Wet Snow Shedding from an Overhead Cable Part 2: Evaluating the Dynamic Response of a Cable Subjected to Wet Snow Shedding

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***Abstract*— A numerical modeling technique using the nonlinear finite element analysis software ADINA is proposed to evaluate the dynamic response of an overhead cable subjected to various snow-shedding scenarios. A time function is associated to the mass and weight of each snow sleeve element, which enables its virtual removal from the model at the time prescribed by the user. In order to simulate the progression of snow shedding along a cable span, adjacent snow sleeve elements are progressively removed in a continuous sequence. The response of a single span of cable subjected to total and partial snow shedding is evaluated. The material properties and the span of the cable used to illustrate the modeling technique match those of a real overhead ground wire.**

I. Introduction

Wet snow accretion on overhead transmission line conductors and ground wires can lead to a number of serviceability, safety and mechanical reliability issues. Unequal sags and large cable oscillations due to the shedding of accreted snow can cause flashovers between phases. Dynamic overloads can cause the fatigue and eventual breakage of wires and conductors, wear of fittings and components, and the collapse of supports.

Overhead cable dynamics has been the subject of a number of numerical studies initiated by McClure at McGill University. A particular branch of this research field emerged in the early 1990's when researchers attempted to model the response of a cable following ice shedding [1]-[6]. It is important to note that the modeling work of Jamaleddine [1], [2] was validated experimentally.

Based on a modified version of the previous ice-shedding models, a snow-shedding modeling technique has been developed for this study using the commercial finite element software ADINA.

II. Modeling Approach

A. Cable model

A single cable spanning 470 m is modeled as a chain of two-dimensional, two-node isoparametric truss elements with prescribed initial strain. It is pinned at the ends and the flexibility of the towers and foundations is not included in the model. To allow for cable slackening, the stiffness of each cable element is prescribed in tension only.

The material properties and the span of the cable used to illustrate the modeling technique match those of a real overhead ground wire commonly used in Southern France, in regions often subjected to severe wet snow events. The cable modeled for this study has the following properties (data provided by Électricité de France (EDF)):

- Material: Almelec-Steel 94.1
- Diameter D = 12.60 mm
- Cross-sectional area A = 94.1 mm²
- Mass per unit length μ = 0.481 kg/m
- Density ρ = 5 111 kg/m^3
- Modulus of elasticity E_t = 112 GPa
- Tension, ultimate T_{ult} = 80 350 N
- Tension, initial (bare cable) T_i = 11 000 N

The initial static position of each node is calculated using the theoretical inextensible catenary equation. The initial equilibrium state is determined by static analysis under the cable self-weight and initial strains.

In the dynamic analysis the cable elements undergo large displacements with small strains and the mass of each element is assumed to be lumped at the nodes. The material nonlinearity (tension-only) and the large displacements expected when the cable is subjected to snow shedding make this problem highly nonlinear. The cable response is obtained by direct time integration of the incremental form of the equations of motion using the Newmark-β trapezoidal rule [7].

B. Damping model

Aerodynamic damping is neglected in this study. When modeling the transient response of an overhead cable following ice-shedding and snow-shedding scenarios, it is believed that most of the structural damping comes from friction between the individual strands of the cable.

Rayleigh damping was incorporated in the model in order to simulate internal damping in the cable. In matrix form, Rayleigh damping is defined as a linear combination of the mass and stiffness matrices:

$$C = aM + bK \tag{1}$$

where C is the damping matrix, M is the mass matrix, K is the stiffness matrix. This form is especially convenient in linear time domain dynamics because it allows uncoupling of the equations of motion in the modal basis and it is easy to evaluate. The Rayleigh parameters a and b can be obtained from the following relationship [8]:

$$a + b\omega_i^2 = 2\omega_i\xi_i \qquad (2)$$

a and b are determined by prescribing the amount of damping at two different frequencies of oscillation. For example, using 3.0% damping on the first mode and 4.1% on the 80th mode of vibration for the ground wire model containing 80 elements:

$\omega_1 = 2.009$ rad/s $\qquad \xi_1 = 0.030$

$\omega_{80} = 51.440$ rad/s $\qquad \xi_{80} = 0.041$

Substituting in (2) and solving for *a* and *b*:

***a* = 0.02374** $\qquad$ ***b* = 0.00155**

Using these Rayleigh constants produced an acceptable amount of damping when modeling a cable subjected to instantaneous snow shedding along its entire span.

