Modeling the structural dynamic response of overhead transmission lines

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Abstract

Static analysis forms the basis of calculations in structural design of overhead power lines. The environmental loads considered in design can be assumed static (icing) or quasi-static (idealized steady wind). However, dynamic analysis is necessary to predict line transient response to shock loads such as those induced by the sudden failure of components or sudden ice-shedding effects on the conductors. This paper summarizes a macroscopic modeling approach to line dynamic analysis where emphasis is put on capturing the salient features of the propagation of such shock loads in a line section. The approach is illustrated with a case study of a line section having suffered two tower failures due to conductor breakages during an ice storm. The cable dynamics model proposed has been applied successfully to several examples, using the commercial software ADINA.

Key words: Finite element analysis; Cable dynamics; Transient response; Cable rupture

1. Introduction

In the design of transmission lines, most calculations are based on static load cases. The environmental load cases are based on statistical data of wind and ice accretion. They provide a good estimate of the extreme forces that a transmission line is subjected to during its service life. In certain circumstances, the dynamic effects also need to be examined. A good example of this would be when a transmission line is subjected to accidental loads such as shock loads induced by conductor ruptures. The occurrence of this type of loading event is rare but unpredictable, and the amplitude of the forces generated is significant.

1.1. Description of a line section

As shown in Fig. 1, the main structural components of a transmission line are the conductors, the shield wires, the insulator strings and hardware, and the suspension and dead-end structures. The response of a line section to cable rupture depends on the interaction between all these components. Usually, the conductors are stranded cables composed of aluminum, galvanized steel or a combination of the two. Shield wires are grounded steel wires placed above the conductors for lightning protection. Conductors are attached to suspension structures via insulator strings that are vertical under normal operation conditions and are free to swing along the line whenever there is a longitudinal unbalanced load. At dead-end structures, the insulator strings are anchored and in-line with the conductors. Following a sudden cable rupture, the longitudinal load imbalance is transferred to suspension towers by the swinging insulator strings whereas the dead-end towers feel directly the shock load propagating in the conductor.

1.2. Background

The global effect of a conductor breakage in a line section is known since the 1950s [1]. Following the rupture, the suspension insulator strings next to the...
failure point swing longitudinally to reach their uppermost position (conductor recoil) and then swing back to their lowest position (conductor bottoming down). This sequence of motion typically produces two peak tension loads in the conductor, followed by free vibrations that are progressively damped out until the final steady-state configuration is reached. The second peak load is usually larger than the first. Based on the results of small-scale physical tests and of a few full-scale tests, longitudinal load impact factors have been proposed by Govers [2] in the 1970s. Impact factors provide an estimate of the maximum longitudinal forces to which the line structures next to the breakage can be subjected.

The use of computer software to study cable ruptures began in the 1980s. The first models of Siddiqui [3] were attempts to evaluate the peak longitudinal loads generated by a breakage using energy balance principles. The work of Baenziger [4,5] included finite element modeling of the cables in two dimensions and some simplified tower modeling. By varying line parameters, these studies have further contributed to the understanding of the peak transient response of a line section to conductor ruptures.

As computer and software evolved, McClure [6-9] proposed to study the problem with a more general finite element approach using ADINA [10], in which a more complete dynamic interaction between all line components could be modeled in two- or three-dimensions. However, modeling limitations mainly arose from computer systems and software that were available when these studies were performed. A numerical model that used to take hours or days to run fifteen years ago can now be processed in minutes. Furthermore, computer storage capabilities greatly influenced the type of model selected with respect to the finite element mesh and the time of analysis. This was especially true for three-dimensional models where only the global behavior of structures in a line section could be observed due to storage limitations. In current software, many improvements have been made and algorithms have been improved (namely in contact analysis by Bathe and collaborators [11-13]). Users in different domains of interests have worked with the software and made it more robust. The addition of improved graphical interfaces in recent years has also provided a more natural way of viewing the results of an analysis.

Other recent noteworthy contributions to the study of cable breakage problems include work by Ostendorp at EPRI [14,15] and by Kempner [16], based on a combination of physical tests and numerical models. This work has led to a convenient method to evaluate the potential of cascading failures in overhead lines under a variety of accidental loading conditions.

2. General modeling approach

Numerical methods based on finite element analysis have the advantage of being applicable to specific line sections with variable degrees of details. The influence of different line parameters can also be studied without having to erect costly scale models. However, the results obtained with an analytical method depend on the numerical parameters selected and therefore necessitate a thorough understanding of the concepts of dynamics and of the physical problem at hand. It is emphasized that careful validation of analytical models with full-scale test results is still lacking.
The following is a description of the modeling approach originally suggested by McClure [6] and enriched by the contributions of several collaborators during the past ten years [17–19].

