

TECHNOLOGICAL DEVELOPMENTS FOR THE STUDY OF GUY CABLE DAMAGE INDUCED BY ATMOSPHERIC ICING ON HIGH VOLTAGE TRANSMISSION LINES

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Abstract: This paper summarizes the experience of Hydro Québec with the development of wind-induced-vibration damping solutions for support cables of guyed transmission towers in extreme Nordic environment.

1. INTRODUCTION

Hydro Québec operates an extensive network of overhead 735 kV transmission lines which stretches over 11000 km. These lines are subjected to extreme weather conditions involving atmospheric icing. In particular guy wires used as supporting cables are prone to rime and snow accretions that can persist on the structures for considerable lengths of time. (See Fig. 1) These icing conditions were found to generate considerable wind-induced vibrations on the guy wires and have lead to severe damage and even breakage of the support cable anchoring system, especially in stiff rock anchors. In order to address this problem and develop mitigation solutions, it has been necessary to collect vibration data from the field. Hydro Quebec has developed, with the support of a data acquisition system manufacturer, a vibration monitoring device designed to collect vibration data over extended periods in harsh cold conditions.



Figure 1. Hard rime accretion on James Bay transmission network

2. RESULTS AND DISCUSSION

Long term in-situ monitoring of vibration of the anchor rod/support cable system has shown significant occurrence of high-amplitude motion events capable of metallurgical fatigue damage in the anchor rods [1]. Stay cables on rock anchors are typically equipped with Stockbridge dampers to mitigate these effects [2]. Laboratory testing of damaged

dampers has enabled to gain a better understanding of the phenomenon and helped in designing a tailored solution to prevent further damage to the anchoring system. This work also shows a significant link between the geomorphology of the local terrain, local weather environment and dominant wind direction with the probability of occurrence of support cable vibration episodes. Terrain modeling and analysis through the use of geospatial software has enabled to evaluate the probability of rime/snow accretion on the structures. Ongoing computational studies on the dynamic response of guyed towers are bringing further understanding of the vibration events and their link to rime accretion on the support cables.



Figure 2. Detail of rime accretion on support cable

3. CONCLUSION

A combination of experimental methods, in situ vibration monitoring and computational modeling are used to assess and improve mitigation solutions for guy wire vibrations induced by persistent hard rime and snow accretions on guyed transmission line supports.

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Technological developments for the study of guy cable damage induced by atmospheric icing on high voltage transmission lines

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Abstract— This paper summarizes the recent experience of Hydro Québec with the development of wind-induced-vibration damping solutions for support cables of guyed transmission towers in extreme Nordic environment. At particular sites near large bodies of water, guy wires are prone to hard rime and snow accretions that can persist on the structures for several weeks. These icing conditions were found to generate considerable wind-induced vibrations on the guy wires and have lead to severe damage and even breakage of the support cable anchoring system, especially in stiff rock anchors. To address this problem, understand its physics and develop effective mitigation solutions, Hydro Québec has used a combination of measures including *in situ* monitoring at problematic sites, laboratory testing of damping devices, and more recently, computational models of guying systems.

Keywords: cable vibrations, wind-induced vibrations, hard rime, vibration monitoring, tuned mass dampers, computational studies.

I. INTRODUCTION

Hydro Québec operates an extensive network of overhead 735 kV transmission lines which stretches over 11000 km. These lines are subjected to extreme weather conditions involving atmospheric icing. At particular sites where local elevation and proximity to large bodies of water create favourable conditions for in-cloud hard rime icing, accretions can persist on the structures for several weeks, and several icing episodes are likely to occur during the year (see Figs. 1 and 2). These icing conditions were found to generate considerable wind-induced vibrations on the guy wires and have lead to severe damage and even breakage of the support cable anchoring system, especially in stiff rock anchors.

