Modeling the Dynamics of Overhead Cables with Ice

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***Abstract* - A literature overview on the modeling of dynamic behavior of overhead cables with ice is presented in this paper, and directions for future work in this area are recommended. The main reasons of severe cable vibrations are the wind acting on asymmetrically iced cables, ice shedding, and unexpected events such as conductor breakage. A number of analytical and numerical models of cable vibrations due to these phenomena have been developed. A numerical tool used widely in recent developments is the finite element method. A finite element model of one span of an overhead cable will be constructed in the present project following various approaches from former publications. This model will serve as a basis for investigating the dynamics of overhead cables with different loads in our upcoming research.**

I. Introduction

OVERHEAD transmission lines are exposed to various types of loads. Most of them act statically, like steady wind, ice accretion, temperature change, or maintenance and construction procedures, but some of them must be treated as dynamic loads, e.g. wind-induced vibrations, ice shedding, forces due to flashovers, or forces due to mechanical de-icing processes. Exceptional events, such as conductor breakage, tower collapse, or drop of conductor suspension assembly, may also cause severe dynamic loads.

The most dangerous type of wind-induced vibration is the galloping that may cause severe damage in the shortest time. This fact justifies the great effort that has been made in the last four decades in order to study this motion and construct a realistic model. High jumps may occur in the transient state of cable vibration after a great amount of ice sheds from one or several spans of an overhead cable. This phenomenon damages some elements of the transmission line and leads to line failure in extreme cases. Similar problems arise due to vibrations developing in the intact spans of the cable following conductor breakage. The dynamic response of transmission lines due to these phenomena has also been studied in a number of publications. Finally, some of the mechanical de-icing techniques result in oscillations which may help to remove ice, but may also damage some elements of the transmission line.

This paper presents a review on modeling of cable vibrations. It should be clear it is not possible to include all the existing models; only a fraction of them will be examined focusing on the ones dealing with galloping, vibrations due to ice shedding, and vibrations due to conductor breakage. Finally, the objectives of our research in this area will be summarized.

II. Wind-Induced Vibrations

Wind-induced vibrations are divided into three categories: (i) aeolian vibration, (ii) galloping, and (iii) wake-induced oscillation. A detailed description of these motions can be found in [6], herein a brief summary is included.

The primary cause of aeolian vibration is the alternate shedding of wind-induced vortices from the top and bottom sides of the cable. Aeolian vibration of the cable occurs when the cable surface is bare and steady, and low-velocity winds (1 to 7 m/s) are present. The peak-to-peak amplitude rarely exceeds one cable diameter, and the amplitude will decrease for higher velocity winds. The frequency of the vibration is approximately between 3 and 150 Hz.

Galloping is usually caused by moderately strong, steady crosswinds acting upon an asymmetrically iced cable surface. This phenomenon has the effect of alternately changing the position of the ice deposit relative to the wind that the cable is exposed. If the upward velocity coincides with a positive aerodynamic lift force, and if the downward velocity is coincident with a negative lift force, accelerating gallop may result. The peak-to-peak amplitude of the gallop ranges from 5 to 300 cable diameters, and may even exceed the sag of the cable. The frequency range of this type of cable motion is 0.08 to 3 Hz, which is ten or often hundred times less than that of aeolian vibration.

Wake-induced oscillation is peculiar to bundled conductors exposed to moderate to strong crosswinds (7 to 18 m/s), and arises from the shielding effect by windward subconductors on leeward ones. Although this motion may occur when there is ice on the conductor, or when it is rainy; it is usually observed when the conductor is bare and dry. The amplitude of vibration is usually not large, although it may appear up to 80 cable diameters. The frequency of this kind of vibration is higher than that of galloping, but lower than that of aeolian vibration, as it appears in the range of 0.15 to 10 Hz.

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Since galloping appears under icing conditions, and causes the most severe damage in a short time, models of this type will be discussed first.

