GALLOPING OF ICED ELECTRICAL TRANSMISSION LINES

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Abstract

A case study is presented of ways to reduce the possibility of galloping being initiated on an existing and on a similar but planned single electrical transmission line. Lines are considered to be covered uniformly along each span with a severe, asymmetrical coating of ice produced by a freezing rain. The most efficient and plausible structural adjustment would be to increase the damping, particularly the conductor's torsional damping. Detuning pendulums can also be effective when added appropriately to an existing line.

Key Words

Flow-induced vibrations, freezing rain, self excited oscillations, vibration initiation

1. Introduction

The galloping or low frequency, large amplitude oscillations of an ice coated, electrical transmission line during or after a freezing rain storm may seriously reduce><the life of the line. Moreover, the economic benefit of reducing the phase spacing, without compromising line reliability, by controlling galloping is typically one quarter to one third of the supporting towers' cost. Although ice melting is a useful control strategy, it is ineffective on larger subtransmission conductors due to their limited current capacity. Therefore, most control methods for an existing line involve add-on devices, the currently most popular one being a detuning pendulum. As the name suggests, the detuning pendulum is a heavy weight which is suspended by a short arm (to largely preserve a clearance) beneath a conductor. However, extensive field trials suggest a reasonable but certainly limited success. Of course, the preferred strategy, but one available at solely the planning stage, is to optimize the line's structural parameters. This approach, however, requires a better understanding of fundamentals as well as an improved mathematical analysis of galloping.

The classical single degree-of-freedom ( dof) theory for the initiation of purely vertical galloping was proposed some 60 years ago by Den Hartog [1]. However, his formula depends only upon the aerodynamic lift derivative and drag force so that a line's structural properties are ignored completely. Moreover, by amplifying the simultaneous rotation of the conductor for easier observation, Edwards and Madeyski [2] found that it was greater than expected in field trials. Nigol and Clarke [3] theoretically confirmed the importance of torsion about 20 years ago. Jones [4] suggested that coupled vertical-horizontal (normal to the line) oscillations could be influential too. A comprehensive 3 dof model, which incorporates combined vertical ( y), twist (θ) and horizontal ( z) movements, has been developed more recently by Yu et al [5,6] not only for the initiation of galloping but also for the ensuing nonlinear dynamic limit cycle. Further refinements were found necessary, however, to accommodate the dynamic change in a line's static tension when detuning pendulums are installed. On the other hand, a major thrust of Yu et al [7] was to derive analytical solutions. Although solutions are too complex to make trends discerned easily, they enable computations to be extremely fast and, hence, interactive. This advantage is particularly attractive because Desai et al [8] found that a purely numerical approach like the finite element method is extraordinarily protracted even when time averaging is used. Therefore, the refined 3 dof model is used here to ascertain the probability of galloping being initiated due to severe icing on a single transmission line. The effect of
detuning pendulums that are distributed along a line is also considered.

2. Overview of Analysis and Experiments

The performance of detuning pendulums has been assessed previously by visually comparing the wind induced oscillations of nearby, nearly identical transmission lines, one of which supports pendulums. If the line having detuning pendulums did not gallop whilst the other line did, then the pendulums clearly worked. Ontario Hydro [9] performed such an experiment for Pennsylvania Power and Light on a 23.6 mm diameter, S51 line with the expected result. This observation was corroborated numerically [10].

<table>
<thead>
<tr>
<th>Table 1: Constant line parameters</th>
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<tr>
<td>Along line stiffness, N/m</td>
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<td>Linear stiffness of adjacent spans, N/m</td>
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<tr>
<td>Total mass per unit length, kg/m</td>
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<td>Total moment of inertia per unit length, kg.m</td>
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<td>Eccentricity, m</td>
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For demonstration purposes, however, a Drake conductor, which is commonly employed for relatively high voltage distribution lines as well as transmission lines, is used to illustrate sensitivities to parameter changes. The basic line properties that remain constant are given in Table 1. On the other hand, the transverse and torsional critical damping ratios, $10^{-4} \leq \zeta \leq 10^{-2}$, as well as the torsional stiffness, $145 \leq GJ \leq 430 \text{ Nm}^2/\text{rad}$, span length, $160 \leq L \leq 380 \text{ m}$, and horizontal static tension, $10 \leq H \leq 35 \text{ kN}$, are varied in the indicated ranges to determine if the changes reduce the probability of initiation. This probability depends strongly upon the wind's angle of attack, $\alpha$, to the particular ice shape formed on the line.

