Effects of Ice on the Dynamics of Overhead Lines Part II: Field Data on Conductor Galloping, Ice Shedding, and Bundle Rolling

David G. Havard and Pierre Van Dyke
Havard Engineering Inc. — IREQ
3142 Lindenlea Drive — 1800, boul. Lionel-Boulet
Mississauga, Ontario — Varennes, Quebec
Canada, L5C 2C2 — Canada, J3X 1S1
dhavard@interlog.com — van_dyke.pierre@ireq.ca

***Abstract*—This paper is intended to review some of the effects of ice or wet snow, which, coupled with wind can create serious loadings and instabilities on overhead power lines. These effects include:**

- **The rebound of conductors following ice shedding**
- **Rolling of bundles due to accumulated glaze or rime ice and wind action in elevated mountain routes**
- **Dynamic loads on supports and motions of single and bundle conductors during galloping with glaze ice and wet snow coverings**

Many of these effects have partial or approximate models supported by field data, to assist in reducing the damage. However, there is a need for more work for complete understanding, including cooperative ventures employing the different resources available to universities and utilities.

I. NOMENCLATURE

d	diameter of the bundle	(m)
D	conductor diameter	(m)
f_{vs}	vortex shedding frequency	(Hz)
g	gravitational constant	(m/s^2)
k	number of subspans	
L	span length	(m)
m	mass of unit length of conductor	(kg)
M_{max}	collapse moment applied to the span	(N.m)
n	number of subconductors	
s	torsional stiffness of the conductor	(N.m^2/rad)
S	sag	(m)
S_N	Strouhal number	(~0.2)
T	conductor tension	(N)
V	wind velocity	(m/s)
θ_{max}	twist angle at collapse	(rad)

II INTRODUCTION

DIRECT observation of the effects of icing on overhead power lines is an absolutely necessary preliminary to any understanding of the many phenomena that can occur. Without such observations, it is possible to make unrealistic assumptions about the mechanisms present, which can lead to incorrect or incomplete solutions based on analysis. But there is a wide range of overhead line designs, of variations in thickness and density of the ice or snow deposits, and of differences of the wind loadings through wind speed and direction.

This paper is intended to review the different influences of ice or wet snow, coupled with wind, that can create serious loadings and instabilities on overhead power lines.

Examples of these effects include:

- The rebound of conductors following ice drop
- The rolling of bundles due to accumulated glaze or rime ice and wind action in exposed spans or in elevated mountain routes
- Aeolian vibration of conductors coated with ice in frequency ranges outside damper capabilities
- The detailed motions of conductors in vertical, longitudinal, transverse and torsional directions during galloping with glaze ice and wet snow coverings
- The dynamic loads on support structures during galloping
- Difference between galloping of single and bundle conductors

III DYNAMIC EFFECTS

A. Ice Drop

Ice drop has been simulated mechanically on test spans to derive estimated rebound heights of the conductors [1,2]. Some studies have also been made to simulate the effect of ice drop using scaled physical models and finite element analytical methods [3,4]. The finite element approach has also been used to determine that a failure of support hardware can be attributed to damage due to ice shedding [5].

These studies assumed that the ice on a span will drop in one piece and the iced and adjacent spans will rebound directly in response to this loss of weight. However, direct observations of the loss of ice during the end of glaze ice episodes show that it "unzips" along the length of the span rather than falling off in one piece. It appears that the observed damage and inferred motions could also be due to the more common and better documented dynamic effects associated with conductor galloping, which can be large enough and repeated often enough to cause damage through fatigue of the structural elements.

More observations of this phenomenon including some passive monitoring, are required to determine whether the extreme motions that have been attributed to ice dropping are real, or are the byproduct of galloping motions.