The problem was first addressed by collecting vibration data from the field. To this end, Hydro Québec has developed, with the support of a data acquisition system manufacturer, a vibration monitoring device designed to collect accurate vibration data over extended periods in harsh cold conditions. Long term *in situ* monitoring of vibration of the anchor rod/support cable system at problematic sites has confirmed significant occurrence of high-amplitude motion

events capable of metallurgical fatigue damage in the anchor rods.

Hydro Québec has been using vibration dampers to prevent premature failure of guy wire anchor rods on its high voltage transmission network for over 15 years [1]. As shown on Fig. 3, these are Stockbridge dampers, which have been used with great efficiency to mitigate vibration in line conductors. However, in recent years, maintenance surveys have indicated a number of damper failures (see Fig. 4) at rime-prone tower sites with rock anchors. The most critical structures were the chainette towers – also called cross-rope suspension towers, on lines located in the James Bay and Lower North Shore areas. This type of structure has four steel support cables to maintain the two lattice masts and the cross-rope suspension in their upright position. A good example of a critical site located in James Bay is shown in Fig. 1 where the supports are fully covered with white rime while the line conductors are bare. A chainette tower is seen in the foreground while guyed-V and H-frame supports appear in the background as several transmission lines share this same corridor.



Figure 1: Rime accretion on James Bay network structures

II. NORTHERN CLIMATE AND RIME/ICE ACCRETION

Rime and/or glaze ice accretion on overhead power line conductors and supports are most often caused by freezing rain [2]. However, in this study, the hard rime deposits are attributed to freezing fog. For a given site or line corridor section, a good indicator of the likelihood of accretion is provided by the wind rose which is a handy tool as it indicates the direction, speed and frequency of the winds. In the James Bay region of Québec, the terrain is rather flat and open, free of obstacles for long stretches. Also, as the terrain presents a very gentle slope on great distances, the main horizontal wind flow is accompanied by a light lifting of air along certain wind directions. On cloudy days, supersaturation of air is easily reached on higher locations where terrain elevation reaches cloud bases. In such areas, line conductors and their support structures happen to be higher than the cloud base; in fact, they are surrounded by fog which is made up of supercooled micro droplets. As long as the wind keeps its direction and a minimum speed, the supersaturation tendency (cooling rising air) causes rime formation on objects. With time, these accumulations may become important. Also, episodes of very cold temperatures that may follow freezing fog events can contribute to harden these rime accretions and make them adhere more strongly to tower members and support cables. Such hard rime deposits are difficult to shed in ambient conditions. As a result, towers can stay covered and exposed to wind for extended periods of time of several weeks. Figure 2 shows an example of large hard rime accretion on a support cable, typical of the cases reported as critical.



Figure 2: Large hard rime accretion on guy cable

III. DAMPING SOLUTION DEVELOPMENT

The guyed-V and chainette suspension towers are the dominant types of supports used in the James Bay 735kV line network. In guyed-V towers, the masts are interconnected by the latticed beam supporting the line conductors, which make these structures stiffer than the

chainette towers. Nonetheless, these guyed towers are relatively flexible – especially the chainette type – when compared to the more traditional four-legged latticed self-supporting towers. Wind-induced vibrations have been a concern for chainette towers since their inception and in 1992, Hydro Québec (IREQ Expertise Mécanique, Métallurgie et Civil) started to conduct a major study to develop passive damping solutions adapted to the support cables of the chainette towers. An example is shown in Fig. 3 where two tuned-mass Stockbridge type dampers are installed on a guy cable. To date, more than 6500 dampers have been installed on the guy cables of chainette towers in the high risk areas.



Figure 3: Dampers installed on guy support cables (James Bay 735 kV network)

Several wind-related phenomena will generate vibrations in a guy cable [2, 3]. In this study, we are primarily concerned with vortex shedding effects in taut cables (as evidenced by monitoring data analysis), even though the eccentric cross-sectional shape of ice/rime deposits may cause aeroelastic instabilities resulting in galloping in some particular conditions [1].