2.1. Macroscopic line section modeling

The objective of the modeling approach suggested is to capture the essential features of the response of the interactive system without having to refine excessively the representation of each component. To study a line section subjected to cable breakage is similar to study the propagation of a shock wave in a highly non-linear system. In addition to the inherent geometric non-linearities of suspended cables, the rupture of a conductor element creates a change in the boundary conditions of the system and induces large, non-linear cable and insulator string displacements. To a lesser degree, P-delta (second order) effects on the displaced towers are also present. Materials can also become a source of non-linearity, especially when supports are damaged.

2.2. Analysis software

The selection of proper software for the analysis of power lines subjected to conductor breakage is of primary importance. First, the software should be able to carry both static and dynamic analyses of individual towers. This includes self-supported and guyed towers. As complete line sections are modeled, cable elements are needed to simulate the conductors and the shield wires (and the guy wires if guyed towers are used). Such elements must accommodate initial strains and simulate the slackness of the cable following the rupture. As a result, the software must offer large kinematics formulations. To simulate cable ruptures, the removal of cable elements during the analysis should be possible. In addition, the software should provide a way to stop the drop of a ruptured conductor when it hits the ground. Another important feature (although not used in the case study presented in Section 3) is post-elastic response modeling.

The choice of ADINA [10] was retained because it meets all the requirements listed above. It has been used successfully for the past decade at McGill University to study different problems related to cable dynamics and towers, such as the seismic behavior of guyed telecommunication masts, the effects of ice shedding from guyed masts and from overhead line conductors, and line component failures.

2.3. Cable modeling

2.3.1. Finite element meshing

Cables are represented by two-node (linear) isoparametric truss elements with three translational degrees-of-freedom available at each node in three-dimensional models (and two in two-dimensional models). Applications with three-node (quadratic) isoparametric elements have also been successful. The selection of the mesh is based on the essential characteristics of the wave problem (initial shock duration), the formulation of the elements (spacing between integration points), and the time increments used in direct integration of the incremental equations of motion. The basic idea is to sample the shock wave passage in the conductor adequately, both in time and space. The required distance between integration points is linked to the speed of propagation of the shock wave and the minimum time increment is selected such that the sampling rate of the initial wave is in the order of 1/10 of the initial shock load duration. Details are given in [6–9,17–19].

2.3.2. Stiffness

The cable elements are modeled using a tension-only linear elastic material such that cable slackness can be achieved in the dynamic simulations. The modulus of elasticity used for conductors is an equivalent composite value that assumes full compatibility of cable strand deformations and layering effects. Strain rate effects are ignored in the models: to our knowledge, such effects have yet to be characterized in stranded cables used in power line applications.

An initial tensile strain is specified for each element in order to avoid singularities in the initial stiffness matrix of the cables. This initial strain is obtained for each element of a specific span from a preliminary static analysis assuming an axially rigid catenary under gravity loads. This same catenary profile also serves to define the initial geometry of the cable profile. Small strains are assumed but large displacement kinematics is considered in a total Lagrangian formulation [10,20].

2.3.3. Inertia

All masses are lumped at the end of each element to the available degrees-of-freedom. In this wave propagation analysis, the lumped mass formulation was found to be preferable to a consistent formulation as results obtained using the former showed fewer spurious oscillations. The use of first order (two-node) isoparametric elements also supported the choice of this formulation. Rotational inertia, which is small in this case, is neglected due to the lumped mass formulation.

2.3.4. Damping

Realistic modeling of damping for transient time-domain analysis is rather complex for the problem at hand. In a typical line section—that is not equipped with any special damping devices—internal damping mainly comes from the cables and the structures. When a cable is subjected to longitudinal shock loads, internal damping arises from the axial friction between the strands.

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and friction induced by bending of the wire. Little research has been carried on the subject and cable manufacturers do not supply this information. Furthermore, most of the research done on cable self damping relates to the study of aeolian vibrations and galloping in intact spans, two instability phenomena dominated by transverse rather than longitudinal motions. It is expected that aerodynamic damping also plays a role, considering the large displacements and velocities of the cables adjacent to the breakage point. However, to our knowledge, no satisfactory model has been proposed to date to account for it in a time-domain analysis. The influence of this source of damping on the transient response of a line section has yet to be quantified.