B. Bundle Rolling

Power lines passing through elevated mountainous regions are subject to the accumulation of rime ice, which can accumulate into massive deposits and lead to rolling of bundle conductors. The same effect can occur with glaze ice accumulation, especially on long spans over valleys and rivers, etc. This is a form of instability that can leave the bundle in its rolled position, with damage to the spacers, and conductors, and loss of service of the line. Utility problems due to this effect have been reported in Japan and Canada [6,7,8]. There is a serious lack of knowledge of the ice or wet snow accumulations and of the moment applied by wind action on this deposit.

Studies carried out at Ontario Hydro [9] simulated this torsional unbalance using full-scale physical models and analytical approaches. The physical modeling was carried out with two- and four-conductor bundles using two span lengths, several arrangements of spacers, and six different spacer types. A total of 58 test arrangements were evaluated, as illustrated by Fig. 1. The tests consisted of incrementally increasing the applied moment up to the point of torsional instability. Then the moment was decreased slowly until the original orientation was restored. In each case the bundle exhibits a sudden roll at the point of instability with the two, generally longest, subspans twisting several times. Fig. 2 shows the plot of moment versus angle of rotation of the middle of the bundle as measured and predicted from the analysis. The analytical model developed represents the behaviour of a general single span

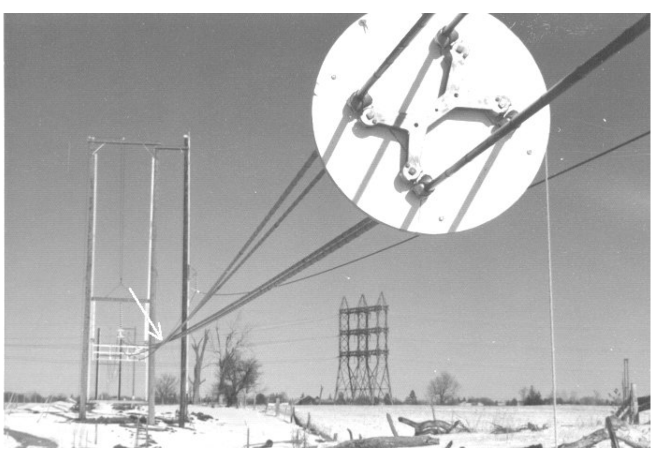

Fig. 1. Outdoor test line at Ontario Hydro used for bundle torsional stability studies showing twisted sub-conductors in mid-subspan (arrow) following collapse [7]

with fixed ends, in which the spacers are rigid and do not slip. The applied moment and angle of rotation at the point of in-

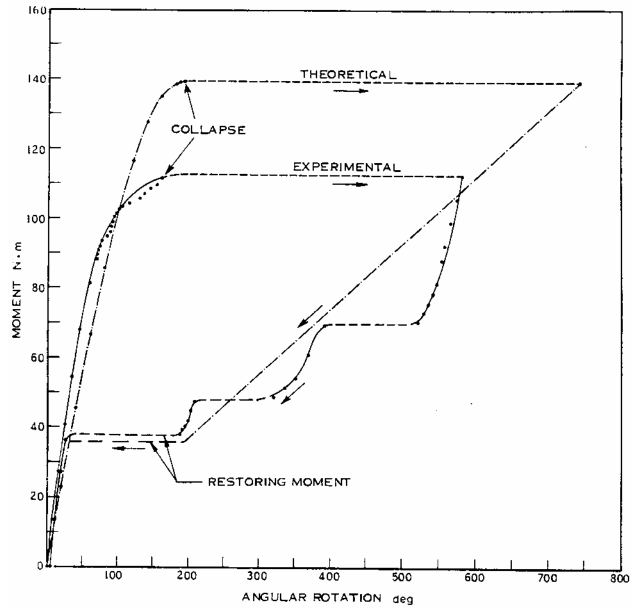

Fig. 2. Measured and theoretical values of applied moment versus angular rotation for a torsional stability test on a two conductor bundle [7]

stability for a simplified span with equal subspan lengths are given in [9] by (1) and (2), respectively.

