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A vibration-sag-tension-based icing monitoring of overhead lines

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SUMMARY

A patented vibration-sag-tension based sensor and method for real-time measuring/detecting atmospheric accretion of all possible types (ice, snow, wet snow, frost, etc. and any of their mixtures as for example rime icing) on overhead lines is presented. Practical experience based on data from sensors installed in different countries allows observing icing events. Some of these events are also presented.

KEYWORDS

Ice Detection, Real-time monitoring, overhead line, transmission line, atmospheric accretion, vibration, icing, conductor ice accretion

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I. Introduction

Icing problems can have a severe impact on the safe operation of overhead transmission lines: additional high severe static loads (abnormal tension increase and/or abnormal increase of sag not related to high electric loads), strong cable motion and/or high/severe dynamic loads (Galloping oscillation and ice-shedding). Atmospheric icing is a complex meteorological phenomenon and different meteorological conditions lead to a large variety of snow/ice and their mixtures and deposits. Ice loads can cause significant damage to electric power transmission networks, especially in combination with wind. Overhead lines can collapse due to the mass of ice deposits, but also additional loads in conductors and support structures induced by so-called galloping oscillation can cause significant damage to the structures. These transient dynamic forces can also cause the cables to swing toward each other and/or toward the towers. Clashing of conductors and flashovers are the most common problems of transmission lines galloping. Repeating power interruption caused by flashovers (as flashovers cause circuit breakers to open) obviously reduces the service quality and can damage the circuit breakers. Also, the conductors can be damaged due to the clashing and flashovers. Ice shedding may have similar consequences to galloping. Sudden ice shedding generates strong cable motion and high/severe dynamic loads, which can cause severe damage to the transmission lines such as tower arm failure or even cascading failures of several towers. Moreover, non-uniform ice accretion on a conductor in adjacent spans results in a longitudinal load at the supports. Such loading may be created either by a non-uniform ice accretion because of the line exposure or owing to ice shedding and can cause severe damage to the transmission line structures [1,2,3,4].

Weather-based ice detection methods and indirect (sensors not directly installed on the line) exist [5,6,7,8] but the main drawback of these systems/methods is that the model and/or sensor is not considering the current in the power line and the real conductor temperature which can be dramatically different from that one related above-mentioned sensor. Indeed, icing appears first at a (surface) conductor temperature around 0 [°C] and a small amount of current can lead to conductor temperature above the threshold of icing. Sag and/or tension of conductor are not monitored at all, and this specific indirect ice monitoring is only a part of the solution.

A real-time direct local measure/detection of ice accretion can be useful in a number of applications, and in particular for monitoring the transmission and distribution network since the accretion of ice, snow, wet snow, frost, etc. and their mixtures can lead to potential clearance violations, as well as infrastructure damage and power outages due to important static and/or dynamic mechanical overloads.

Fig. 1: Ampacimon™ vibration-based sensor [9]. (top) sensor at rest on a table and (bottom) sensor installed on a single conductor (picture taken during installation).

(3D) Vibration-based sensors as shown in figure 1 (self- powered, maintenance free and directly installed on the conductor) have been first deployed worldwide for dynamic line rating and forecast (up to a few days) concerns i.e., mainly sag monitoring and wind measurement at line level [9,10,11,12,13,14,15]. Extended applications based on vibrations measurement as mechanical event analysis (fatigue analysis, abnormal mechanical change, creeping, icing, and atmospheric accretion monitoring) have been identified and implemented since a lot of very useful information are available in conductor vibrations / motion readings. Based on vibration measurements, any abnormal change of orientation of the sensors (3D vibrations monitoring) as sometimes observed during eccentric weight of the ice deposit large enough to significantly twist the conductor (depending on span's configuration) and any abnormal increase of sag is automatically monitored in real-time thus giving very useful information to grid operators.

Moreover, additional embedded tension measurement has been included to detect change of apparent weight at the early step of accretion [1]. The simultaneous increase of sag and tension (despite the computation of ice weight) can provide the information of icing at the first stage of the physical phenomena. This (very) early detection of accretion and alarm is helpful for Transmission System Operator (TSO) and Distribution System Operator (DSO). It allows re-configuring electrical loads (if possible) to stop phenomena at early stage (icing prevention by joule effect). The electrical heating of conductors by the Joule effect offers a potential method for preventing ice accretion on the conductor surface [8]. This prevention method should be activated a certain time before and during the freezing precipitation. the current in the powerline conductor is increased in such a way that it keeps the conductor surface temperature slightly above the freezing temperature.

