Effect of ice and snow on the dynamics of transmission line cables Part I: Aeolian vibration, wake-induced oscillation and galloping motions

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***Abstract*— The objective of this paper is to give an overview of the effect of ice and snow accretions on the dynamics of transmission line cables. In fact, modifying the cable section will alter its behaviour regarding flow-induced vibration phenomena, such as aeolian vibrations and wake-induced oscillations, that already exist on a bare cable. Moreover, galloping, another type of flow-induced vibration, may then appear (except for particular cases, galloping does not occur on a bare cable). The mechanisms involved and the consequences of these three phenomena are described in this paper.**

I. Nomenclature

d cable diameter
f vibration frequency
f_v vortex shedding frequency
P wind power
S Strouhal number
V wind velocity
Y vibration amplitude
y_{max} maximum galloping amplitude along the span

II. Introduction

POWER transmission line cables are exposed to natural winds and may therefore be subjected to wind-induced vibrations like aeolian vibrations and wake-induced oscillations (in the latter case, only on bundles). These hazardous vibrations, which may impair the reliability and lifespan of cables and their accessories, may be attenuated using damper devices and/or spacers or spacer-dampers when required. However, when ice precipitations accrete on the cables, the severity of the two phenomena may increase dramatically, and another phenomenon called galloping may appear. The three types of vibration in the presence of ice are described in the sections that follow.

III. Aeolian vibration

Aeolian vibration is caused by the shedding of vortices alternately from the top and bottom of the cable. The difference between the high velocity in the free stream and the low velocity in the wake creates an alternating pressure unbalance. The cable then vibrates at a frequency that will tend to be synchronized with vortex shedding. The vortex frequency (f_v), cylinder diameter (d) and wind velocity (V) may be related through the Strouhal number (S) [1]:

$$f_v = \frac{SV}{d} \qquad (1)$$

On transmission line cables, the frequency range may vary from 3 to 150 Hz and the amplitude may reach the magnitude of the conductor diameter at the antinode.

The wind power (P) transferred from the wind to a vibrating conductor may be expressed in the following general form [2]:

$$P = d^4 f^3 fnc\left(\frac{Y}{d}\right) \qquad (2)$$

where Y is the vibration amplitude.

The vibration amplitude is determined by a power balance between what is provided by the wind and what is dissipated by the cable self-damping and by any dampers.

Ice and/or snow precipitations will affect aeolian vibrations through different mechanisms. A snow cover may smooth terrain obstacles that would normally contribute to wind velocity fluctuations. A more constant wind velocity and azimuth will result that is more propitious to severe aeolian vibrations.

When ice is present, other factors will also contribute to increasing the severity of aeolian vibrations. For example, iced conductors may lock the cable strands together so that cable internal damping through strand slippage decreases. Moreover, it is well known that internal cable damping depends heavily on the cable's mechanical tension. The ice weight will increase cable tension, which will also reduce conductor self-damping.

Rawlins has observed on overhead ground wires that the vibration amplitude in the presence of ice was much more severe than what he was measuring on a bare cable in the same conditions [3]. Using equation (2), he explained that the ice accretion increases the cable diameter and, given the same frequency, aeolian power increases to about the fourth power of diameter. He also observed that as the ice builds up and the cable diameter increases, the cable frequency becomes smaller as was expected according to equation (1) and sometimes remains the same. Of course, if the cable section deviates too much from a circular section, the Strouhal number may also vary.

Rawlins concluded that the increase in aeolian vibration power seems the most likely cause of the episodes of damper fatigue in apparently well-protected lines. When overpowered, the dampers would permit larger amplitudes, capable of inducing fatigue in the dampers themselves.

Over the years, Hydro-Québec, among other utilities [4], also experienced numerous fatigue failures of various Stockbridge-type dampers on its lines (Fig. 1). Studies aimed at understanding the phenomenon have led researchers to conclude that aeolian vibrations under icy conditions could cause this fatigue problem. Consequently, it was decided that significant improvement of the dampers' fatigue endurance was needed.