$$M_{\max} = \frac{nkTd^2}{2L} Sin\left\{\frac{2\theta_{\max}}{k}\right\} + \frac{4ns\theta_{\max}}{L} \quad (1)$$

$$\theta_{\max} = \frac{k}{2} Cos^{-1}\left\{\frac{-4s}{Td^2}\right\} \quad (2)$$

These studies provided simplified modeling of the phenomenon and a simple tool to predict the critical conditions that can cause the bundle to roll over. This model allows the number of spacers to be selected to resist the rolling instability for a preselected amount of ice and wind moment. In studies of recent rolling instabilities, the model shows that in a region of similar ice accumulation, the longest spans are at greatest risk, and the resistance to rolling can be increased by the use of a larger than normal number of spacers.

If the spacers retain their grip on the conductors, the bundle will naturally return to its normal orientation once the ice has melted off. But if the clamps slip on the conductors, the restoration of the bundle to its normal orientation can be a very difficult and costly procedure.

While there are models that can lead to numbers and locations of spacers to resist this rolling effect, the ice accretion conditions, for which special designs should be considered, need to be determined.

C. Aeolian Vibration

Aeolian vibration occurs at a well-understood range of wind speeds, and the resulting frequencies of vibration are controlled by vibration dampers matched to that range of wind speeds, and the conductor diameter. This is described by the well established Strouhal relation (3).

$$f_{vs} = S_N\left(\frac{V}{D}\right) \quad (3)$$

But when conductors carry an ice or wet snow coating, the effective diameter is increased, as illustrated by Fig.3, and the frequencies of aeolian vibration are much lower. Consequently, there can be aeolian vibration modes, which occur with frequencies below the lowest frequency at which the damper can absorb the wind energy, and the damper can then be damaged by these modes of vibration. These lower vibration modes are different from galloping, which occurs more commonly when ice is accreted on the conductor and strong winds drive the large amplitude motion. The aeolian vibration occurs under lighter steady winds, and can cause the damage such as illustrated by Fig. 4.

D. Conductor Galloping

Perhaps the most misunderstood phenomenon is conductor galloping. This dynamic effect produces very large amplitude vertical motions of conductors when a modest to strong wind blows on ice or wet snow covered conductors. Following the introduction of vertically oriented double circuit power lines early in the 1900s, flashovers between adjacent phases during ice storms led to the circuits being forced out of service with resulting power outages. Analysis of the dynamics of large pure vertical motions, notably by Den Hartog [10], presented a rationale for the energy flow into the moving conductor and the sustained galloping motions.

Fig. 3. Example of build–up of low density ice accretion on conductors

Fig. 4. Failed Stockbridge type dampers damaged by low frequency aeolian vibration of conductors covered with hoar frost

Later, measurements were made of the motions of a number of single conductor spans during galloping by Edwards and Madeyski [11]. They used targets placed on to the conductors during the galloping events to reveal the torsional component of the motions, and recorded both vertical and torsional modes using movie cameras. Frame by frame analysis of these video films showed that there was dynamic torsional motion simultaneous and synchronized with the very visible vertical motions. This is illustrated by the sample record shown in Fig. 5. The torsional motions of single conductors are hard to see from the ground due to the distance and small thickness and transparency of the ice coating.

This torsional motion is also present when bundle conductors gallop and is more visible through the oscillations of the spacers. These torsional motions were the focus of further studies at Ontario Hydro [12, 13], and led to development of first torsional dampers, and later torsional detuning pendulums, Fig. 6, to modify the motions during galloping.