Damping has little effect on the maximum transient cable response since it usually occurs during the first or second peak. However, including numerical damping in the cable model is necessary to filter out spurious modes of vibration introduced by the finite element discretization of the cable. Artificial numerical damping has been used successfully in previous cable dynamics models. Modification of the parameters of the integration technique (Newmark-β with $\delta > 0.5$, $\alpha > 0.25$) provides useful algorithmic damping that filters out undesirable higher frequencies. Also, the modified technique provides some amplitude decay that resembles viscous damping, and a small amount of period elongation. For this study, the parameters of the Newmark-β integration operator were set to $\delta = 0.7$ and $\alpha = 0.4$.

C. Snow model

Accreted snow is modeled using non-linear spring elements (generic lumped parameter elements) with zero stiffness and damping properties (Fig.1). Snow sleeve elements only have an assigned mass, and their weight is modeled as vertical loads acting on the nodes. The snow load of each element is governed by a time function and its mass varies according to the same time input: this enables the virtual removal of any snow element from the cable at the time prescribed by the user. The propagation of snow shedding is modeled by removing the mass and weight of neighboring elements at time intervals corresponding to the desired speed of shedding.

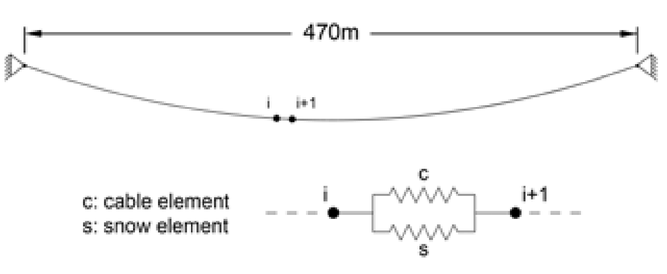

Fig.1 Simplified snow-covered cable model

Snow properties were specified by EDF for this study. The range of snow density values was set between 0.20 g/cm³ and 0.60 g/cm³, and the maximum radial accretion size was set to 4.2 cm. The worst-case scenario for this ground wire model (i.e. 4.2 cm radial, 0.60 g/cm³) corresponds to an overload of **4.19 kg/m**, or **41.1 N/m**, that is nearly 9 times its self-weight. This overload is used in the next sections whenever the cable is said to be “snow-covered”.

A more detailed account of the finite element modeling procedure, including a thorough explanation of damping modeling, time step selection and mesh size validation can be found in [7].

III. Wet Snow Shedding Models

A. Sudden Total Shedding

Although instantaneous shedding of wet snow accretion on the entire cable span is highly unlikely, it has been used in the past as a worst-case scenario to simulate ice shedding in laboratories and on full-scale experimental lines [1], [2], [9]. To simulate ice shedding, sand bags attached along a cable were dropped simultaneously by triggering explosive devices.

Total wet snow shedding is simulated numerically by removing all snow elements at the same instant. The response of the overhead ground wire model subjected to total shedding is shown in Figs.2a and b. The amount of overall damping displayed is very similar to what was observed by Dalle and Ratier while performing full scale experiments [9].