Fig. 1: Stockbridge dampers with missing masses on a transmission line

A new type of vibration damper has been developed [5] and, since the durability of the aeolian vibration damper was the main concern, its articulation is based on a proven technology used for the Hydro-Québec spacer damper. Such a technology allows stops to be incorporated in the articulations to avoid damaging dampers under severe ice storm conditions. This articulation is based on elastomeric cylinders located in cavities in such a way that the arm rotation not only produces shear in the elastomer but also compression to minimize any risk of cracking. Performance tests conducted on a laboratory span, on a full-scale test line and measurements on a transmission line have shown that the Hydro-Québec damper is as efficient as a Stockbridge damper for controlling aeolian vibrations on a conductor.

Regarding damper endurance, laboratory fatigue tests were conducted and the endurance of the damper was confirmed at the experimental line. During galloping tests conducted at the experimental test line, single Condor conductors were covered with 63-mm D shape artificial ice to induce conductor galloping. The shapes were found to induce severe aeolian vibrations of the order of 50 mm peak-to-peak around 10 Hz. During the first tests, the Stockbridge dampers lasted from a few hours to two weeks (Fig. 2). During subsequent tests, the Hydro-Québec dampers were used and they all lasted through eight weeks of testing without any damage.

These results show that, for areas where icing is severe, it is possible to design and install aeolian vibration dampers that will sustain the increase of power involved.

Fig. 2: Stockbridge dampers damaged during galloping tests at IREQ's test line

IV. WAKE-INDUCED OSCILLATION

A review of the effects of ice on wake-induced oscillations will be restricted to subspan oscillations since the rolling, twisting or vertical galloping (without ice) involves little distortion of the bundle cross section and is generally less demanding on line hardware. These phenomena occur only at bundle conductors with subconductors arranged one after the other in the direction of the wind. When subspan oscillations appear above a critical wind velocity, the cable span in the wake of an upstream cable may then be excited to oscillate, typically in an elliptical orbit [2], [6]-[10]. As shown in Fig. 3, the leeward conductor acquires its oscillation energy when it moves downstream with the strong flow of the outer wake, and upstream against the weaker flow of the inner wake. The subspan oscillation frequency corresponds to the natural subspan frequencies, which generally range from 1 to 5 Hz. The severity of subspan oscillations is shown as a function of wind velocity and azimuth in Fig. 4 for a typical quad bundle.

Wake-induced oscillations are mainly influenced by the spacing to diameter ratio (a/d) of the bundle, the subspan length (distance between spacers), the distribution of spacers along the span (mismatched or uniform subspan lengths), and the angle of attack or tilt of the bundle.

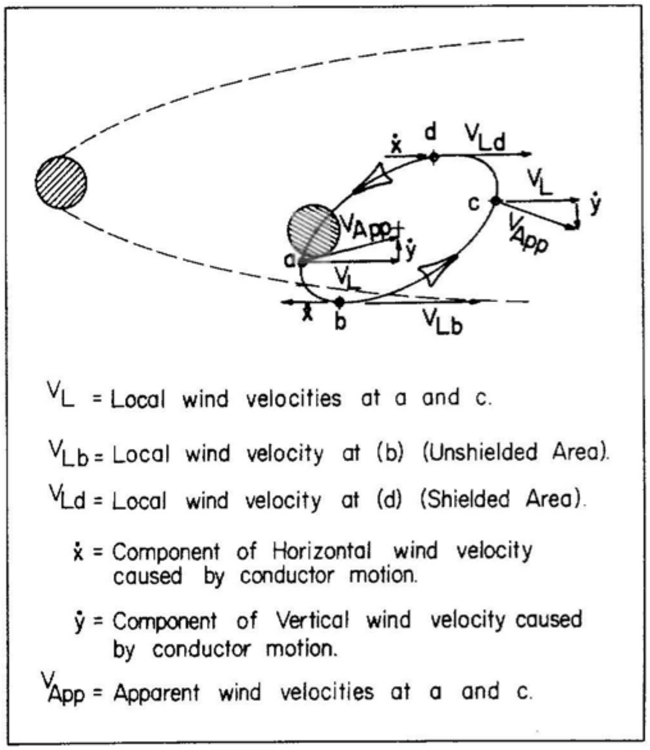

Fig. 3: Typical orbit of a circular cylinder in the wake of another cylinder [2]