II. Apparent Weight

The present method and sensor provide a way to detect/measure atmospheric accretion on power lines by means of two independent measures / methods, the results of which being complemented and combined. These two methods determine the apparent weight of conductor and corresponding amount of ice/snow (and their mixtures) on power lines:

(i) The measurement of the sag of the suspended span; and
(ii) The measurement of the (local) tension of suspended conductor

In a purpose of analysis and explanation of the method, the computation and formulae are simplified by assuming uniform loading (i.e., conductor weight per unit length, ice and wind) along suspended cable a levelled span (or small difference in level of attachments) having a small sag/span length ratio (which is largely true for overhead transmission lines where the order of magnitude of the sag is small compared to the span). In most cases, sag is small compared to span length and the following expression is an approximate parabolic equation of the sag equation. It is usually NOT valid for long, steep, nor deep spans such as may be found in river, lake or fjords crossing or spans having a very high difference in level of attachments; cases for which additional terms of the series expansion of the hyperbolic cosine must be considered [16]. In any case this does not change the method to compute the sag and additional terms are easily added if needed. The sag of a suspended cable is representing the largest vertical distance between the catenary and its (imaginary) chord. It is well-known and well-defined in literature [16]. It is given by the following parabola formula:

$$S = \frac{wL^2}{8H} \qquad (1)$$

Where S [m] is the sag, H [N] is the mechanical tension, L [m] the span length and w [N/m] is the resultant force of conductor weight, wind pressure and ice loading, per unit length, given by

$$w = \sqrt{(w_c + w_{ice})^2 + {w_{wind}}^2} \qquad (2)$$

Where w_c [N/m] is the weight of conductor per unit length, w_{wind} [N/m] is the pressure due to wind and w_{ice} [N/m] is the potential additional weight due to any accretion (like ice loading); w_{ice} and w_c are acting in a vertical plane and w_{wind} is acting on a horizontal plane. In the case of no accretion and no wind, the resultant weight per unit length is equal to conductor weight per unit length (w=w_c).

By measuring both sag and tension, it becomes possible to determine the change in conductor apparent weight due to ice/snow. Using equation (1) and equation (2) and considering no wind or negligible pressure due to wind for simplicity, the product of sag and tension gives a coefficient p [N/m] which is directly linked to the total resultant weight per unit length:

$$p = SH = \frac{wL^2}{8H} = \frac{w_c L^2}{8H}(1 + \frac{w_{ice}}{w_c} \quad (3)$$

Noting d/dt [1/s] the time derivation of equation (3) and noting that conductor weight w_c and span length L are constant over time, the rate of accretion is given by

$$\frac{d}{dt}(SH) = \frac{L^2}{8}\frac{dw_{ice}}{dt} \quad (4)$$

Sag S and tension H can be obtained in different ways. Wind and corresponding wind pressure (acting on the span) can be estimated using vibrations-based method and sensor [8,12,13,14] (fig. 1) but wind pressure w_{wind} is generally negligible compared to conductor weight per unit length and potentially problematic ice overload.

i. *Sag from Vibration Measurement*

The sag is easily obtained by using a vibration-based sensor, with no need of any data [9,10,11,15]. Such a sensor is then called a direct sag measurement device. It is not influenced by any errors that could exist in the topology, the conductor data or the sagging conditions. In case of no accretion and no wind (negligible wind pressure), the sag is given by (see also eq. 1):

$$S = \frac{w_c L^2}{8H} = \frac{m_c g L^2}{8H} \quad (5)$$

where m_c [kg/m] is the mass per unit length of the conductor and g [m/s^2] is the gravity constant and equal to 9.81 [m/s^2]. Mass per unit length m_c and weigh per unit length w_c are simply related to each other by $w_c = m_c g$.

