covering any possible load cases in which I_T is exceeded but with less wind. This is because transmission structures usually perform very well in withstanding vertical loads.

Per the BCH standard [1], I_{TO} shall meet the minimum values as given in Table VII.

TABLE VII. MINIMUM REQUIRED ICEONLY LOAD

Reliability Level	1	2	3	4
Return Period T (yrs)	50	100	200	400
Ice Thickness I_{T0} (mm)	17.5	20	25	30

VI. UNEQUAL ICE LOAD CASES

The unequal (or unbalanced) ice load case "UnEqIceT" is also derived from the IceWind load case. It is intended to capture the possible non-uniform ice deposit along a line. For the purpose of designing a particular structure, it is assumed that the ice deposited on one side of the structure is $0.7I_T$, and no ice is deposited on the other side, without wind at the ambient temperature of -5 °C. The no ice condition may apply to any or all of the phases on one face at a time only (not both faces at the same time), and the remaining phase(s) shall assume ice of $0.7I_T$ on both sides.

To illustrate the load cases, assume an arbitrary *n* phases (that may include conductors, skywires, telecom wires, etc.) on both sides of a particular structure. The unequal load cases will consist of

- No ice on any combination of all of the *n* phases on the left hand side of the structure, and ice of $0.7I_T$ on all remaining phases.
- No ice on any combination of all of the *n* phases on the right hand side of the structure, and ice of $0.7I_T$ on all remaining phases.

This approach is consistent with BCH's traditional practice of using ½" (12.7 mm) or ¼" (6.35 mm) ice on one side and no ice on the other side, and is considered to be sufficiently conservative, but not overly conservative.

In contrast, IEC 60826 [2] recommends to use 70 % of T-year ice weight on one side, and 28 % of T-year ice weight on the other side. BCH's preference is to use ice thickness over ice weight to avoid possible confusion between ice thickness and ice weight. It is worth mentioning that the ice density is always assumed to be 900 kg/m^3 (for glaze ice) unless noticed otherwise.

For dead-end structures, these load cases are not necessary because the broken wire load cases always prevail.

For the purpose of checking ground clearance, the load case "UnEqIce50" should be used in which 50-year ice is used instead of T-year ice. Accordingly the conductor temperature is assumed to be 0 °C instead of -5 °C. It is assumed that the 50-year ice I_{50} is applied on the particular span in question, and half of the ice ($0.5I_{50}$) is applied on all other spans. This load case is intended mainly for checking conductor clearances to highways or railways, or any other important ground features. and is a site-specific load case.

VII. BROKEN WIRE LOAD CASES

These load cases "BW-IceWind", "BW-IceOnly", and "BW-WindOnly" constitute the three security load cases. They apply to deadend structures only, and are intended to stop cascading failure in case any damage or failure is initiated in a tension section (between two deadend structures). They are all derived load cases from their respective IceWind, IceOnly, and WindOnly load cases for an intact line, by assuming any number of wires on one face at a time (not both faces at the same time) are broken with remaining wires intact and fully loaded.

Similar to the unequal ice load cases, the broken wire load cases may be illustrated as below.

Assume an arbitrary *n* phases (that may include conductors, skywires, telecom wires, etc.) on both sides of a particular deadend structure. The broken wire load cases for IceWind, IceOnly, or WindOnly will consist of

- Broken wires on any combination of all of the *n* phases on the left hand side of the structure, and intact wires on all remaining phases under the T-year extreme loads.
- Broken wires on any combination of all of the *n* phases on the right hand side of the structure, and intact wires on all remaining phases under the T-year extreme loads.

The broken wire load cases play a critical role in ensuring that deadend structures perform well to prevent cascading failure under any design extreme ice and wind loads.

Per IEC 60826 [2], broken wire loads are usually assessed based on the so-called "residual static loads" that may not be adequate to stop cascading failure under extreme ice and wind conditions.

VIII. CONSIDERATION OF GALLOPING

The load case "Galloping" is intended for checking wire-to-wire clearance during design galloping events. Traditionally, galloping was not considered in BCH. However, the winter conditions in BC seem to suggest that galloping should be considered as a design factor. In addition, investigations into several recent flashover events on BCH OHTLs indicated that they were very likely caused by galloping. The reason why galloping did not seem to cause major problems historically might be that most of OHTLs in BCH are single circuit lines with flat configuration without shield wire. Therefore, it is recommended that for any new transmission lines galloping should be taken into proper consideration.

It is recommended that the CIGRE method [10] be used as a starting point. It is preferred that the galloping reduction factor (GRF) take the value of 1.0. However, GRF may take the value of 0.75 as minimum if necessary and with proper approval. For long spans (>400 m, say), Toye's method [11] may be used and, again, GRF of 1.0 is preferred, and minimum of 0.75 may be applied if necessary and with proper approval.