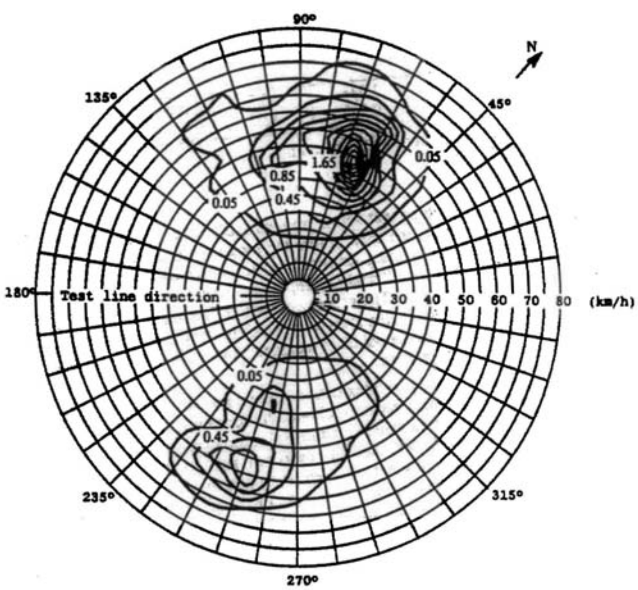

Fig. 4: Maximum values of the subspan oscillation instability index of a quad bundle [7]

Two of these parameters may be affected by ice accretion. The first is the ratio a/d, which usually lies between 10 and 20 for transmission lines. For such numbers, there will be no significant aerodynamic coupling leading to the excitation of the windward subconductor. However, experiments on a full-scale test line have shown that the leeward conductor may experience excitation forces large enough to cause conductor clashing. Moreover, during subspan oscillations, the windward subconductor will be excited through mechanical coupling provided by the spacers staggered along the span. Such occurrences seldom happen anymore since subspan oscillations are mitigated by an adequate installation of spacers along the span. However, if a significant amount of ice accretes on the subconductors, the a/d ratio will decrease, which will increase the aerodynamic forces acting on the leeward conductor to a point where significant subspan oscillations may occur while the phenomenon would have been controlled under normal conditions.

Moreover, it has been shown that for quad bundles, subspan oscillations are more severe for a negative bundle tilt of approximately 10º ([2], [7]) (a negative bundle tilt means that the leeward conductor is located below the windward one), with the conductor in the wake being located at an optimum position to receive energy through an elliptical oscillation. Unequal ice accretion between the two subconductors may bring such a tilt that would be more propitious to subspan oscillations.

Vertical subspan oscillations of the subconductors with ice accretion were observed on 400-kV quadruple bundle lines, lasting for several hours [11], with the result that the oscillations put extreme stress on the spacers. However, this type of problem happens infrequently compared to those observed during galloping or aeolian vibrations in the presence of ice.

V. Galloping Conductors

Cable galloping is a movement-induced excitation where ice accretion on the cable produces an aerodynamically unstable profile where, as the cable oscillates, the angle of apparent wind flow attack on the ice section provides aerodynamic forces, thus providing energy to the cable. The first to provide an aerodynamic explanation for the galloping phenomenon was Den Hartog [12] based on the slope of the curve of the aerodynamic force coefficient of the ice section. Parkinson [13] added the effect of the system damping on the stability criterion. However, Simpson and Lawson [14] demonstrated that conductor bundle galloping instead responds to a flutter phenomenon. A large number of studies have been devoted to the subject, including the effect of torsion and/or horizontal displacement in conjunction with vertical displacement, among other aspects. For a more detailed description of the phenomenon, as well as a bibliography on the subject, the reader may consult references [2] and [6].