The fundamental frequency is a frequency that is not easily observed directly on cable structure (except for very tight cables, like in violin). Indeed, the cable dynamics is known from literature and explained for example in [17]. There are so-called "in-plane" and "out-of-plane" modes, both being affected by end-span fixation. So that a deep analysis is needed to extract that fundamental value from a full spectrum, as is observed on a span vibrating under natural turbulent wind. Generally, there is no easy access to that fundamental mode. It is much easier to deduce it from higher modes (2, 3, 4, etc.). It is given by [17]:

$$f_0 = \frac{1}{2L}\sqrt{\frac{H}{m_c}} \quad (6)$$

We can now use equation (6) about the frequency and introduce the sag formula (1) in it. By replacing H by its value we obtain:

$$f_0 = \frac{1}{2L}\sqrt{\frac{H}{m_c}} = \frac{1}{2L}\sqrt{\frac{(\frac{m_c g L^2}{8S})}{m_c}} = \frac{1}{2}\sqrt{\frac{g}{8S}} \quad (8)$$

The square of that equation is giving the following relationship:

$$S = \frac{g}{32}\frac{1}{{f_0}^2} \quad (9)$$

Thus, sag is obtained by knowing the fundamental frequency. No other data are needed. As can be seen in the formula the sag is not influenced by any errors that could come from the topology knowledge, the conductor data nor even from weather data. This method has been patented for power line applications.

Exterior conditions such as load, weather, topology, suspension movement, creep, presence of snow/ice, etc. affect the sag and are therefore automatically incorporated into frequency readings. Furthermore, it does not need to be calibrated as the sag is deduced from the detected frequencies and not from signal amplitude.

ii. Tension Measurement

A local (embedded) tension measurement using an imposed (infinitesimal) deflection of the cable inside the sensor (figs. 2,3) at sensor location is preferably used since there is no need to uncouple conductor from tower during installation as it is done using tension measurement at tower location. An infinitesimal deflection of the cable applied through the sensor produces a tangential force proportional to mechanical tension in the wire/cable (relation depends on wire size and type in practice) [1,18]. The deformation produced by the force is measured by an integrated strain gauge sensor [1,18]. This kind of sensor (output from strain gauge) must be calibrated to specific wire size and type in practice. A preliminary test is done on a laboratory short span (5-6 [m]) to check that everything works properly but it is also checked on real installation (as tension and sag must be dependent through the parabola approximate, eq. 1). Discrepancies from laboratory test readings before installation and outputs readings once installed on a real line can exist. Discrepancies can be related to dominant end-effects on short laboratory spans and/or to deformation of wires of the conductor in real installation (diameter is not perfectly the same on the short-span and the real-span due to aging; conductor can be deformed over time in real situation, wires are not as stressed as installation or short span etc..). As vibration-based sag measurement is obtained without the need of any data, the raw tension sensor output from strain gauge can be fitted to sag using equation (1) in case of period of no accretion and no additional loads, for example during summer, with high ambient temperature, low wind. Therefore, there is no need to calibrate sensor on wire size and type on laboratory before installation.

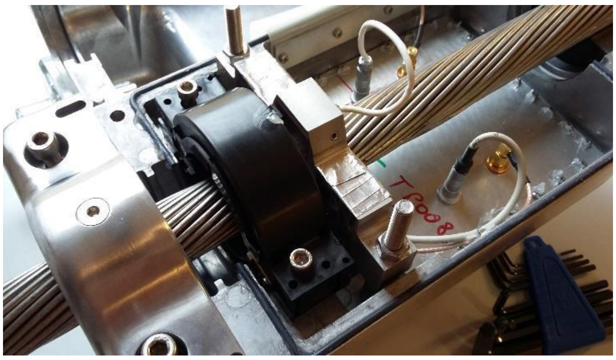

Fig. 2: Ampacimon™ ADR Sense opened during installation on a laboratory conductor. Current Transformer (CT, black piece) for power supply and embedded local strain gauge mechanical sensor for tension measuring is visible at its right.

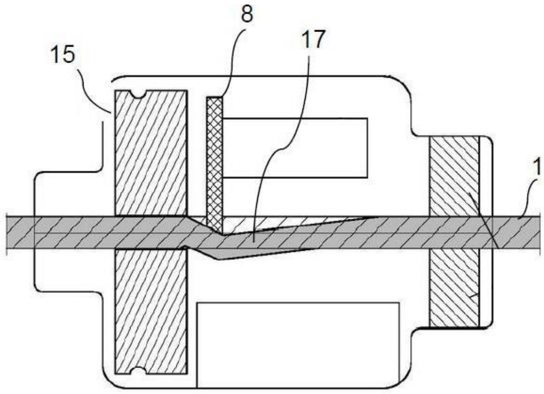

Fig. 3: A cross-sectional view of the monitoring device taken along a vertical plane. An imposed infinitesimal deflection (17) is applied to conductor (1) through a tension / strain gauge sensor (8) is schematically highlighted [1]. Sensor is powered from current in the conductor (1) thanks to a Current Transformer (CT) power supply (15).