In the classical vortex shedding model, the eddy shedding frequency, F is a function of S (Strouhal number), wind speed (U) and the equivalent diameter of the cable (D) across the wind stream:

$$F = \frac{SU}{D} \quad (1)$$

F is therefore independent of the vibrational properties and boundary conditions of the oscillating cable. Large rime accretions on cables increase their equivalent diameter and the increased area exposed to wind generates considerable vibration power input in the cable as this power input is a function of D^4 . The initial selection of the Stockbridge dampers used on the guy cables was essentially based on the extrapolation of the tuned-mass damping model used to mitigate Aeolian vibrations in overhead conductors, with appropriate equivalent conductor diameter. This solution did not prove fully effective as damaged dampers (see Fig. 4) were observed at several sites on rock. It remains to be established whether or not the damaged dampers still served

a useful role in vibration mitigation until they were replaced by new devices. To globally address this issue, an experimental study was conducted in 2004-2005 which included field monitoring of guy cables and laboratory vibration tests on Stockbridge dampers.



Figure 4: Typical damper failure of initial damping solution for guy support cables

The monitoring study enabled identification of the recurrence of vibration events and the frequency and magnitude of the oscillations of the head of the anchor bars. Laboratory testing of damaged dampers has enabled to gain a better understanding of the phenomenon and helped in designing a tailored solution to prevent further damage to the anchoring system. These tests have shown that the failure mode observed in the field was not caused by Aeolian vibrations but rather by a high amplitude low frequency mode more related to galloping. Subsequent over sizing of the dampers was implemented and proved to be effective for the long term protection of the guy cable anchoring system. At present, this is the mitigation solution employed at rock sites, while sites on soil have not shown any signs of such vibration problems. However, a few incidents of damper failures have been observed despite the implementation of the improved solution.

The problem appears almost unique to Hydro Québec with its lines on flexible supports in areas exposed to hard rime and steady wind. No other similar problems have been reported in the open scientific literature on transmission lines. Adverse effects of wind-induced guy cable vibrations are also a concern in other types of structural applications such as cable-stayed bridges and telecommunication masts. Although some considerations for vortex shedding and galloping may be introduced at the design phase, the usual approach for these structures – as in most cable-stayed applications – has been to adapt field solutions after construction, on an “as per needed” basis. This reactive

approach is clearly not sustainable; relatively new structures are found deficient and the structures’ reliability become dependent on regular inspection, maintenance, and repair, which costs are usually prohibitive.

A recent and comprehensive state-of-the-art review of theory and applications has been published by the International Association for Bridge and Structural Engineering (IABSE) [4]. Most structures located in cold climate are given proper consideration for atmospheric icing and cable de-icing is an efficient solution for strategic structures. However, “unforeseen” damage has occurred on many relatively new cable-stayed bridges in the United States, as reported by Palmquist [5] who explains that some design flaws may result from a more general lack of understanding of structural vibrations in flexible structures. It should be mentioned that the guy cable parameters observed in bridges are quite different from those used in transmission line supports, in terms of configuration, size, mass, length and every-day tension. Another practical difference is that vibration monitoring and mitigation in bridges is facilitated by easy access to the structure.

The guying systems used in short telecommunication masts share more similarities with guyed transmission supports than cable-stayed bridges, namely in terms of overall flexibility and transverse lateral stiffness. They are also prone to wind-induced vibrations and galloping: these problems are relatively well-known and summarized in a review published by the Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE) [3]. Design for fatigue endurance is further complicated by the fact that some fatigue damage can occur at all wind speeds. The most damaging are gusty winds and ice storm conditions, usually associated with large mean cable tensions, but lower wind speeds on ice-covered cables can lead to more dangerous situations.

