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A novel ice-shedding model for overhead power line conductors with the consideration of adhesive/cohesive forces

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ABSTRACT

An ice-detachment failure model is proposed for iced overhead electrical conductors to predict the transient response of line systems subjected to shock loads. The model considers the bending strains in the ice deposit, the adhesive force at the ice–cable interface and the cohesive force within the ice. It is implemented into finite element analysis by setting a critical vertical acceleration corresponding to inertia forces overcoming the adhesive/cohesive forces on the ice chunk. The model is validated by results from reduced and real scale de-icing tests of glaze ice but the approach can apply to different types of atmospheric icing.

1. Introduction

In cold regions, atmospheric icing is one of the major external loads threatening the reliability and mechanical security of overhead high voltage electric transmission lines. Excessive accreted ice on conductors can induce electric faults, such as flashovers, due to insufficient clearances, and mechanical damages to transmission line systems, such as hardware/insulator component failure, cable breakage, tower deformation and collapse [1,2].

To prevent and mitigate the icing disasters on electrical structures, efforts have been put into developing effective and practical anti-icing and de-icing techniques [3]. A portable mechanical device for de-icing overhead ground wires (GWs) and optical overhead ground wires (OPGWs), called DAC (De-icer Actuated by Cartridge, see Fig. 1) has been developed by Hydro-Québec and some of their prototype test results have been used in this research. DAC takes advantage of the brittle characteristics of glaze ice at high stain rates ($>10^{-3}$/s) [4–6]. As shown in Fig. 2, the piston suddenly pushes the cable to generate a transverse shock wave, resulting from gas expansion when DAC is fired. When the shock wave propagates along the span, it can break the ice deposit into small fragments. Details of this device can be found in [4–6]. A series of laboratory reduced-scale tests [4,6] and real-scale tests [5] on a test line section had been carried out to validate the effectiveness of the DAC and to optimize its parameters; the results of these tests will be used for comparisons in Section 3 of this paper.

On the other hand, the dynamic response of electric transmission line-tower systems due to icing events, especially the phenomenon of ice shedding, has been studied for decades. Very approximate practical models were suggested as early as the 1940s (reported in [7]), which were later improved by Morgan and Swift [7], with an initial focus on the cable rebound height from the initial configuration of the iced cable.

With the development of numerical simulation techniques and finite element (FE) analysis, Jamaleddine et al. [8] were the first to use commercial nonlinear FE software [9] to model the nonlinear dynamic responses of transmission lines after sudden ice shedding. The FE models were validated by several experiments on a two-span reduced-scale (3.322 m each span) line section, where ice shedding was simulated by sudden release of dead weights suspended on a wire.

Later, Roshan Fekr and McClure [10] pursued a computational study of 21 ice-shedding scenarios on a two-span line section, where ice shedding was simply modeled by a sudden change in density of the iced cable when transferring from static to dynamic analysis. With the variation of several parameters (such as ice thickness, span length, difference in elevation between end and suspension points, number of spans per line section, presence of unequal spans and partial ice-shedding on sub-spans), improved understanding of the dynamic response of transmission lines after ice shedding was achieved.

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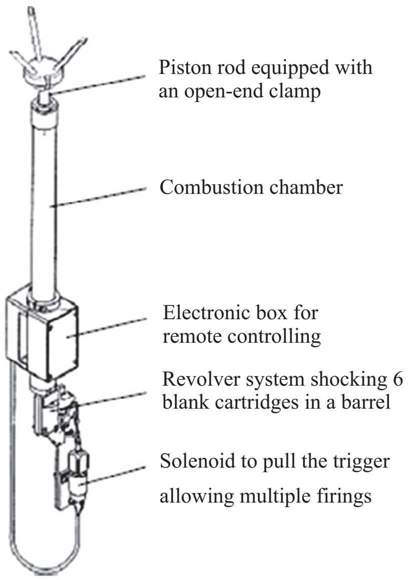

Fig. 1. Schematic of DAC prototype (adapted from [4]).

Following the same approach, Kollár et al. [11] simulated the dynamic response of a five-span line section after three types of ice shedding scenarios: (1) instantaneous shedding of the whole span, (2) propagating shedding along the span at a pre-defined speed, and (3) propagating shedding along the span with discrete sudden shedding of large ice chunks. The numerical results showed good agreement with the real-scale tests conducted by Van Dyke and Laneville [12]. Vibration of bundled conductors was also studied more recently by Kollár and Farzaneh [13–15], and the modeling methods were validated by comparing with a small-scale twin bundle laboratory test [14].