III. Measurements & Observations

Practical experience shows that real-time monitoring of 3D vibrations, sag and tension allows identifying atmospheric icing related events. Typical observations from different installations are shown in next sections.

i. Abnormal Sag Increase

Real-time monitoring conductor vibrations allows getting sag values with no need of data (sec. II). Any abnormal increase of sag is easily detected. Figure 4 shows the relation between sag and mean conductor temperature, also known as state change equation (SCE) in literature [16]. In normal operation (no icing) sag increases (tension decreases) as conductor temperature increases – the theoretical sag-(mean) conductor temperature relationship SCE is a cubic curve (in fact almost linear) [20]. In order to distinguish between cases of increased sag for the line caused by ice loads and caused by high line temperature, a combination of sag, current and temperature is analyzed. Furthermore, the combination of tension and sag at the same time allows distinguishing such different cases as explained in previous sections. However, any abnormal sag increases are easily monitored, looking at abnormal measured according to SCE (fig. 4). Since conductor temperature is greater or equal to ambient temperature, SCE can be displayed at ambient temperature (lower bound of sag-temperature relationship). Any increases over the lower bound are linked to larger sag occurrences due to solar heating and/or Joule effect. Variability over this lower bound related to ambient temperature is quite small in that case as load was quite low during that period and solar heating has a relative moderate effect on conductor heating.

As one can see on figure 4, an abnormal increase of sag at temperature close to 0 [°C] is related to icing. Ice accretes first at surface conductor temperature close to freezing temperature and sag increase subsequently (at that temperature first). During this abnormal sag increase the load was quite constant and low (< 100 [A]) thus load couldn't explain such an increase. Moreover, during this period, ambient temperature was close to 0 [°C] and twist of conductor was observed (see also sub section ii).

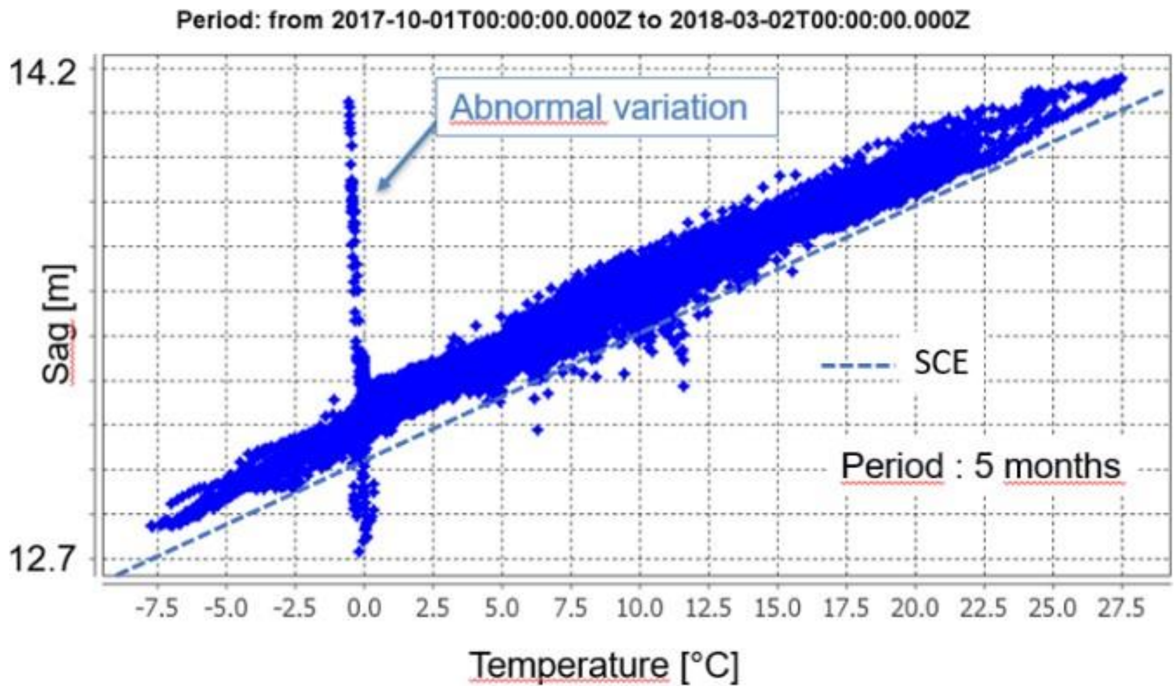

Fig. 4: Measured vibration-based sag vs. (mean) temperature of conductor (5 months of data) on a single conductor dead-end span (conductor: 210Alac, span length: 389 [m]). Abnormal sag related to icing at temperature close to 0 [°C] is visible. State Change Equation (SCE) (as determined from measurement) is highlighted (dashed line) and statistically fits the lower bound of data as explained in the text (sec. i).