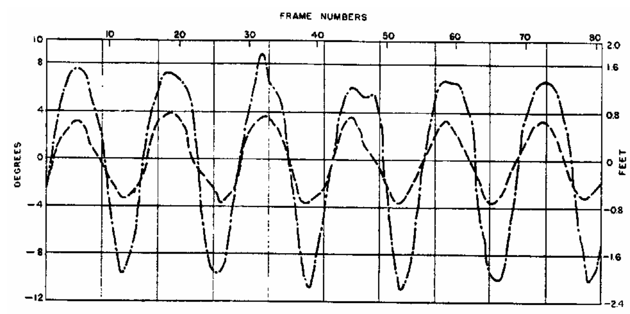

Fig. 5.Vertical and torsional galloping motions from frame by frame analysis of movie film of a single conductor span with midspan target. - - - - - vertical - . - . – torsional, horizontal scale 0.5 sec. intervals

Fig. 6. Detuning pendulums for galloping control installed on a 345 kV line.

Extensive field trials were carried out on operating power lines, mainly in North America, included systematic observation of motions of the overhead conductors during galloping occurrences. The field sites were set up to include identical spans of conductors with and without the galloping controls subject to the same conditions of ice or wet snow and wind. The program generated an extensive database on galloping motions with and without the control devices. These observations led to standards for the amount of detuning pendulum mass and arm lengths needed, and statistically supportable conclusions on the effectiveness of the detuning pendulums [14,15].

Fig. 7 and 8 show the peak to peak galloping amplitudes observed on large single conductor lines with and without detuning pendulums respectively, from 43 different galloping events. The amplitude values are scaled by dividing by the sag, to normalize data from different span lengths. The dotted lines indicate 90 % confidence limits on the data. The figures show that the maximum amplitudes observed on the single conductors can exceed the sag of the span, and that the detuning pendulums reduce the motions to about one third. Slightly greater proportional reductions in galloping amplitudes were observed on two- and four-conductor bundle conductor lines.

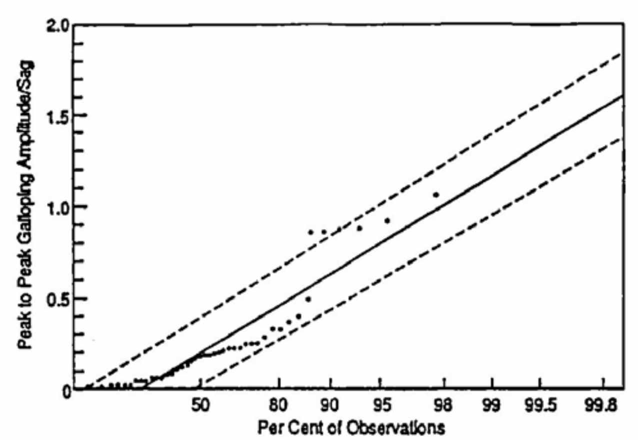

Fig. 7. Peak to peak galloping amplitudes of large single conductors without galloping controls from field observations during 43 different galloping events. Values normalized by dividing by sag [15]

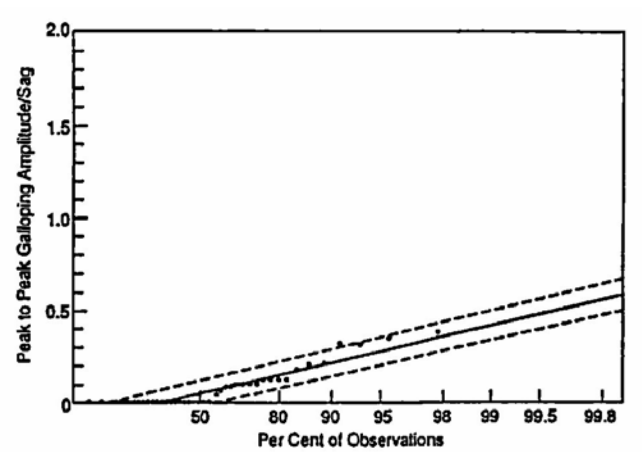

Fig. 8. Peak to peak galloping amplitudes of large single conductors with detuning pendulums from field observations during 43 different galloping events. Values normalized by dividing by sag [15]

The data obtained in these field studies were also used to develop empirical relationships between maximum galloping amplitude and span properties. Simple relationships describing peak to peak galloping amplitude versus span length, and peak to peak galloping amplitude divided by sag versus span length, for single conductors are shown in Fig. 9, [16]. The equivalent observations for bundle conductors are from a more limited range of span lengths, but the maximum observed values conform to the envelope around the data.