Considering the above arguments, simplifications had to be made and damping is simulated for all conductors and shield wires by using of a viscous discrete dashpot applied in parallel to each cable element (in the axial direction of each element). To model damping properties of cables in such a way in ADINA, so-called "non-linear spring elements" are required for dashpots to be aligned with the cable element axis [10]. The procedure to determine the appropriate damping constant of each element is described by Roshan Fekr [18] in relation with analysis of ice-shedding effects. Based on good numerical experience (but still lacking real-scale physical test validation), damping constants are set to represent equivalent viscous damping ratios of 2% critical for bare cables and 10% for iced cables.

It is emphasized here that the addition of damping has little influence on the salient features of the initial transient cable response. However, the introduction of damping in the models is beneficial numerically as it allows the filtering of unwanted spurious high frequencies inherent to discretization.

### 2.3.5. Cable rupture

Cable rupture is modeled using the element death option available in ADINA [10]. The element death is triggered by the analyst—it is not a death-upon-rupture. The breakage is set to take place one time step after the initial static equilibrium configuration is calculated, using the restart option. Various uses of the element death options are possible: elimination of one single element at any location along the ruptured span or of several or all elements of the span. The cable rupture involving the cable element next to the suspension point causes the largest dynamic effects in the rest of the line section. In this case, the elimination of that single element or the elimination of all span elements both yield the same results.

### 2.4. Suspension string modeling

Suspension insulator strings are modeled using a single two-node isoparametric truss element without initial strain. Successful models have also been made with hermitian beams. Actually, a refined model is desirable to account for local slackening effects in the flexible insulator strings, if such a detailed analysis is needed. However, in our proposed macroscopic approach, refined string meshing has not been done. Insulator strings are assumed to be made of linear elastic material with a large axial rigidity compared to that of the suspended conductors. Their mass is lumped at the end nodes and no damping is included.

### 2.5. Tower modeling

Tower modeling can vary within the full spectrum of possible idealizations: towers can be simply assumed as rigid supports or every member can be represented in detail. In two-dimensional models, it has been our practice to start with simple models where only the cables and the suspension strings are represented while the interaction with the supports is neglected. However, the recent work of Lapointe [19] has shown that for cable rupture problems, such simplified planar models may yield overly conservative results (in the order of 15–30%) for cable tensions at dead-ends and close to the rupture point, when compared to the results obtained with more realistic detailed three-dimensional models of the suspension towers.

#### 2.5.1. Stiffness

Although flexural effects of tower flexibilities can be studied in two-dimensional models, only three-dimensional models can represent the contribution of intact conductor spans and the interaction of the shield wires. Such effects can take place only if both the torsional and flexural rigidities of the supports are included. Earlier work by McClure [6] on three-dimensional models showed that the response time is significantly delayed in comparison to two-dimensional models. It also indicated that the presence of intact wires is important as it reduces the maximum load amplitudes and the magnitude of the displacements calculated. Torsional displacements are non-negligible. The dynamic interaction (inertia effects) between intact conductor spans and the suspension structures were found negligible for relatively rigid classical towers. However, shield wires participate to the dynamic response of the line section. All of these findings were confirmed by Lapointe [19], as shown in Section 3.

#### 2.5.2. Inertia

Accurate modeling of the tower mass (lumped approach) and stiffness is achieved by detailed modeling of each member. Such detailed tower models are readily available since they are used for static tower design. Space truss models of lattice towers are acceptable although frame-truss models are more realistic since main
leg members are usually continuous with multi-bolted connections that can transfer secondary bending moments. The latter are also more appropriate in post-elastic analysis. So far the detailed tower models used have had the linear elastic material properties of structural steel, neglecting strain rate effects.

The authors find useful to conduct a frequency analysis of the individual towers modeled as quality control: unrealistic natural frequencies or mode shapes are good troubleshooters.

2.5.3. Damping

Since the transient response near the cable attachment points at the supports is the main focus of the analysis, no damping was considered in the tower models. Considering that the shock loading propagates from the cable attachment points throughout the tower, non-discrete damping such as Rayleigh damping is not a good representation of the energy dissipation by friction in the tower connections.

2.6. Other numerical considerations

To minimize residual errors in the calculated response, equilibrium iterations must be performed regularly during numerical integration to ensure that the stiffness matrix of the system is updated adequately until convergence is reached in the displaced configuration. The full Newton method is used with line searches to accelerate convergence. We suggest that the convergence be checked against tolerances based on energy and displacements. These tolerances (ETOL and DTOL, respectively) are defined in [10,20]. The values used for these numerical parameters in the case study are presented in Section 3.