ii. Twist of Sensor / Conductor

As wet snow accretes on a conductor, it tends to twist it and so to expose a fresh conductor surface for further accretion (fig. 5). Thus, conductors that have low torsional rigidity can have higher ice loads. In long single conductor spans, the eccentric weight of the deposit may be large enough to significantly twist the conductor. Since the conductor span is fixed against rotation at the ends, this eccentric ice load will twist the conductor most at mid-span and the angle of twist will become progressively smaller going from mid-span towards the supports. Bundled conductors have higher rotational stiffness than single conductors which leads to differences in ice accumulation and shedding. Anti-torsion devices like counterweights, detuning pendulum or spacers can reduce the amount (and shape) of snow deposit and even accelerate the snow shedding. Therefore, the observed twist, as illustrated on figure 5, depends on the span's configuration (single conductor, bundled conductors, interphase spacers, detuning pendulums, etc) and depends on measurement sensor location along the span (sensor locally does change torsion rigidity and moment of inertia, as detuning pendulum do, both in a different way). 3D vibration and orientation measurement allow detecting twist of conductor/sensor (figs. 5,6,7,8).

Figure 6 illustrates the measurement of the twist thanks to 3D static orientation measurement of gravity. Figure 7 shows the measurement during an accretion event. According to axes orientation at rest (fig. 6), during no accretion period, VERT axis is aligned with gravity (reading close to gravity; 1[g] in absolute value) and TRANS axis is perpendicular to gravity (reading close to 0 [g] as perpendicular to gravity). On figure 7, one sees the twist of conductor as VERT axis and TRANS axis rotate around 09:00 and around 18:00 (2017, Dec 11th). During these periods VERT and TRANS axes rotates as VERT axis is not anymore aligned with gravity and TRANS axis is no more perpendicular to gravity. Both events have different amplitude of twist, probably due to different additional weights of accretion.

Fig. 5: Theoretical illustration of ice deposit and twist during icing with wind.

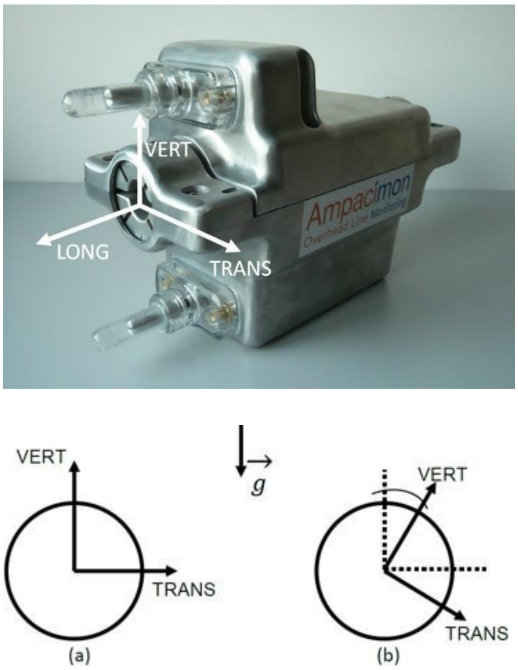

Fig. 6: (top) Sensor at rest on a table and axis reference (vertical VERT, transversal TRANS and longitudinal LONG) and (bottom) A cross-sectional view of the conductor/sensor and illustration of the determination of twist using gravity and orientation of VERT and TRANS axes of measurement (a) no twist : VERT axis is aligned with gravity and TRANS axis is perpendicular to gravity and (b) twist : VERT axis is not more aligned with gravity and TRANS axis is no more perpendicular to gravity.