A more sophisticated set of relationships was developed in [17]. Better correspondence with the data was obtained when the peak to peak galloping amplitude was divided by conductor diameter, and the span length was represented by a conductor span parameter. This conductor span parameter was given by (4):

$$100\,\frac{T.D}{mg.L^2} = \frac{100.D}{8S} \tag{4}$$

This parameter has values in the range of 0.015 to 1.1, and generally the value is in reverse order to the span length. Fig. 10 shows the resulting relationship for single conductor observations and Fig. 11 for two-, three-, and four-conductor bundle data. These curves were found to be in agreement with numerical simulations of single and bundle conductor galloping using a finite element approach [18]. These are full three-dimensional simulations, including torsional freedom, and they model a full line section. Wang and Lilien use a database of aerodynamic lift, drag and moment properties of ice coatings from many different sources. The chosen ice shape was relatively eccentric given high values of lift, drag and aerodynamic moment.

This detail about the chosen ice shape serves as a reminder of another aspect of the galloping phenomenon that needs to

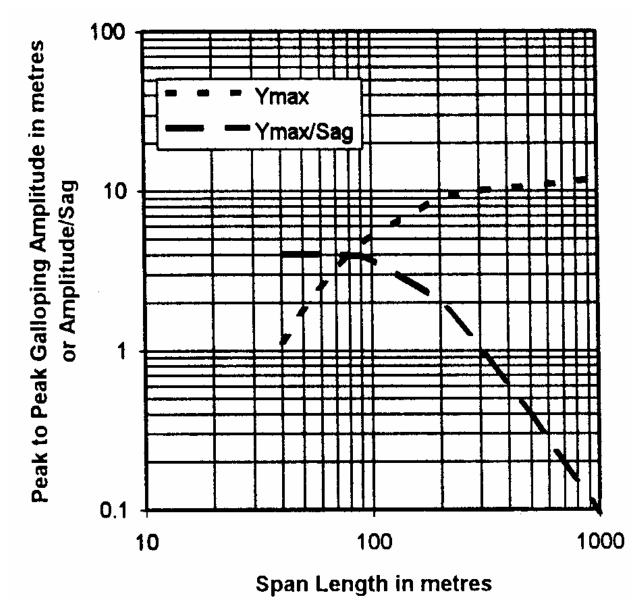

Fig. 9. Peak to peak galloping amplitude and peak to peak galloping amplitude divided by sag as a functions of span length for single conductors [16]

be studied more carefully. There is a number of theoretical approaches to describe the behaviour of the conductor under ice and wind action, but none of these fully account for the ability of conductors to gallop with virtually no ice in place. There are many records of galloping in which the ice thickness is less than 3 mm, and the changes to the section proper-

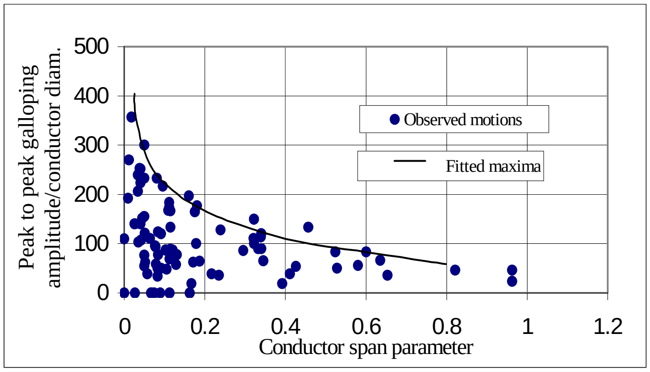

Fig. 10. Variation of observed maximum peak to peak galloping amplitude / diameter on single conductors as a function of the conductor span parameter [17]