Field observations indicated that the maximum galloping amplitude (peak-peak) rarely exceeds 12 m [11]. Thus, the galloping amplitude (peak-peak) may be capped to the maximum value of 12 m if necessary and with proper approval.

It is further recommended that the representative galloping weather condition shall assume 96 Pa wind and 0 ºC conductor temperature with 6.3 mm ice.

The requirement for the minimum GRF of 0.75 is intended not only for galloping itself, but also for other conductor motions not explicitly considered, such as conductor jumping due to ice or snow shedding (ice or snow dropping), any conductor motions under gusting wind or under any joint actions of ice and wind.

The well-known CIGRE method for galloping [10] is plotted in Figure 2 in terms of Y/S as a function of S/Dc for both single and bundle conductors. Here, Y (m) is the (vertical) galloping amplitude (peak-peak); S (m) is the conductor sag under the galloping condition; Dc (m) is the conductor diameter. It can be observed from Figure 2 that the galloping amplitude Y as predicted by the CIGRE method may be questionable if S/Dc < 20 for single conductors, or S/Dc < 170 for bundle conductors. In addition, it is usually believed that, for the same conditions otherwise, bundle conductor tends to gallop greater than single conductor. However, the CIGRE method predicts the opposite for S/Dc < 480.

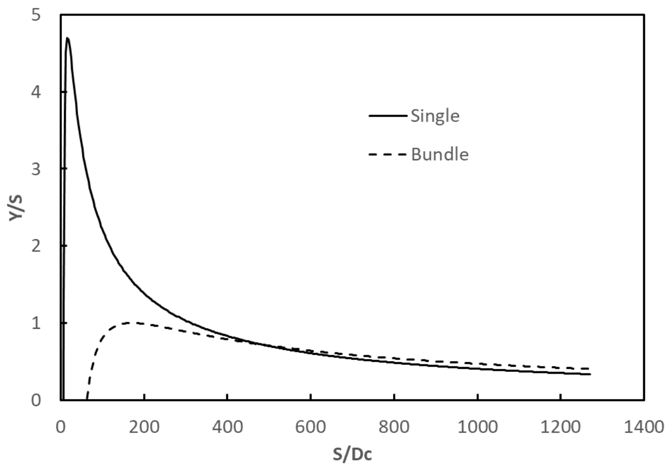

Figure 2. Illustrating the CIGRE method for galloping.

A semi-empirical equation was derived [12] and it takes the following simple form:

$$Y = 2.71\sqrt{S}/n \tag{4}$$

where both Y and S are in meters, and *n* is the number of loops for galloping. Y shall not exceed the maximum value of either 4S or 12 m, whichever governs.

Eq. (4) applies to both single and bundle conductors, as well as any number of loops of galloping.

For the single loop galloping (*n* =1), Eq. (4) is compared with the field galloping data of both EPRI [11] and Ontario Hydro [13] in Figure 3. Clearly, Eq. (4) provides an upper bound limit for majority of cases.

Various galloping analysis methods are compared in both Figures 4 and 5. Following observations may be made from the comparison:

- Davison's method predicts a constant ratio of Y/S = 1.2 for single loop galloping. This is significantly different from both the CIGRE method and Eq. (4) for n = 1 (or Lu-Loop1 in Figures 4 and 5).
- Toye's method predicts an almost constant ratio of Y/S = 0.354 for double loop galloping. This is significantly different from Eq. (4) for n = 2 (or Lu-Loop2 in Figures 4 and 5).
- As shown in Figure 4, the CIGRE method predicts that Y/S decreases with decreasing S when S is adequately small, and could even be negative.
- As shown in Figure 4, the CIGRE method predicts that galloping for single conductors is much greater than the galloping for bundle conductors for relatively small sag values (say < 10 m).
- As shown in Figure 5, the CIGRE method predicts that galloping amplitude decreases linearly with decreasing conductor diameter.
- Eq. (4) provides an alternative to the CIGRE method. An advanced method similar to Eq. (4) has been provided in the commentary of the BCH standard [1].