IV. TERRAIN ANALYSIS AND METEOROLOGY

Recurrence of vibration events monitored in some sectors led to the investigation of the link between the local terrain geomorphology and the probability of guy wire vibration episodes. Through the use of GoogleEarth™ software, a detailed mapping of all vibration events observed on the grid was made. The study indicated that the tower sites most prone to guy cable fatigue damage share similar geomorphologic characteristics such as local higher elevation, line orientation with respect to dominant wind directions, height of forest cover, and presence of large unfrozen bodies of water as sources of humidity for in-cloud icing and hard rime formation on structures. These findings are very important because they allow correlating the results at observed sites to other sites with similar conditions.

V. UNRESOLVED ISSUES AND FURTHER RESEARCH

Hydro Québec’s recent experience has confirmed that traditional mitigation methods and models for damping

Aeolian vibrations of overhead line conductors do not systematically provide good results when applied to support guy cables. First of all, the dynamic characteristics of guy cables (length, mechanical tension and natural frequencies) are very different than those of line conductors and ground wires, which make them sensitive to different frequencies of the wind power spectrum. Also, dynamic interactions taking place between the guying system and the supported structure cannot be ignored like in conductor vibration models. In line conductors, bare conditions at very low temperature are usually the most severe conditions for which mitigation is fine tuned. The conditions are much more variable for guying systems that may require damping in both the bare and iced conditions, and in a range of wind and ice combinations depending on the dynamic characteristics of the guy wires.

Even where some Stockbridge damper solutions appear to have prevented visible damage to guy wires at observed critical sites, some crucial issues remain unresolved:

- Assessment of the mechanical integrity of the guy wire anchor rods under different soil conditions;
- Validation of a physical model to explain the guy cable behavior leading to Stockbridge damper damage with bent upper link;
- Assessment of the vibration-protection performance of damaged Stockbridge dampers and its influence on the fatigue endurance of guy wires and their anchor system;
- Extrapolation of cable damping solutions for the chainette tower to other guyed towers types such as guyed-V towers and dead-end masts used as straining towers.

To address these issues, IREQ and McGill University have recently joined forces in a research project that combines field monitoring studies and computational modeling. In particular, a better understanding of the following aspects is necessary to provide “holistic” engineering solutions:

- Wave propagation and dynamic interaction effects between guy wires, supported masts, and line conductors. Different input frequency bands will trigger different phenomena.
- Soil-structure interactions in flexible towers and their role in attenuating or exacerbating vibration problems in various components.
- Influence of ice accretion deposits (density, cross-sectional shape and longitudinal patterns) on the dynamic characteristics of guy cables (natural frequencies and internal damping).

A new and improved set-up for field measurements is being tested to collect cable vibration data with higher resolution and to measure the mast response.

VI. COMPUTATIONAL MODELING STUDIES

Commercial finite element software offers all the necessary features to model complex solid mechanics problems such as nonlinear vibrations in guyed towers. The issue is to apply existing tools with proper insight to focus

modelling to the adequate scale that will retain the essential features of the actual structural response. The models are constructed and validated by successive levels of complexity, starting with individual cables and ending with full guyed tower models in interaction with conductor spans in the case of the chainette tower, with soil-interaction effects at the guy anchors. At this stage, models have included individual guy cables/anchors with no mechanical damping, as follows:

- Validation of dynamic characteristics (natural frequencies and internal damping) obtained from ambient vibration measurements;
- Study of the effect of rime ice accretion (quantity and configuration) on the dynamic characteristics of guy cables;
- Study of the effect of the guy anchor rod and hardware on the dynamic characteristics of the guy cables;
- Modeling of individual guy anchors with consideration of foundation flexibility and soil interaction (inertia and damping effects).

Full chainette tower models have been constructed and are awaiting validation with field measurements.

VII. CONCLUSION

A current collaborative research project involving McGill University and Hydro-Québec’s research institute (IREQ) combines experimental methods, in situ vibration monitoring and computational modeling to assess and improve mitigation solutions for guy wire vibrations induced by persistent hard rime and snow accretions on guyed transmission line supports.

VIII. ACKNOWLEDGMENTS

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