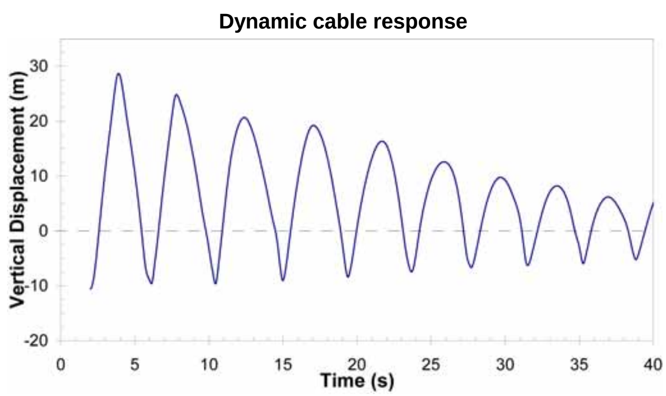

Fig.2a Vertical displacement at the mid-span point, following sudden shedding on the entire span

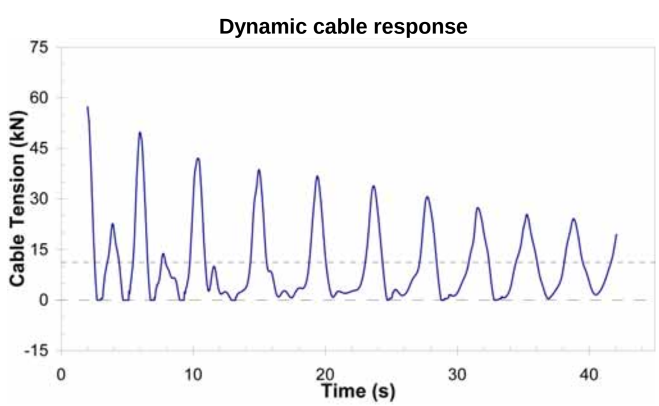

Fig.2b Cable tension at one end, following sudden shedding on the entire span

B. Total Shedding Progressing at a Constant Rate

Based on observations reported in the field and during the experimental part of this study, it appears that snow does not usually shed in a sudden manner from an overhead cable; instead, shedding progresses along a cable like a fracture, at various speeds [10].

Pierre Guilbeault, an experienced test engineer at Hydro Québec's Research Institute (IREQ), made some observations on wet snow accumulations on the Hydro Québec experimental line in Varennes, Québec, in 2001 [11]. He observed snow shedding from phase conductors (non-energized) in a random and partial manner. In contrast, some overhead ground wires shed in an "unzipping" fashion along their entire span; these progressive shedding events caused large cable oscillations with mid-span displacements of the order of a few meters. Some of the fallen snow chunks were weighted, and the snow overload was roughly estimated at 5 kg/m [11]. Observations were made on the day of the event, when snowfalls were moderate. Weather conditions reported for this 30-hour long snow event were as follows: 40 to 60 cm of snow accumulation on the ground, some periods with large precipitation rates, air temperature between 0°C and 1°C, and wind speeds between 10 m/s and 15 m/s [12].

Wet snow shedding observations are rare and there are only a few mentions of them in the scientific literature. Field and laboratory observations have shown that a wet snow sleeve subjected to heat tends to shed naturally from an overhead cable upon reaching a critically high liquid water content (LWC) value [10], [14], [15] . A snow sleeve can also be ripped from a cable before reaching its critical LWC value, if the cable is subjected to a strong enough vertical jump [7]; the magnitude of the acceleration required to shed a wet snow accretion depends on its state. When the LWC of a wet snow sleeve approaches its critical value, its shedding can be triggered by a small vertical acceleration (less than 1*g* or 9.81 m/s²). Such accelerations can be generated by a small wave traveling along the cable, or by oscillations caused by partial shedding on the same span.

To the authors' knowledge, this is the first time that observations of progressive snow shedding through unzipping are reported. For this mode of shedding to happen, the LWC of the snow sleeve must be high enough to reduce significantly its cohesive strength, and shedding must be triggered by a transverse wave traveling along the ground wire. The speed c at which a wave progresses along a taut cable can be estimated by the following wave mechanics equation:

$$c = \sqrt{\frac{T}{\mu}} \tag{3}$$

where T is the tension in the cable and μ is the mass of the cable per unit length. Substituting the properties of the ground wire model into (3) gives a speed of 111 m/s. This speed was also observed in preliminary finite element models, when a traveling wave was generated by a strong impulse [7]. It is interesting to note that the unzipping shedding phenomenon described by Guilbeault was only observed on ground wires.