A. One-Degree-of-Freedom (1DOF) Models of Galloping

The investigation of galloping dates back to the 1930s, when a condition for this motion to build up, the so-called Den Hartog criterion, was derived [4]. The first theoretical models of galloping were also proposed a long time ago [15], [17], and have been followed by many further developments. A 1DOF model of vertical galloping, which represents the basic ideas of galloping models, will be presented in this subsection [2].

This model includes a spring-supported mass which is exposed to a steady horizontal flow of velocity U and density ρ as sketched in Fig. 1. The mass is allowed to move in the vertical direction. The vertical displacement is denoted by y. The mass and stiffness per unit length are m and k_y, respectively. The steady fluid dynamic forces acting on the mass are the lift force and drag force per unit length:

$$F_L = \frac{1}{2}\rho U_{rel}^{\;2} D C_L \quad \text{and} \quad F_D = \frac{1}{2}\rho U_{rel}^{\;2} D C_D , \qquad (1)$$

respectively. The width D is a dimension that describes the section of the mass, while C_L and C_D are the lift and drag aerodynamic coefficients, respectively. The equation of motion for this model is derived and the stability of the solution is examined in what follows.

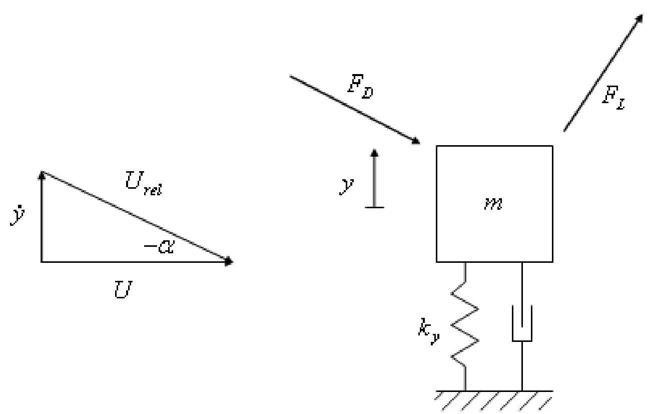

Fig. 1. 1DOF model of vertical galloping

When the model translates downward, the angle of attack may be obtained from the formula (see also Fig. 1):

$$\alpha = -\arctan\frac{\dot{y}}{U} . \qquad (2)$$

The velocity of the fluid relative to the moving mass is the vector sum of the free stream velocity and the induced vertical velocity:

$$U_{rel}^{\;2} = \dot{y}^2 + U^2 . \qquad (3)$$

The vertical force is the sum of the vertical components of lift and drag:

$$F_y = F_L \cos(-\alpha) - F_D \sin(-\alpha) = \frac{1}{2}\rho U^2 D C_y . \qquad (4)$$

Substituting (1) into (4) yields the vertical force coefficient:

$$C_y = \frac{U_{rel}^{\;2}}{U^2}\left(C_L \cos\alpha + C_D \sin\alpha\right). \qquad (5)$$

For small angles of attack, α, U_{rel} and C_y may be approximated as follows:

$$\alpha \cong -\frac{\dot{y}}{U} , \quad U_{rel} \cong U \quad \text{and} \quad C_y(\alpha) \cong C_y\Big|_{\alpha=0} + \frac{\partial C_y}{\partial \alpha}\Big|_{\alpha=0} \alpha , \qquad (6)$$

where the terms in the power series for C_y may be computed by using (5):

$$C_y\Big|_{\alpha=0} = C_L\Big|_{\alpha=0} \quad \text{and} \quad \frac{\partial C_y}{\partial \alpha}\Big|_{\alpha=0} = \left(\frac{\partial C_L}{\partial \alpha} + C_D\right)\Big|_{\alpha=0} . \qquad (7)$$