Galloping amplitudes may reach the cable sag and cause flashovers or cable clashing. Such amplitudes also induce dynamic forces in the cable, which are transmitted to the towers through the suspension hardware. Significant galloping may occur at the first natural frequency of the span up to approximately 3 Hz. A minimum wind velocity of the order of 10 km/h is required to cause galloping and the severity of the phenomena increases with the wind velocity up to about 60 km/h for transmission lines. The minimum wind velocity required to cause galloping depends on system damping.

Galloping may occur at a single frequency or at a mix of different natural frequencies of the span, or it may occur as relatively steep traveling waves moving along the span.

Galloping modelling may be useful for understanding the phenomenon, though it has its limitations, the main one being that the ice accretion shape over the cable is not known and may vary along the span, on each cable of the same span, and from span to span. Moreover, for a wind direction perpendicular to the cable, the ice section will appear to have a certain shape. As the wind azimuth deviates from the perpendicular, the apparent ice section shape becomes more elongated and the shape afterbody is increased accordingly. In such cases, the aerodynamic force coefficients will vary with the azimuth and the instability criterion will vary accordingly. A recent field test conducted on a test line [15] showed that in some cases skew winds may be more critical than normal winds, which was explained on the basis of a change of aerodynamic force coefficients due to a change of aspect ratio of the section. This result emphasizes the fact that a mathematical model based on aerodynamic coefficients corresponding only to a direction perpendicular to the section considered will not provide adequate results for different wind directions.

A review of galloping control methods was conducted by a CIGRE task force in 2000 [16]. One of the conclusions was that no control method can guarantee that galloping will be prevented under all conditions. Interphase spacers virtually ensure galloping faults will not occur, but do not necessarily prevent galloping. Their usage is growing and their design is undergoing further development.

The effect of galloping on conductor fatigue has been a topic of discussion on many occasions and a study was done to better understand its effects.

Galloping tests were performed at the Hydro-Québec test line in Varennes on a single Condor conductor (Figs. 5 and 6) where the performance of different suspension clamps was compared regarding conductor fatigue [17]. D sections (Fig. 7), which are generally assumed to produce severe galloping [2], [18], were used to induce conductor galloping without being dependent on the temperature and precipitations. These profiles with a height of 75 mm were attached to the conductor in the middle span only. Their mass per unit length was 1.0 kg/m for the first test and 3.0 kg/m for the second test. When covered with D-sections, the mechanical tension of the conductor increased to 41 and 55% RTS for the first and second tests, respectively.

A “hinged armor wire support” (HAWS) clamp (Fig. 8) (made of helical rods, an elastomer insert and a clamp housing) and standard metal-to-metal (Fig. 9) clamps were installed on the same conductor at each end of the middle span where galloping was induced.

The severity of vibrations was assessed using the fy_{max} values where f is the frequency (Hz) and y_{max} (m/s peak) is the maximum amplitude reached along the span. This product is frequently used to indicate bending stress levels at the end of the span.

The protocol included tests at different tension levels for the conductor. However, the following results include only the

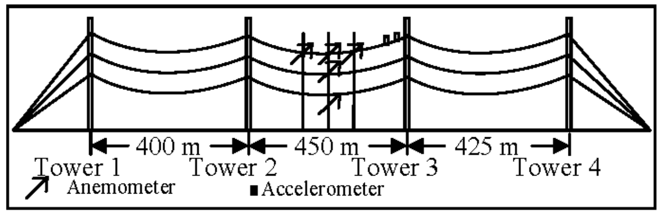

Fig. 5: Varennes test line layout for galloping tests

Fig. 6: Hydro-Québec test line in Varennes

Fig. 7: D-section on conductor to produce galloping motions

Fig. 8: HAWS clamp

highest tensions considered, which include the effect of the weight of the D-section.