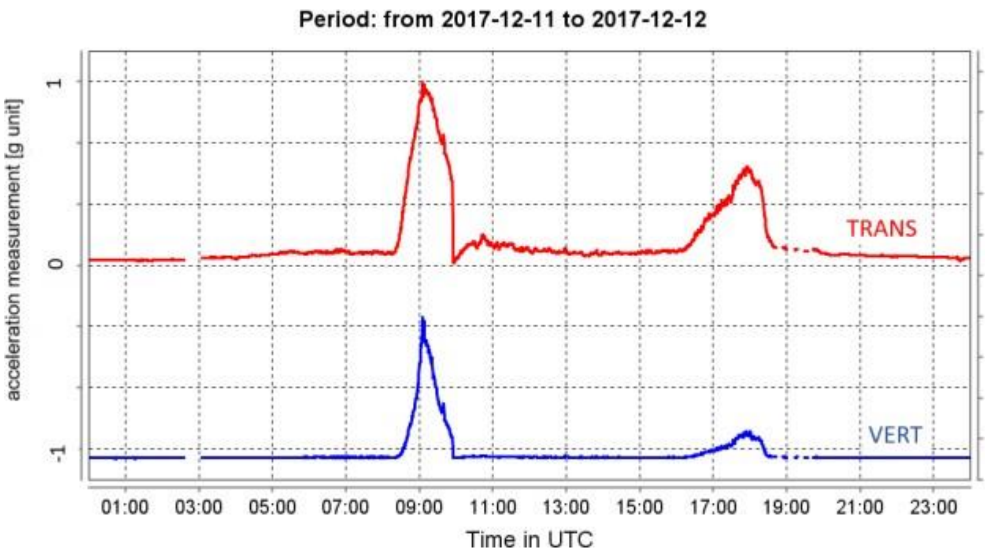

Fig. 7: (top) One day of measurement of acceleration along VERT and TRANS axis (see fig. 6 for axis orientation at rest) from a sensor installed on a single conductor suspension span (conductor: 210Alac, span length: 304 [m]). During no accretion, VERT axis is aligned with gravity (reading is gravity : 1 [g] in absolute value) and TRANS axis is perpendicular to gravity (reading close to 0 [g]). Twist of conductor due to icing is visible around 09:00 and around 18:00 (2017, Dec 11th).

iii. Ice Shedding

Ice-shedding induced potential large dynamics motions of conductor. Figure 8 shows such an event measured by vibration-based sensor. According to axes orientation at rest (fig. 6) one sees the twist of conductor as VERT axis is aligned measures –gravity at the beginning of the day and measures +gravity at 06:00, meaning a rotation of 180 [degree]. This is also confirmed by the reading from TRANS axis (figs. 6,8). After the ice-shedding, VERT and TRANS axes go back to normal orientation (VERT axis is aligned with gravity and TRANS measures small value as it is perpendicular to gravity) leading to torsional movements of the conductor.

Amplitudes of accelerations depends on the wind excitation and different amplitudes are visible (moderate increase of amplitudes on VERT axis at around 12:00-14:00 are related to Aeolian vibrations, i.e., perpendicular to wind speed and mainly vertical movements for power lines in that case).