In this section, the response of the ground wire is evaluated by assuming that a transverse wave can cause a snow sleeve to shed as it progresses along the entire span. The transverse wave is not included in the model: snow unzipping is simulated by sequentially removing all the snow sleeve elements in the dynamic model, starting from one end, at the rate of 111 m/s. The response of the cable subjected to this unloading scenario is shown in Figs.3a, b and c. The zero value on the displacement plots represents the static position of the bare cable.

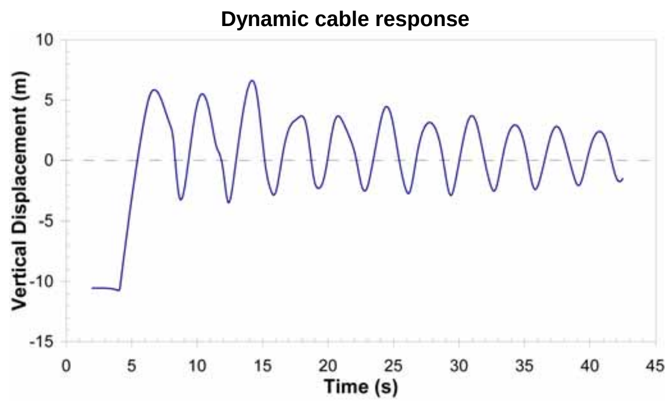

Fig.3a Vertical displacement at the mid-span point, following total shedding at 111m/s

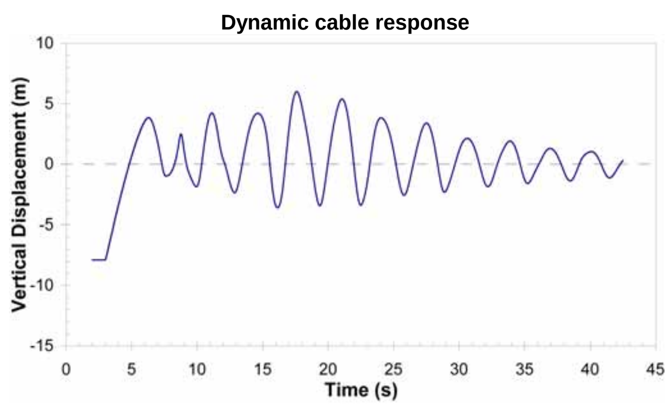

Fig.3b Vertical displacement at the first quarter-span point, following total shedding at 111m/s

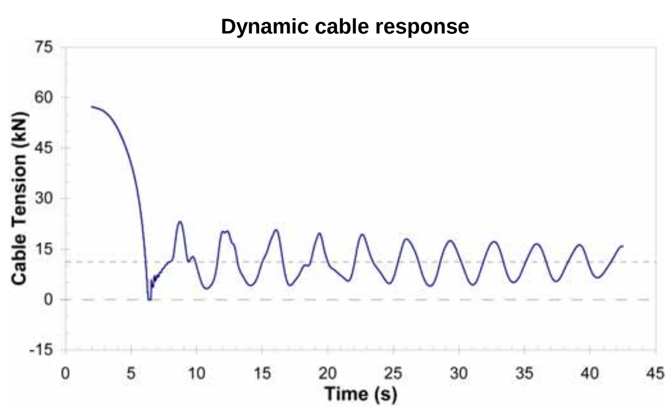

Fig.3c Cable tension at the end point, following total shedding at 111m/s

Some observations:

- The maximum cable jump at the mid span is 6.62 m and it occurs at the third peak. The maximum cable jump is 6.01 m at the quarter span (91% of the maximum mid-span value) and it occurs at the fifth peak. These displacement values are of the same order as those described by Guilbeault in his observations on wet snow unzipping [11].

- The cable becomes slack during the first rebound. Once the cable is totally unloaded the tension oscillates between 4 kN and 20 kN (± 8 kN oscillation).