The equation of motion for the model presented is written in the form:

$$m\ddot{y} + 2m\zeta_y \omega_y \dot{y} + k_y y = F_y , \qquad (8)$$

where ζ_y is the damping factor due to dissipation within the structure, and $\omega_y = \sqrt{k_y / m}$ is the natural frequency in radians per second. Substituting (4) and (6) into (8) yields the following linear equation:

$$m\ddot{y} + 2m\omega_y\left(\zeta_y + \frac{\rho U D}{4m\omega_y}\frac{\partial C_y}{\partial \alpha}\Big|_{\alpha=0}\right)\dot{y} + k_y y$$
$$= \frac{1}{2}\rho U^2 D C_L\Big|_{\alpha=0} . \qquad (9)$$

The term in parentheses is the net damping factor of vertical motion:

$$\zeta_T = \zeta_y + \frac{\rho U D}{4m\omega_y}\frac{\partial C_y}{\partial \alpha}\Big|_{\alpha=0} , \qquad (10)$$

which is the sum of structural and aerodynamic components. The solution to (9) takes the form:

$$y = \frac{\rho U^2 D C_L\big|_{\alpha=0}}{2k_y} + A_y e^{-\zeta_T \omega_y t}\sin\left(\omega_y\sqrt{1-\zeta_T^{\;2}}\,t + \phi\right). \qquad (11)$$

The net damping factor determines whether the vibration is stable. Vibrations will decay with time for all angles of attack for which $\zeta_T > 0$. Thus, the condition for stability of the model is as follows:

$$\frac{\partial C_y}{\partial \alpha} > 0 , \quad \text{or equivalently} \quad \frac{\partial C_L}{\partial \alpha} + C_D > 0 , \qquad (12)$$

which is called Den Hartog criterion. By setting $\zeta_T = 0$, the critical velocity when galloping instability occurs may be obtained from (10):

$$U_{cr} = -\frac{4m\omega_y\zeta_y}{\rho D \frac{\partial C_y}{\partial \alpha}}, \quad (13)$$

where f_y is the natural frequency in cycles per second.

A 1DOF model of torsional galloping was also presented in [2]. The 1DOF motion of the mass in this model is described by the angle of rotation, θ, about a pivot. The angle of attack, α, changes with the angle θ, and the angular velocity $d\theta/dt$. The dynamic force acting on the mass is the torque involving the torque coefficient, C_M. This coefficient depends on the angle of attack, α, and the condition of galloping can be obtained in terms of $\partial C_M / \partial \alpha$.

B. Improved Models of Galloping

Higher DOF models of galloping were developed by following the approach presented in the previous subsection. In these models, the aerodynamic coefficients are formulated as functions of the angle of attack, and, as such, they determine the aerodynamic force or torque.

The simplest composition of the 1DOF models of vertical and torsional galloping is a 2DOF model that allows vertical translation and rotation of the mass [3]. Two nondimensional parameters are defined, relating to the aerodynamic force and the damping force in pure plunge and in pure torsion; and stability conditions are presented in the plane of these parameters. Inertially coupled vertical and torsional galloping was studied in [22] by considering eccentricity, i.e. the distance between the center of mass and the elastic axis, in the 2DOF system. An alternate 2DOF model was developed in [9], where the rotation of the cable was ignored, but the horizontal components of lift and drag forces were taken into account.

A 3DOF oscillator was developed in [20] and [21]. In these studies, a 6DOF system is first formulated with the following general coordinates: longitudinal movements of the left and right supports of the cable, longitudinal, vertical and transverse movements of the cable as well as rotation of the cable. Then, the equations of motion of the 3DOF system are derived by eliminating the longitudinal displacement components. Finally, stability conditions as well as natural frequencies of the periodic, two-dimensional quasi-periodic and three-dimensional quasi-periodic motions are determined.