As a significant improvement on ice-shedding modeling, Kálmán et al. [4] were the first to propose a failure criterion for the ice deposit and to implement it into FE models. This allowed to simulate the shedding propagation of ice along the span after an external shock load aiming to remove the ice deposit, instead of using instantaneous shedding or pre-defined propagation sequence along the span as done in previous studies. The maximum allowable plastic stress failure criterion (referred to simply as stress criterion) takes account of both axial and bending stresses of the glaze ice deposit (assumed as bilinear isotropic beam), and automatically sets the ice element to “death” (in ADINA, the mass and stiffness of the element are eliminated from the global mass and stiffness matrices [9]) when the maximum allowable plastic stress is reached at any integration point within the ice beam element. Detaching (i.e. sudden “death”) of the ice element can be readily and successfully simulated in this way. The stress criterion was later validated by four scenarios of tests on a 4 m reduced-scale single span line section [6], in terms of cable measured tensions and mid-span displacements. This model was overestimating the shedding rate, however, not taking into account that some ice chunks remain attached to the cable even if combined stresses are exceeding the specified strength.

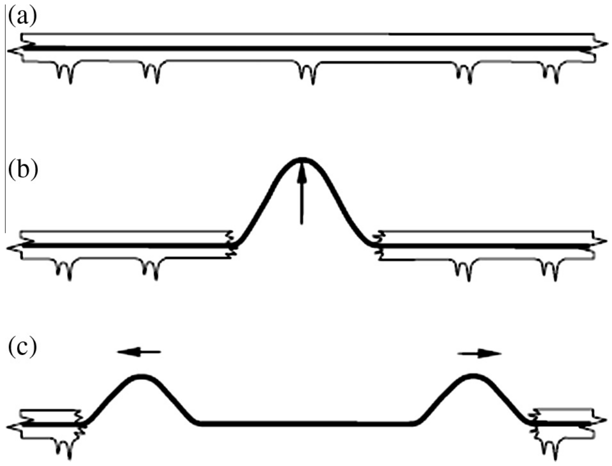

Fig. 2. Schematic of transverse wave propagation and ice breaking: (a) iced cable section before the shock load; (b) during the shock load imposed by DAC; (c) a short moment after the impact (adapted from [4]).

With a view to address some of the shortcomings of Kálmán’s work, Mirshafiei et al. [16,17] proposed a maximum effective plastic strain criterion (referred to simply as strain criterion), by which the ice element is set to “death” when the ice around the ice–cable interface starts to yield, and the corresponding plastic strain at the ice beam surface is set as “the maximum allowable plastic strain”. So, the maximum allowable plastic strain varies for different ice thickness scenarios. The strain criterion leads to almost the same values as the stress criterion, in terms of cable tensions and mid-span displacements, but provides a better prediction of the ice shedding rate, i.e. the fraction of the ice shed in the span in percentage.

However, despite these numerical improvements, some observations made during the tests cannot be explained by the two above ice rupture criteria: (1) in the 4 m reduced-scale single span tests, most of the ice was broken into small fragments after the impulse load while it still remained on the cable (Fig. 3), and only 5–9% of the initial ice was shed from the cable (referred as “effective ice shedding” in [4,6,16,17]), whereas, in the numerical results, this fraction varies from 57% to 90% (predicted with the stress criterion) [6] or from 24% to 81% (predicted with the strain criterion) for different test scenarios [16,17]; (2) real-scale tests by Hydro-Québec indicate that 6–7 times more energy is needed to break up concentric ice accretions than eccentric deposits [5]; (3) there is still a thin but rough coat of ice left on the real scale cable after ice shedding. These observations show the necessity to take into consideration not only the adhesive force at the ice – cable interface but also the cohesive force within the ice for a more realistic ice failure criterion, which would yield a more accurate prediction of ice shedding rate and consequently improve the consistency of predicted results of both cable tensions and mid-span displacements.

In [18], the authors outlined the general features of the proposed new ice-shedding model which takes into consideration the adhesive characteristics of the ice/conductor pair and the cohesive strength of glaze ice. A preliminary analysis of the acceleration distribution along a single span confirmed the good potential of the new criterion.

In this paper, the ice detachment failure criterion is implemented in FE modeling, with a user-defined failure model introduced in commercial software ADINA (version 9.0.3, released in May 2014). The new model is explained in detail and the previous experimental results from both reduced scale and real scale tests are compared with the FE models for validation.

2. Ice detachment failure criterion

2.1. General force balance concept

For glaze ice, the simple concept of the ice detachment failure criterion introduced is to compare the inertia forces (with gravity) acting on the fractured ice segments present on the cable, and the ice adhesive or cohesive stress resultants, after the effects of the ice