It is very difficult to discern, from the ground, the exact shape of ice (and its eccentricity) on a vibrating line. Moreover, the ice shape will evolve over time and it will be influenced by the environmental conditions and the terrain. Aerodynamic measurements on stationary models of ice samples generated in a freezing rain simulator [11] suggest that a strong steady side wind, the temperature of the impinging rain droplets and the total precipitation are the major environmental influences. The C11 ice profile shown in Fig. 1 represents a heavy precipitation which causes the costliest damage in Manitoba [10]. The corresponding aerodynamic forces and moment are measured in a wind tunnel by reasonably assuming a quasi-static behavior [12].

The aerodynamic moment is balanced at the line's static equilibrium position by the moments arising from the eccentric weight of the ice and the line's torsional stiffness. The ranges of plausible static rotations were computed by assuming that a given wind is always normal to the line but permitting it to rotate $180^\circ$ in plan. (Field experience indicates that galloping often happens in the days immediately following a freezing rain storm - after the wind has changed direction.) The wind speed was increased progressively, at a given static rotation, until the critical value at which galloping may be initiated was determined. An increase (or decrease) in the critical wind speed as a result of changes in a line's parameters or the addition of detuning pendulums implies that the static profile is more (or less) stable and, thus, the initiation of galloping has a lower (or higher) probability. Each plausible static rotation produces a corresponding critical wind speed. A Gumbel type I function [13] was used to determine the probability distribution of the mean wind speed. The distribution, at a given static rotation, for all such speeds greater than the critical wind speed gave the probability of initiation of that angle. Finally, the probabilities for each integer degree angle in the plausible static rotation ranges were summed to produce the overall probability of initiation.

About 98% of the galloping incidents observed in the field involve up to 3 oscillation loops per line span [14]. On the other hand, the number of loops per span in different directions need not coincide. Therefore, up to 27 combinations of 1, 2 and 3 loops per span in the vertical, horizontal and torsional directions were evaluated.
3. Results

Figs. 2 and 3 give larger isoprobabilities in increasingly darker shades. Thus the lightest region indicates the smallest probability and the corresponding structural parameter values are considered optimum. Fig. 2 suggests that the span length, $L_x$, and horizontal static tension $H$, should both be small but that the torsional stiffness, $GJ$, should be large for identical transverse damping ratios $\xi_T$ and $\xi_R$ of 0.001. On the other hand, it was found that all three damping ratios should be as large as possible to reduce the probability of galloping.

Fig. 3 shows the effect of adding (a) one or (b) two detuning pendulums for different locations of one pendulum as well as for various values of the torsional damping ratio, $\xi_T$. Each pendulum corresponds to the standard design of Ontario Hydro [9] viz. 14 kg with a 149 mm radius of gyration. If considered, the second of the two pendulums is located invariably at 41.7 m from the left support of the 125 m span. A comparison of Figs. 3(a) and 3(b) suggests that, regardless of $\xi_T$ (and the other damping ratios), two detuning pendulums usually produce a lower probability than one pendulum. Moreover, the almost uniform coloring of Fig. 3(b) implies that the second pendulum desensitizes the probability's dependence upon $\xi_T$ except at the smallest and less practically relevant values of $\xi_T$. Thus the extra pendulum seems to make torsion less important although the mechanism for its "detuning" requires further investigation. The result of adding a single pendulum, on the other hand, can be seen from Fig. 3(a) because the pendulum has no influence when located at the ends of the span (0 and 125 m). This figure shows, not surprisingly, that the effect of the pendulum's position is symmetrical about the span's midpoint. However, the positioning only becomes important close to the ends at the smallest damping ratios.

Fig. 2: Trends of galloping initiation when $\xi_T = \xi_R = 0.001$ and $\xi_T = 0.01$

Fig. 3: Effects of torsional damping when $\xi_T = \xi_R = 0.001$ for (a) one and (b) two detuning pendulums
4. Conclusions

It is interesting to note that the Den Hartog criterion for the initiation of vertical galloping is not satisfied in the examples yet galloping may occur. As expected, greater structural damping invariably reduces the probability of galloping so that the use of self-damping conductor could be beneficial. Moreover, the natural aging of a transmission line leads to a greater torsional stiffness [3] which would also be helpful here. Conversely, although a reduction in either the span length or the conductor's tension would reduce the probability of galloping, the associated economic penalty would be unattractive. The effect of modifying existing structural parameters by introducing detuning pendulums has been seen to depend upon the number and locations of the pendulums. The probability of initiating galloping is generally lowered with additional identical pendulums which should be located away from the midspan.

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References