The models discussed above represent the galloping of a single cable. The galloping of a multi-span transmission line, however, is more complicated, and the interactions between adjacent spans and their supports can be modeled most conveniently by applying discrete models. A multi-DOF finite element model was introduced in [5], where the stability of a cable with wind and ice load was examined. A three-node, isoparametric cable element having three translational and one torsional DOF at each node is used to model the conductors, while linear static springs simulate the insulator strings and remote spans. Support towers are either assumed to be rigid or their equivalent stiffnesses can be considered at the connection of the conductor and the insulator string. A finite element model of a transmission line will be discussed in more detail in the next section.

A 3DOF hybrid model of galloping of a bundle conductor using finite element mode shapes was developed in [23]. In this model, the single cable approach is extended to a bundle configuration having any number of cables. Analytical methods are used to investigate the initiation conditions and steady state amplitudes of galloping, while mode shapes are determined numerically using the finite element technique.

III. Further Sources of Cable Vibration

Wind-induced vibrations were discussed in the previous section. Severe dynamic loads may also be caused by vibrations due to ice shedding, or by exceptional events such as conductor breakage. A survey of the modeling of cable vibration due to ice shedding and conductor breakage is presented in this section.

A. Ice shedding

Ice shedding is a physical phenomenon that occurs when ice or snow on a conductor or ground wire suddenly drops off under certain temperature and wind conditions. The shedding mechanism is complex and difficult to precisely determine due to the great number of variables involved in the process. The analysis of ice deposits collected below or along the lines after ice shedding tends to confirm that the most probable detachment mechanisms are: (i) sudden release of the ice along the entire span, on one or several spans, (ii) movement of the ice along the cable toward the middle of the span where it suddenly drops off, and (iii) random detachment in lengths of 5 to 20 m along the entire span.

Ice shedding generates strong cable motion, which applies transient dynamic forces to the towers and causes the cables to swing toward each other and/or toward the towers. These dynamic forces may result in consecutive collapses of the towers, while the reduced clearances can make the cable clash, leading to flashovers. The first studies on ice shedding concerned maximum jump height of a cable following sudden ice release. Former methods for calculating jump height are assessed and an alternate method is presented in [12]. A number of criteria for compact line design have been formulated according to the maximum jump height. A mathematical model was developed in [8] in order to study both the static and dynamic effects of ice shedding on overhead lines. In this paper, loads applied to the towers as well as the cable motion following ice shedding are examined, and simulation results are compared to experimental observations.

A finite element model of a two-span transmission line is presented and several ice-shedding scenarios are discussed in [18], using the ADINA finite element software. The catenary configuration of this model is shown in Fig. 2. Two-dimensional two-node isoparametric truss elements with large kinematics are used for cable modeling. Each cable element has four degrees of freedom corresponding to the horizontal and vertical translations at each end. A constant initial prestrain corresponding to the installation conditions is prescribed as an initial condition for all cable elements. Cable material properties are defined for tension only, assuming the absence of compression and small strain Hookian tension. Cable is assumed to be perfectly flexible in bending and torsion. The Young's moduli used in static and dynamic analyses are the same. Structural damping of the cable is modeled with equivalent viscous damping, while aerodynamic damping is not considered, due to its complexity. The flexibility of the towers and their foundations are not modeled and the cable ends are assumed to be rigidly fixed at both ends of the line section. The suspension string is modeled with two two-node beam elements. The damping of the insulator string is not modeled, because its effect is negligible compared to cable damping. Ice loads are simulated by increasing the density of the cable elements in the static analysis, and cable density is suddenly decreased in the dynamic analysis when ice shedding occurs. Also included in this paper are time histories of cable displacement and cable tension after ice shedding, as well as some conclusions about the effects of ice thickness, span length, partial ice shedding, elevation at central support, unequal spans, and number of spans on the dynamic response of the line section.