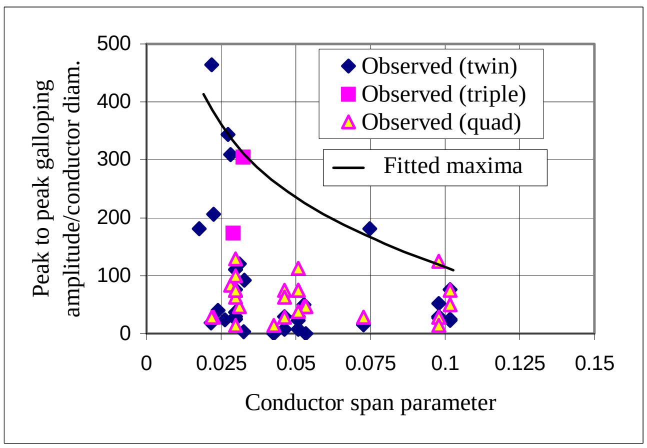

Fig. 11. Variation of observed maximum peak to peak galloping amplitude / diameter on bundle conductors as a function of the conductor span parameter

ties, and to the aerodynamic lift, drag and moment, appear to be insufficient to generate the forces required to drive the motion. It appears that the change in roughness of the conductors from one part of the surface to the other is enough to cause the motions. The physical mechanism involved in this needs to be studied to derive a better understanding, and possibly to lead to better control methods.

The detailed evaluation of the films of galloping motions from the field data also offered an opportunity to review the existing design practices for incorporating clearance within tower head dimensions to avoid conductor clashing during galloping [19,20]. The presently used design practices inscribe an elliptical envelope around the conductors after a swing-out from vertical due to wind forces. This practice has served to limit the number of conductor clashes to some extent. But in some cases it is non-conservative, especially for short distribution class spans, and for longer spans where two-loop, lower amplitude galloping is indicated to occur. In contrast, there have been many observations of large amplitude, single loop galloping on these longer spans.

The film analysis indicated that the profile shown in Fig. 12 is a reasonable alternative to the present practice. The envelope has the following features. The motions are virtually all in the vertical plane with horizontal motions always less than 10 percent of the sag. The vertical motion is asymmetrical about the stationary point of the conductor, with the average position being at the lower quarter point of the motion. For some span lengths, the field data show larger vertical peak to peak amplitudes than past design methods, as indicated in Fig. 9, 10 and 11. The main effect of this revised clearance envelope would be shorter cross arms of the tower and possibly larger vertical separations between them.

There is also a clear difference in the galloping phenomenon, where the precipitation is due to a thin layer of glaze ice, as for most events in North America, and a more pronounced layer of wet snow or rime in mountainous regions, as often reported from Japan. In the countries where glaze is more common, galloping is seen in all overhead lines, whether of single or bundle construction. In the regions susceptible to wet snow, single conductors appear to gallop far less frequently than do bundle conductors. A study of the statistics of galloping outages in The Netherlands [21] showed that the country can be divided into two regions; one subject mainly to glaze ice, and the other where wet snow is more common. The above difference in galloping behaviour was found to correspond well with the weather differences. This leads to galloping control approaches designed to convert bundle conductor into single conductor lines. The reasons for these differences remain unresolved.

There are also varying opinions among experts as to the relative frequency of galloping on single versus bundle conductors [22]. This extends to applications in which bundle lines in Europe have been "despacered" as a mitigation technique against galloping. There are clearly differences in the "span parameter" derived using (4) above, which indicates that there could be different sensitivities, possibly related to the deposition of glaze ice versus wet snow or rime. This span parameter has difference is highlighted in Fig. 13, which represents data from lines invovled in 166 separate galloping events. This topic remains unresolved at this time.