1) Test line results at 41% RTS

The first test lasted 38 days during which time the wind conditions provided about 57 hours of galloping. There was no conductor damage during this test and the fy_{max} values recorded are shown in Fig. 10.

2) Test line results at 55% RTS

For the second test, the D-section mass was increased to 3.0 kg/m and, consequently, the conductor tension increased to 55% RTS. After six days of testing, a visual inspection revealed that the first aluminum layer of the conductor was broken at the outlet of the metal-to-metal clamp in the middle span (Fig. 11 and 12). There was no apparent damage at the HAWS clamp. The fy_{max} values recorded during those first six days are shown in Fig. 13.

The conductor was cut on each side of the metal-to-metal clamp and a 20-m section was replaced with a new conductor using compression joints before continuing the test. The fy_{max} values recorded for the remaining 46 days of the test are shown in Fig. 14. At the end of the test, the clamps were removed and six broken wires were found under the metal-to-metal clamp (Fig. 15), while there was no damage under the HAWS clamp.

Fig. 9: Metal-to-metal clamp

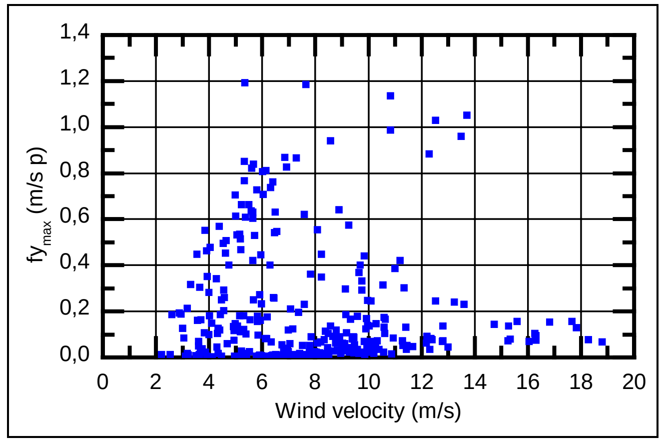

Fig. 10: fy_{max} at 41% RTS after 38 days of the first galloping test

The results obtained during the two tests showed that the clamp/conductor combination was severely stressed and it was made very clear that the HAWS clamp could handle the kind of excitation involved while the metal-to-metal clamp led to conductor fatigue at the same level of excitation. However, at

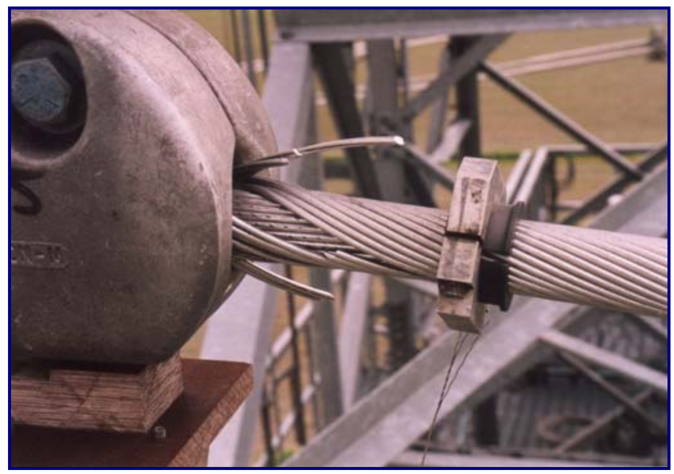

Fig. 11: Damaged conductor under the metal-to-metal clamp in the 450-m span after six day of the second galloping test