C. Partial Shedding Progressing at a Constant Rate

We recall that this numerical modeling study is part of a broader wet snow study emerging from a partnership between Électricité de France and the CIGELE Industrial Chair on Atmospheric Icing of Power Network Equipment at Université du Québec à Chicoutimi, in collaboration with McGill University. In the experimental part of this wet snow study, man-made wet snow sleeves – 2.5 m in length – were observed to shed naturally (i.e. without being subjected to a sudden transverse load) at speeds up to 14 m/s [10]. This speed is used in this section to evaluate the cable response in three partial shedding scenarios.

There are no precise field records for the length of partial snow-shedding segments; Admirat describes them as ranging from a few meters to a few tens of meters in length [15]. To study the effect of partial wet snow shedding, snow segments of different lengths are removed from the snow-covered cable model at a rate of 14 m/s; the shedding sequence is initiated at the mid-span point, and snow elements are removed symmetrically towards both cable ends. Since Roshan Fekr and McClure [4] have confirmed that dynamic cable responses are greatest when accretion shedding occurs at the center of the span, this shedding sequence is expected to generate the largest displacements at that point. The effects of three different shedding lengths were compared:

- 4 elements (5% of the total cable length, or 23.5 m)
- 6 elements (7.5% of the total cable length, or 35.25 m)
- 8 elements (10% of the total cable length, or 47.0 m)

The following observations were reported:

- The response of the ground wire model subjected to these partial shedding scenarios is shown in Figs.4a to e. The most obvious feature showing from the response plots is that cable oscillations following partial snow shedding are approximately proportional to the amount of snow removed. Displacement oscillations for the 10% scenario are twice as large as for the 5% scenario (at the mid-span and at the quarter-span points).
- Cable tension oscillations are also approximately proportional (Fig.4e). For the 10% shedding scenario the tension oscillates from 48 kN to 56 kN (± 4 kN oscillation).
- Vertical acceleration plots were generated to get a better understanding of their magnitude along the ground wire. The plot in Fig.4c shows the vertical acceleration of the node adjacent to the last snow-shedding element. In other words, this corresponds to the acceleration of the snow-loaded node closest to the mid-span point once the shedding process is over. Acceleration magnitudes are generally larger for a longer shedding length, but they are not proportional to the shedding length. For the 10% and 7.5% scenarios, the largest upward acceleration reaches 2.25 m/s². For 5% shedding the maximum upward acceleration is 2.0 m/s².
- The bottom plot in Fig.4d shows the vertical acceleration at the quarter span (more than 100 m away from the last snow-shedding element). Upward accelerations reach a maximum of 1.75 m/s² for 10% shedding and 1.5 m/s² for 5%. Maximum quarter-span accelerations are approximately 75% of those generated at the node adjacent to the last snow-shedding element.

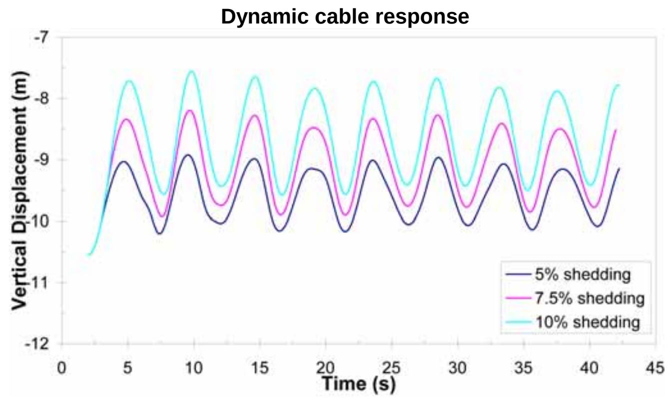

Fig.4a Vertical displacement at the mid-span point, following partial shedding at 14 m/s