The final galloping related issue is the dynamic loadings that can occur on the support structures during galloping. These loads are applied repeatedly to the support structures during each galloping event. A recent paper [23] included a

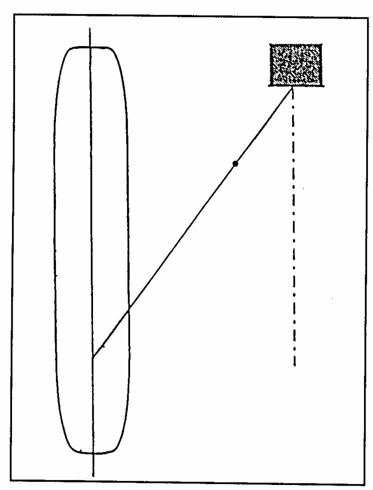

Fig. 12. Proposed modified galloping motion envelope based on analysis of films of observed galloping occurrences [15]

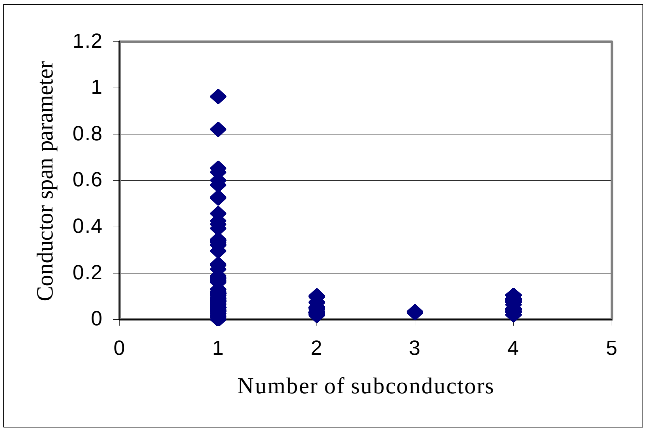

Fig. 13. Conductor span parameter as a function of number of subconductors. This shows a clear distinction between single and bundle conductors, and the similarity among all types of bundle conductor [17]

survey of field measurements work, plus some simplified analysis on this topic. That survey of field measurements revealed that the vertical loads applied to the tower arms and to the support hardware and insulators was up to 2.0 times the static vertical load with ice on the conductor. The survey also showed that the horizontal loads applied to dead end or strain structure could be as high as 2.8 times the static tension in the conductors. These loads are not normally included in the design of the structures, and are generally assumed to be covered by other extreme loadings such as heavy ice loads and maximum wind loads.

IV. CONCLUSIONS

This paper has highlighted a number of unresolved issues involving icing of overhead lines that are worthy of further study.

1. Ice drop may or may not be a sudden release of a full span of ice, and may be mistaken for the effects of galloping.
2 Monitoring stations need to be installed in critical locations subject to bundle rolling to provide field data on the phenomenon and the effectiveness of remedial measures.
3. Special dampers need to be developed to reduce the amplitudes of aeolian vibration of overhead lines subject to the build up of hoar frost.
4. Aerodynamic studies of wind flow around moving conductors with thin ice accretions are needed to understand the mechanism causing galloping to initiate.
5. Studies of these phenomena require the cooperation of electrical utilities and universities. Universities have the potential capability to further the understanding of the mechanics of overhead line behaviour, and conduct physical and numerical simulations of the phenomena, while the utilities have the potential to install monitoring and recording devices to measure key variables on line prone to ice and wind storms.