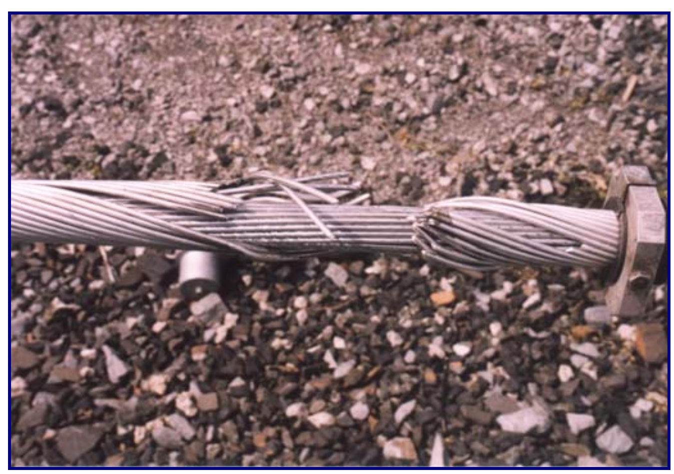

Fig. 12: Damaged conductor under the metal-to-metal clamp in the 450-m span after six days of the second galloping test

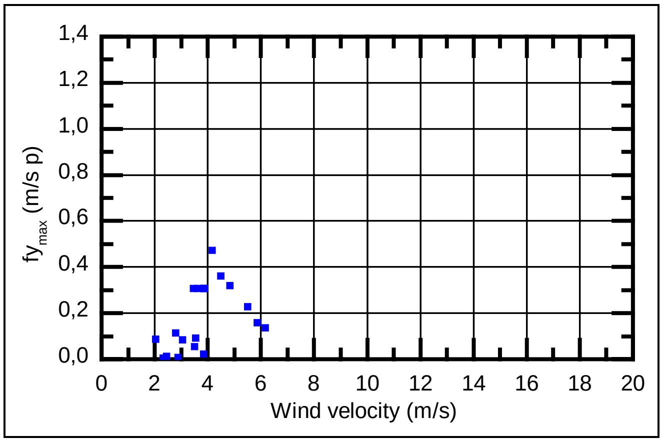

Fig. 13: fy_{max} at 55% RTS after six days of the second galloping test

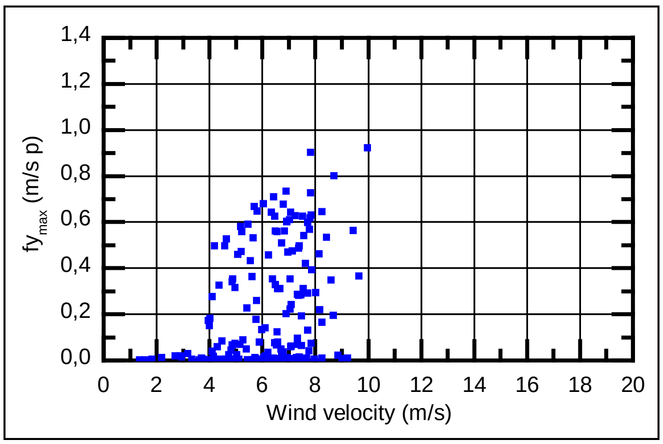

Fig. 14: fy_{max} at 55% RTS for the 46 remaining days of the galloping test

Fig. 15: Damaged conductor under the metal-to-metal clamp in the 450-m span at the end of the second test

this point, this result does not mean that all suspension clamps must be replaced where galloping has been observed. Fatigue tests are actually conducted to evaluate the conductor's lifespan at the amplitude levels observed and the results will be weighted with the number of galloping events expected on the lines where galloping has been observed to determine whether it is necessary to replace the suspension clamps at these locations.

VI. Conclusion

This paper presented an overview of the effect of ice and snow accretion on aeolian vibration, waked-induced oscillation and galloping in transmission line cables. These phenomena have been studied for many years from a theoretical or experimental standpoint and extensive field observations have been made but few remedies are available for eliminating the onset of galloping or for attenuating the effects of aeolian vibrations or wake-induced oscillation on iced cables. Moreover, the presence of ice on cables may completely invalidate any expected tower dynamic loads or line hardware life expectancy deduced on the basis of bare cables.

VII. References

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