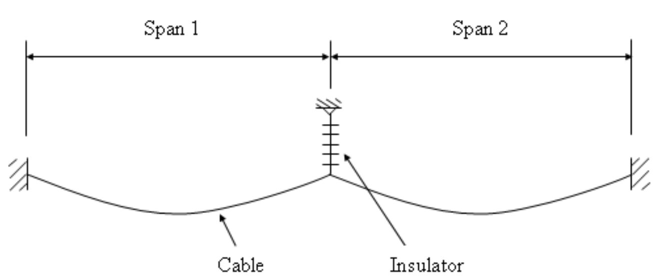

Fig. 2. Catenary configuration of a transmission line with two spans for modeling its dynamic response due to ice shedding

Finite element modeling of the dynamic response of overhead transmission lines due to ice shedding makes it possible to simulate transmission line failures. For example, a tower failure following ice shedding was simulated in [19] by applying the model discussed above.

B. Conductor Breakage

The most severe dynamic loads are usually associated with exceptional events such as cable breakage or tower collapse. Both experimental and theoretical studies have been done to understand better the line behavior under these effects, in order to improve line design. A technique for calculating the maximum impact load following the breakage of conductors or insulators is described in [16]. In this paper, the time history of cable tension after breakage was observed and the peak dynamic force was determined, based upon the conservation of energy principle. After breakage, indeed, the tension decreases rapidly to a minimum of the order of 5-30 % of the initial value and stays at this level for a few fractions of a second. Then, it increases to reach a first peak which coincides with the maximum swing of the suspension assembly. A series of peaks and notches follow until the final state is reached, typically few minutes after the cable breakage. Reflecting waves from the adjacent supports may cause considerable peak tensions on the first tower and a second higher peak occurs in many cases. A possible explanation of this process in terms of energy is provided in [16] as follows. The first peak is due to a sudden release of elastic energy stored in the first span adjacent to the breakage point. The system uses this energy to horizontally accelerate the released span away from this point. The second peak results from the transfer of gravitational energy to kinetic energy. Once the cable attains its highest possible position, it starts to fall down. This second peak reappears periodically until dynamic effects are completely dissipated.

An extensive experimental investigation on the dynamic response of broken wires was carried out and results are reported in [13]. A mathematical model of the transient response of transmission lines due to conductor breakage was constructed in [11], and simulation results were validated by comparing them to experimental results published in [13]. The finite element software ADINA was used to formulate the model and solve the governing equations. The problem of conductor breakage in a transmission line section is a free-vibration problem induced by a sudden release from an initial static configuration. Since the amplitudes of motion and the fluctuations in cable tension are usually large, this problem becomes a truly nonlinear one. Nonlinearity arises from different sources. The main sources of geometric nonlinearity are the cable action, the swinging motion of rigid suspension assembly as well as the large displacements and rotations of tower members. Material nonlinearity is also present though unimportant, and therefore is not considered in the model. In order to model the cable, two-node cable elements were chosen.

Four three-span models were examined in [11]. Suspension rods are simulated as stiff elastic two-node truss elements in the first two models. The difference between them appears in the number of cable elements in the central span. The structure of these models is shown in Fig. 3(a). In the third model, support flexibility is simulated by a lumped mass-spring idealization of the support structures, as represented in Fig. 3(b). The fourth model is more refined and includes the overhead ground wire, as shown in Fig. 3(c). None of the models includes damping. Cable breakage is simulated as an initial condition in a dynamic analysis. Time histories of cable tension and displacement are studied, and the two peaks in cable tension mentioned in the first paragraph of this subsection are obtained. The first peak tension is significantly reduced when support flexibility is assumed to be caused by the dissipation of elastic bending energy in the support structures modeled with springs. With the inclusion of the overhead ground wire in the model, the maximum displacement at the suspension point adjacent to the breakage point is reduced, which is mainly due to the lateral restraint imposed by the overhead ground wire.