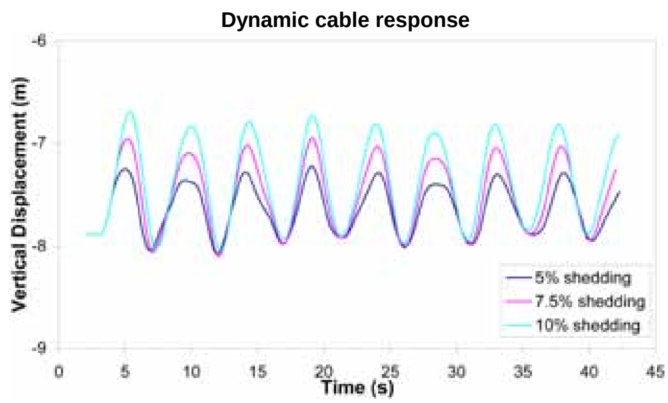

Fig.4b Vertical displacement at the quarter-span point, following partial shedding at 14 m/s

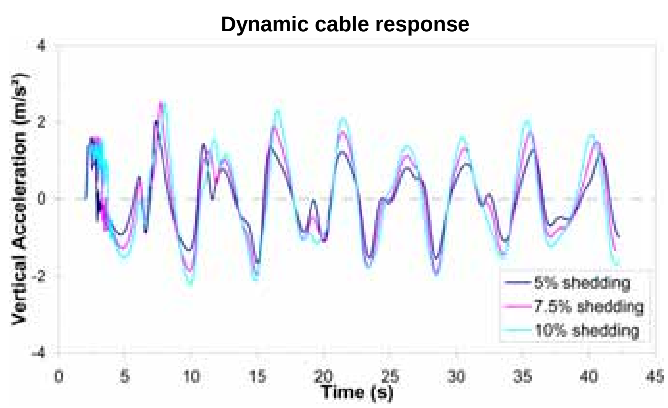

Fig.4c Vertical acceleration of the node adjacent to the last snow-shedding element, following partial shedding at 14 m/s

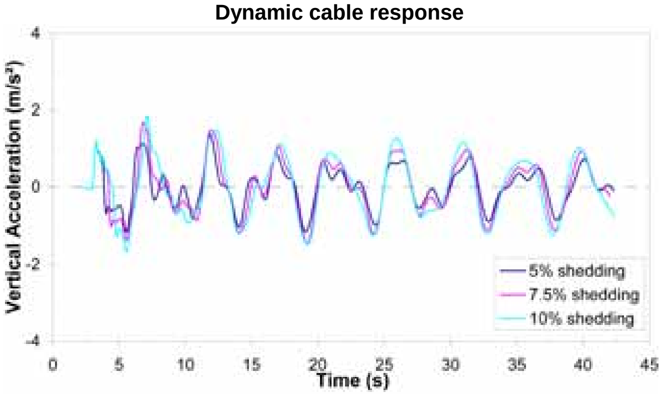

Fig.4d Vertical acceleration at the quarter-span point, following partial shedding at 14 m/s

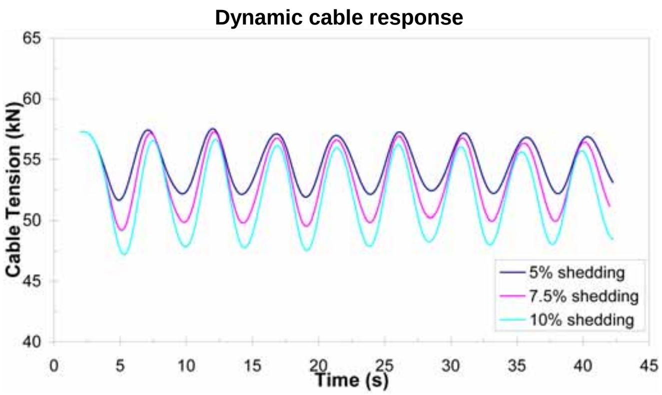

Fig.4e Cable tension at the end point, following partial shedding at 14 m/s

IV. Discussion

Rayleigh damping proved to be adequate when evaluating the response of an overhead cable subjected to snow shedding. Amplitude decay was displayed in the response of the ground wire subjected to sudden shedding (Figs.2a and b) and it also appeared in the total unzipping snow-shedding scenario once the transient oscillations had faded (Fig.3a, b and c). However, Rayleigh damping should be used with caution: the Rayleigh constants used in this study are specific to the snow-free ground wire model used. Very little damping showed up in the partial-shedding cases because the Rayleigh parameters were adjusted for the bare cable model only, not for the snow-covered cable model.