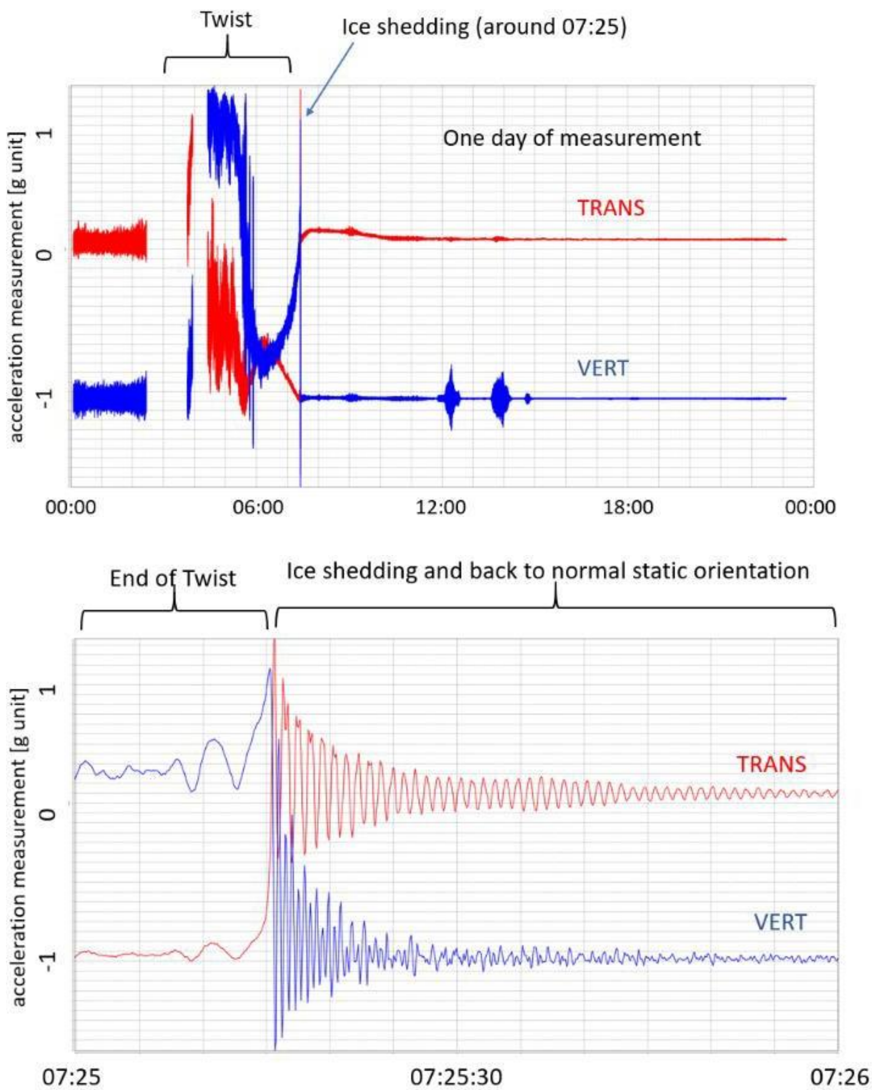

Fig. 8: (top) One day of measurement. Acceleration along VERT and TRANS axis (see fig. 6 for axis orientation at rest) on a single conductor dead-end span (conductor: 248AMS, span length: 227 [m]) and (bottom) zoom on the period of ice-shedding and large dynamic acceleration and corresponding torsional movement.

iv. Apparent Weight / Additional Weight

Figure 9 shows the time evolution of apparent weight per unit length normalized by conductor weight per unit length (reference value equal to 1 [dimensionless] during no accretion) thanks to the combination of vibration-based sag and tension measurements as explained in previous sections during winter 2018-2019. Additional weight of accretion has reached 22% of weight of conductor in that case. Abrupt change (decrease) of apparent weight around November, 21st is related to ice-shedding (see also sub section iii).

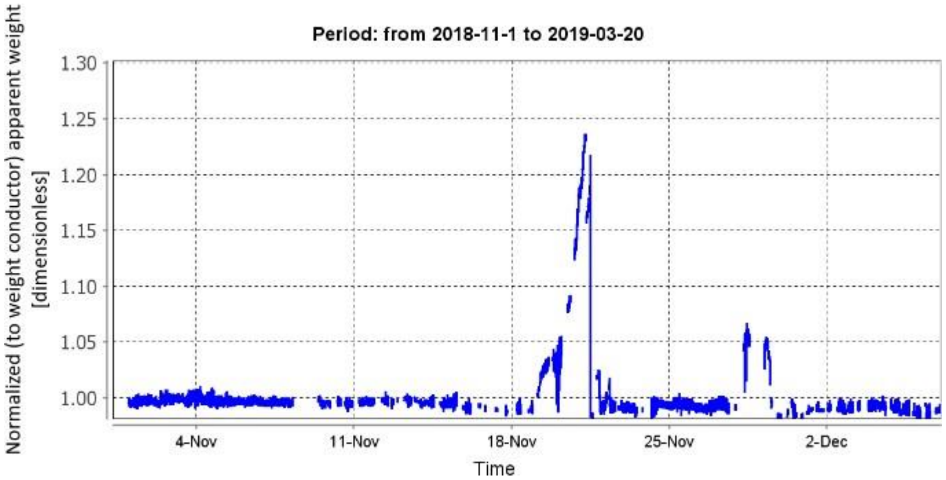

Fig. 9: time evolution of apparent weight per unit length normalized by conductor weight per unit length (reference value equal to 1 [dimensionless] during no accretion). Measurements from a sensor installed on a single conductor suspension-anchoring span (conductor: 243-AL1_39-ST1A, span length: 152 [m], mass per unit length : 0.9798 [kg/m]).