V. REFERENCES

[1] V. T. Morgan and D. A. Swift, “Jump height of overhead line conductors after the sudden release of ice loads”, Proc. IEE., Vol. 111, No. 10, 1964, pp. 1736-1746.
[2] J. R. Stewart, “Ice as an influence on compact line phase spacing”, Proc. IWAIS, Hanover, New Hampshire, 1983, pp. 77-82.
[3] A. Jamaladdine, R. Beauchemin, J. Rousselet, and G. McClure, “Weight-dropping simulation of ice-shedding effects on an overhead transmission line model”, Proc. IWAIS 1996, pp. 44-48.
[4] M. R. Fekr and G. McClure, “Numerical modeling of the dynamic response of ice shedding on electrical transmission lines”, Proc. IWAIS 1996, pp. 49-54.
[5] M. R. Fekr, G. McClure and D. Hartmann, “Investigation of transmission line failure due to ice shedding effects using dynamic analysis”, Proc. IWAIS 1998, pp. 11-16.
[6] M. Manukata, Y. Yoshida, and H. Ishii, “Determination of spacer intervals in quadruple conductor transmission lines”, Sumitomo Electric Technical Review, No. 1, 1963.
[7] Y. Matsubayashi, “Theoretical considerations of the twisting phenomenon of the bundle conductor type transmission line”, Sumitomo Electric Technical Review, No. 3, 1963.
[8] M. St-Louis, C. Hardy, and J-P. Bellerive, “Bundled-conductor spacers: Hydro-Quebec’s experience”, Paper Presented to the Canadian Electrical Association, Transmission Section Meeting, Montreal, 1993.
[9] O. Nigol, G. J. Clarke and D. G. Havard, "Torsional stability of bundle conductors", IEEE Paper No. F 77 224-9, January 1977.
[10] J. P. Den Hartog, “Transmission line vibration due to sleet”, AIEE Trans., Vol 51, 1932, pp. 1074-6.
[11] A. T. Edwards and A. Madeyski, "A Progress Report on the Investigation of Galloping Transmission Line Conductors", AIEE Trans, Vol. 75, part 3, August 1956, pp. 666-686.
[12] O. Nigol and G. J. Clarke, “Conductor galloping and control based on torsional mechanism”, IEEE Paper No. C74 016-2, 1974.
[13] D. G. Havard and O. Nigol, "Control of torsionally induced conductor galloping with detuning pendulums", IEEE Paper No A78 125-7, January 1978.
[14] D. G. Havard and J. C. Pohlman, "Five years' field trials of detuning pendulums for galloping control", IEEE, July 1983, Los Angeles, USA, Trans. PAS, February 1984, pp. 318-327.
[15] D. G. Havard, "Fifteen years field trials of galloping controls for overhead power lines", IWAIS '95, 7th International Workshop on Atmospheric Icing of Structures, Chicoutimi, Canada, June 3-6, 1996.
[16] D. G. Havard, "Analysis of galloping conductor field data", IWAIS '98, 8th International Workshop on Atmospheric Icing of Structures, Reykjavik, Iceland, June 8-11, 1998.
[17] J. L. Lilien and D. G. Havard, "Galloping Data Base on Single and Bundle Conductors Prediction of Maximum Amplitudes", IEEE, Trans on Power Delivery, Vol 15, No. 2, April 2000, pp. 670-674.
[18] J. Wang and J. L. Lilien, “Overhead electrical transmission line galloping. A full multi-span 3-dof model, some applications and design recommendations”, IEEE Transactions on Power Delivery, Vol. 13, No. 3, pp. 909-916, July 1998.
[19] "Galloping Conductors", Design Report No. 1, Rural Electrification Administration, Transmission Branch, 1962, Rev 1982.
[20] Transmission Line Reference Book, “Wind Induced Conductor Motion”, Electric Power Research Institute, Palo Alto, CA, 1980.
[21] W. J. Wijker and P. H. Leppers, “25 years of galloping experience in the Netherlands”, CIGRE SC22-WG11TFG Report 87-0, 1987.
[22] R. R. Gibbon, P. H. Juul,, H. B. White, W. J. Wijker, “Damage to overhead lines caused by conductor galloping”, ELECTRA No 94, pp. 71-76, May 1984.
[23] D. G. Havard, “Dynamic Loads On Transmission Line Structures During Galloping – Field Data and Elastic Analysis”, Fifth International Symposium on Cable Dynamics, Santa Margherita, Italy, 15-18 Sept, 2003.