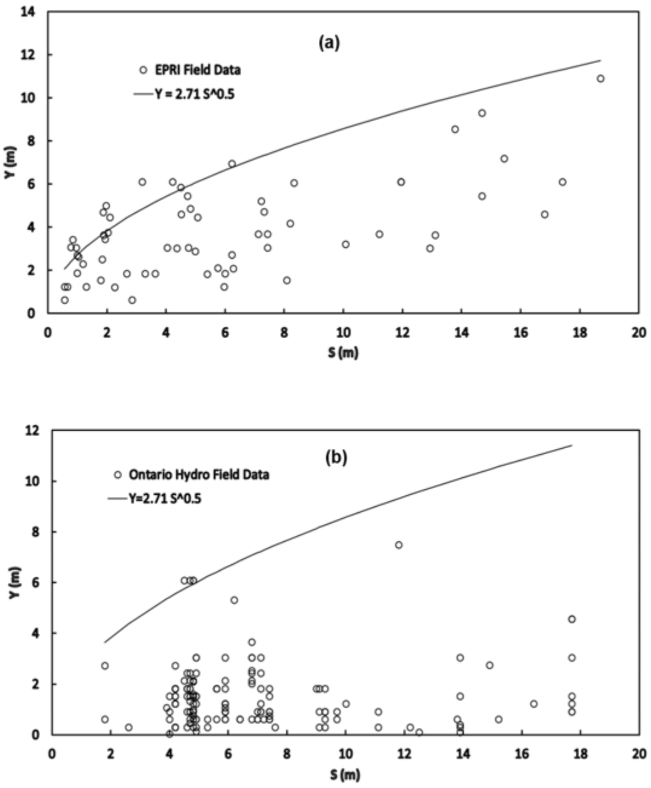

Figure 3. Comparison of Eq. (4) to the field data of (a) EPRI [11]; and (b) Ontario Hydro [13].

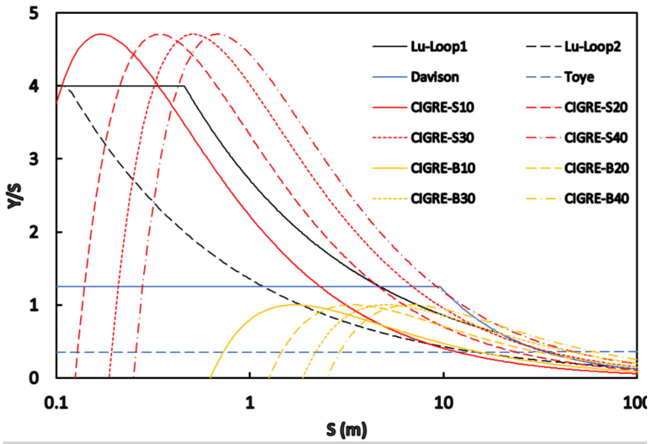

Figure 4. Comparison of various galloping analysis methods in terms of Y/S as a function of S. Here S10 and B10, for example, stand for single and bundle conductors having conductor diameter of 10 mm.

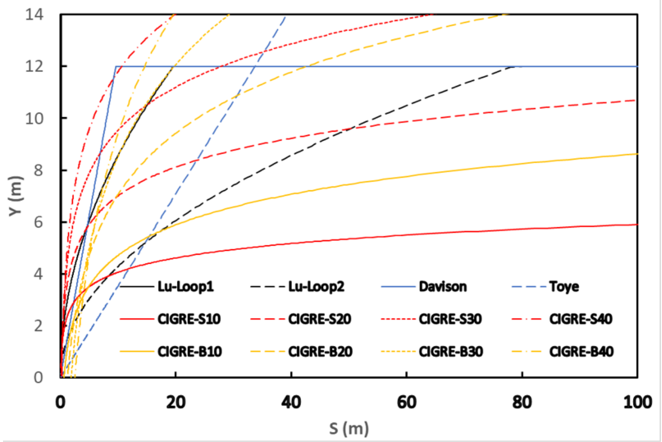

Figure 5. Comparison of various galloping analysis methods in terms of Y as a function of S. Here S10 and B10, for example, stand for single and bundle conductors having conductor diameter of 10 mm.

IX. CONCLUSIONS

Following conclusions may be made from this paper:

- It has been demonstrated that use of doubling return periods for a higher reliability level seems to be more appropriate than use of tripling return periods as specified in the IEC 60826 standard, at least for the province of British Columbia.
- Cascading failures may be prevented effectively by proper strength coordination among various line components, and more importantly, by designing deadend structures to withstand all the broken wire conditions under all of the extreme design ice and wind load cases.
- It has been recommended that T-year extreme ice be combined with weekly maximum gust wind pressure. The effect of wet snow may be taken into account equivalently by applying a wind area amplification factor of 1.5.
- Keeping the traditional IceOnly load case may be a good practice for a robust design without significantly increasing the engineering and construction cost. The T-year IceOnly thickness may take the value of 1.5 times the T-year ice thickness.
- The unequal ice load case has been recommended to be 70 % of T-year ice thickness on one side and no ice on the other side. This seems to be a better alternative to the IEC 60826 approach of 70 % of the T-year ice weight on one side and 28 % of the T-year ice weight on the other side.
- Various common galloping analysis methods, particularly the well-known CIGRE method has been examined critically. As a result, a semi-empirical, yet simple equation has been recommended as a potentially better alternative to the CIGRE method.

While references have been made to the current BC Hydro engineering practice in great details, the opinions in this paper remain those of the authors, and may not necessarily represent the views of any other individuals or organizations.

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