One prototype sensor was recently (January 2019, 29th) installed at Dead Water Fell (DWF) test site on Scotland/England border in the UK (EA Technology [21]) (fig. 10). As test line is not a live-line, sensor was powered up by constant power supply (meaning continuous available data). Sensor was installed during a period with some deposit on conductor (fig. 10). Snow has been cleaned up close to sensor location for installation purpose. Correlation between sensor output readings and sag (see section II) has been computed a few days after installation with no ice period and first data with ice during the few days after installation has been postprocessed. In practice, sensor is preferably installed on real-line before winter and accretion events to allow configuring tension measurement outputs (sec. II) and computation of apparent weight.

Figure 11 shows the time evolution of accretion weight per unit length normalized by conductor weight per unit length at Dead Water Test site during the few days after installation. Additional ice weight per unit length has reach 80 % of the weight of conductor per unit length.

Further research is underway to achieve deeper analysis of all observed events and recorded data from installation at Dead Water Fell test site (correlation of icing with weather data measured at test site location, and estimation of measurement accuracy).

Fig. 10: Ampacimon™ vibration-based sensor [9] installed on single conductor (Conductor : ACSR LA-180, span length: 190 [m]) at Dead Water Fell test site (owner : EA Technology [21]) Sensor has been installed during a period with some deposit on conductor. Snow has been cleaned up close to sensor location for installation purpose (no snow in front of the sensor and snow behind sensor).

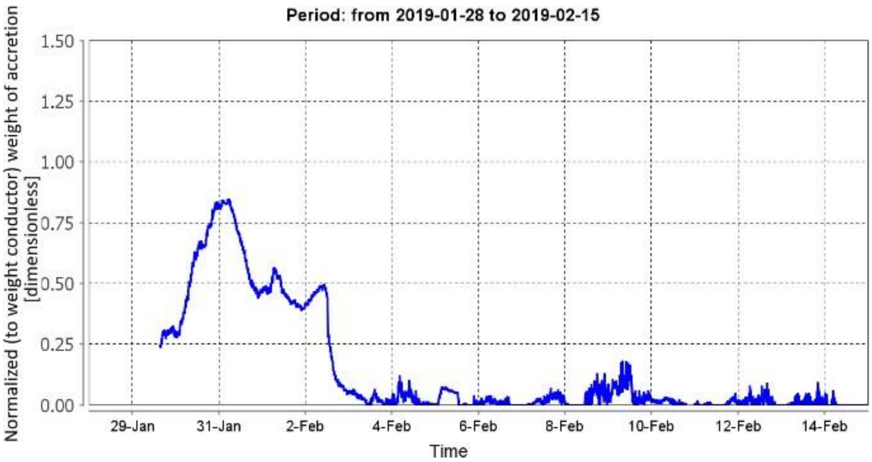

Fig. 11: time evolution of accretion additional weight per unit length normalized by conductor weight per unit length. Measurements from a sensor installed at Dead Water Fell test site (see fig. 10) on a single conductor dead-end span (Conductor : ACSR LA-180, span length: 190 [m], mass per unit length : 0.676 [kg/m]).

IV. Conclusions

The method and sensor according to the present paper has several advantages over the methods proposed in the art since sag and tension (and icing) are simultaneous monitored in real-time without need of any, otherwise unavailable and/or uncertain, data or uncertain models. Monitoring of icing on power lines is available in real-time combining 3D vibrations of conductor, sag and tension measurements. Thanks to 3D vibrations measurement any abnormal mechanical behavior (twist, abnormal sag increase, ice shedding, galloping…) is easily measured, observed and detected and alarm can be sent to grid operator. Moreover, Field experiments with the presented monitoring sensor provide interesting information on conductor behavior for both network operation and conductor diagnosis (measure and identification of any abnormal event and potential subsequent damages on wires of overhead power transmission lines). Some examples are given in the paper including abnormal sag increase, icing, ice- shedding.

By measuring sag and tension simultaneously the weight per unit length of icing or mixtures deposits is available in real-time at line location and early warning to melt icing and rime deposits can be provided. No doubt that such a new on- site real-time measurement will help TSO's or DSO's to monitor the grid.

Moreover, the sensor according to the present paper is also measuring wind at line level in real-time and provides interesting information on conductor behaviour from fatigue to wind gust and rating, including any kind of small or large vibrations, including icing or not, and buffeting for both network operation and conductor diagnosis. A such approach becomes a need for asset management, measuring and understanding combined effects of ice or wet snow and wind on overhead power lines including overloading and aeroelastic instabilities and for operating the lines in a more known environment.

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