An interesting result is the demonstration that the effects of shedding of short wet snow segments (small shedding ratios) close to the mid-span point are proportional to the amount of snow removed. For instance, in section III.*C*, mid-span displacements and cable tension amplitudes were doubled when the snow-shedding percentage was doubled. However, this trend is not expected to continue if longer segments are removed from the cable span (e.g. 25%, 50%, etc.), since the mass being removed will shift gradually towards the ends of the cable.

In section III.*C*, the upwards acceleration due to partial shedding reached 2.25 m/s² on the remaining snow accretion. In reality, this acceleration might be sufficient to trigger more shedding along the same cable span since most of the snow would have reached a relatively high LWC. However, we think that the expected variability of the physical properties of a real snow sleeve (in size, shape, density and LWC) over a span of a few hundreds of meters is likely to stop the progression of shedding under such a small acceleration. This requires further investigation.

The numerical modeling procedure presented is a very useful tool when combined with field observations. In section III.*B*, cable jumps were found to match approximately those described by Guilbeault in his account of wet snow unzipping [11]. More scenarios should be modeled in order to evaluate the effects of other plausible snow-shedding cases. Current records of natural snow-shedding events seem to indicate that the worst scenario would correspond to total unzipping at the maximum possible speed (i.e. the speed at which a transverse wave travels along a cable). More field observations are necessary to confirm this hypothesis and to further validate this modeling technique.

Observations of wet snow shedding are rare and often localized; in order to ensure comprehensive observation, hundreds of kilometers of overhead lines would need to be monitored. Hopefully, the latest advances in remote monitoring technology can provide researchers with more autonomous and affordable tools.

V. Conclusion and Potential Future Work

This numerical modeling study improved our understanding of wet-snow shedding from overhead cables. In many aspects, the snow-shedding model developed for this study is similar to the ice-shedding models of McClure *et al.* [1]-[6]. What really differentiates it from its predecessors is the fact that each cable and snow sleeve element is assigned a separate time function, allowing the user to prescribe the instant at which any snow element may disappear from the model. This, in turn, allows the numerical modeling of a wide variety of shedding scenarios.

To demonstrate the capabilities of the technique, the responses of an overhead ground wire subjected to different snow-shedding scenarios were simulated. Some interesting observations were made about wet snow shedding for the particular cases studied:

- Total unzipping of a wet snow sleeve progressing at the same speed as a transverse wave leads to displacement amplitudes of the order of a few meters.
- Partial shedding of a wet snow sleeve (shedding 5% to 10% of the total span) initiated at the mid-span point produces cable tension amplitudes and displacement oscillations proportional to the amount of snow removed.
- If the LWC of a snow sleeve is uniform along most of its span, the vertical accelerations generated by partial shedding might be sufficient to trigger more shedding on the same span. However, this aspect requires further investigation.

A significant improvement to this numerical model would be to add a failure criterion to the material definition of the snow elements, as done recently by Kálmán [16] for ice-shedding models. However, since wet snow sleeves can shed by themselves upon reaching high LWC values, their failure criterion does not need to be based on mechanical properties. Instead, we suggest that snow elements could be removed automatically from the model when their vertical acceleration exceeds a pre-defined threshold (e.g. 5 m/s^2 upward acceleration).

Snow shedding generates cable tension oscillations that affect adjacent spans. The numerical model developed could be used to study the effect of total and partial shedding on multiple spans of overhead cables. An even more ambitious evolution of the model would be three-dimensional and would include ground wires, phase conductors and the flexibility of the support structures.

VI. Acknowledgment

This work is the first of a series of wet snow investigations emerging from a partnership between Électricité de France (EDF) and the CIGELE Industrial Chair on Atmospheric Icing of Power Network Equipment at Université du Québec à Chicoutimi (UQAC), in collaboration with McGill University. Funding for this study was generously supplied by EDF within the framework of this partnership.

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