A more recently developed model [10] includes not only the cable and suspension string, but also the tower. Damping is introduced in the cable modeling, although no damping is considered for the towers. The basis of the modeling approach is the same as that of the model discussed above. This more complete three-dimensional model considers a six-span overhead transmission line including the conductors, the shield wire and the insulator strings. This model is used to explain the failure of two towers in a line section due to conductor breakage in an ice storm. The time history of the torsional moments in the tower shafts at three different suspension structures is analyzed. This clearly shows that the torsional moment at the two structures adjacent to the broken conductor exceeds its design value. One of the structures, however, is assumed to resist this moment. The torsional moment decreases at this structure after the peak, while it continues to increase at the other structure. This process results in the failure of the structure with increasing moment about 0.5 s after the initial cable rupture. Following this failure, the third structure is subjected to large unbalanced longitudinal and torsional loads and fails.

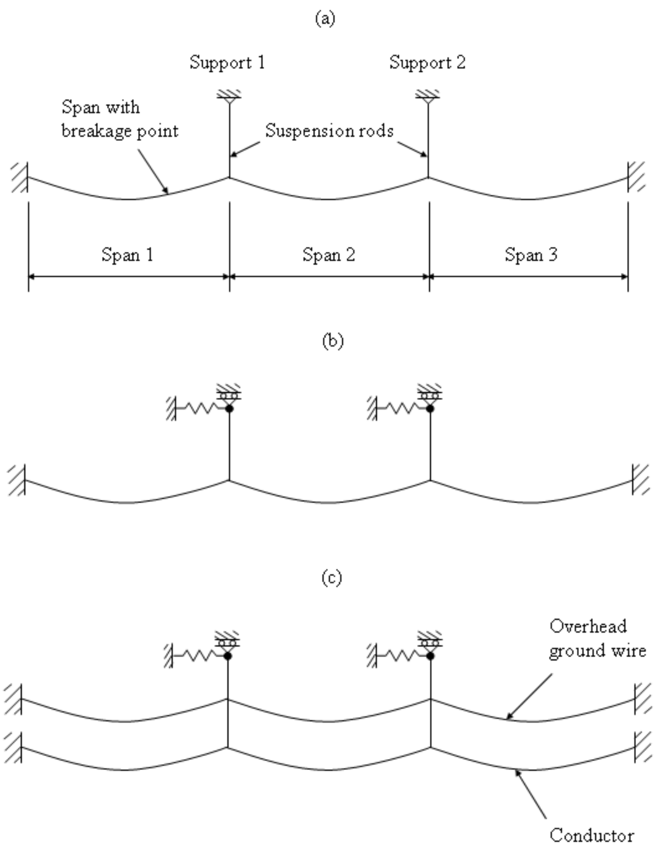

Fig. 3. Catenary configurations of a transmission line with three spans for modeling its dynamic response due to conductor breakage with: (a) rigid suspension rods, (b) flexible supports, (c) flexible supports and including overhead ground wire

IV. Recommendations for Future Work

Our future work in this project will consist in elaborating a finite element model of a single span of transmission line whose dynamic behavior will be examined under different loads. The main goal will be to determine the ranges where these loads are associated with ice shedding and line damage. Vibrations may appear useful as long as they help removing ice without damaging the transmission line. It should be noted, however, that vibrations, strong enough to provoke ice shedding, have also been observed to weaken cables or damage towers under some circumstances (e.g. [14], where a tower ice removal technique using low-frequency, high-amplitude vibrations was examined).

A finite element model for a single span of overhead cable was constructed by using the software ADINA [1] and following the approach presented in [18]. The main directions towards the improvement of this model are as follows.

- Defining ice as a different material by including its properties in the model. Thereby the effect of vibrations on the ice and on the cable can be considered separately, e.g. to allow for the fact that ice may break in the model without affecting the cable.
- Extending the model of cable – ice composition for more than one span of a transmission line.
- Including characteristics of the tower at the supporting end of the cable, which will allow simulating the effects of developing vibrations on the tower.

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