The implicit integration method selected is the Wilson-θ method with \( \theta = 1.4 \) to ensure an unconditionally stable solution. The choice of this particular procedure is based on satisfactory results obtained in previous research by McClure and collaborators. As mentioned in Section 2.3, the selection of an adequate time increment for integration and the selection of the finite element mesh size are interrelated. For wave propagation problems using an implicit direct integration method, a procedure suggested by Bathe [20] is recommended. This procedure is based on concepts used in finite difference solutions. Detailed considerations are discussed in [19] for the case study presented here.

3. Case study

The macroscopic modeling approach described above is now illustrated with a case study of a double-circuit 120 kV line section that suffered two tower failures during an ice storm that occurred in the Lanaudière region during the Fall of 1997. The line is owned and operated by TransÉnergie, a division of Hydro-Québec.

3.1. Description of observed line damage

Visual inspection and photographs of the damaged line hinted that the probable failure trigger was the simultaneous rupture of two conductors that became in contact or otherwise suffered arcing and strong short circuit currents. The damaged section of the broken conductors showed a cup-and-cone type of failure with signs of metal melting on the external envelope. The rupture is attributed to the failure of some strands under the effect of a short circuit between the two conductors followed by tension failure of the reduced section. The line was loaded with \( \approx 20–25 \) mm of radial ice.

Fig. 2 shows a view of the damaged line section where it is seen that the failure mode is torsion of the mast below the lower crossarms. The two uppermost conductors of the same circuit in the span in the foreground were sectioned. The two damaged towers shown were adjacent to the broken wires but the other adjacent tower (not shown) was still standing without apparent damages.

The non-linear dynamic analyses performed utilize two- and three-dimensional models of this line section. Considering the uncertainty on the actual amount of ice on the cables at failure, three different uniform conductor loads have been considered: the bare condition, 20 and 25 mm of radial ice accretion. Only a few comparative results of the two series of models with 25 mm of ice will be presented here while more details are found in [19].

3.2. Line data

Fig. 3 is a simple two-dimensional sketch of the line section studied. It is composed of five suspension structures and two dead-end structures for a total of six slightly inclined spans. The dead-end structures are assumed to be perfectly rigid in all models. The broken conductor location is indicated by dashed lines between structures \#4 and \#5.

Fig. 4 presents an outline of the suspension tower. It is a lattice steel tower with narrow base (BOC type) especially designed to minimize the footprint in agricultural areas. The broken conductors were the two uppermost phases of a same circuit (on the left of the center line in Fig. 2).

The conductors are 54/7 CONDOR ACSR stranded cables. The material forming the inner core strands is galvanized steel whereas the outer strands are aluminum. The shield wire is a 7-strand galvanized steel cable. Essential cable properties are listed in Table 1. The conductors are attached to the suspension structures by
single insulator strings of 1.4 m in length and 40 kg in weight.

3.3. Summary of modeling assumptions

3.3.1. General

In two-dimensional models, only one conductor supported by the insulator strings is specified in a vertical plane. Neither the suspension structures nor the dead-end towers are modeled, although it is easy to represent their effect with a simple lumped parameter mass/spring/dashpot system. However, the first step is to ignore the influence of the flexibility of supports and the insulator strings are attached to fixed points. The two extremities of the conductor in the end spans are also fixed. Because truss elements are used to model both conductor and string elements, the end points are actually pinned. Variations of this model have also been used to verify the effects of different line parameters such as the number of spans adjacent to the broken span and the effect of support failures.

The three-dimensional model includes the six conductors of the line, the shield wire and the insulator strings. All members of the suspension structures are modeled as a frame-truss system. Linear-elastic three-dimensional hermitian beam elements are used for the main legs, main crossarms and horizontals. Proper moment releases are applied to each beam element. All other members are linear-elastic two-node truss elements. In addition, the towers are assumed to be fixed on rigid foundations. The tower material is structural steel, taken as linear elastic. Dead-end structures are represented by fixed points.

3.3.2. Cable dynamics features

The final mesh selection for all the cables was 30 equal-length two-node isoparametric truss elements per span, with a time integration increment of 1.5 ms (Wil-
son-θ method with $\theta = 1.4$). Each cable element has a length of 10 m, and the shock wave speed computed in the two-dimensional models is of the order of 7 km/s. To confirm this choice of mesh size and time increment, Fig. 5 compares the calculated tensions in a conductor element for 30 and 80 elements per span.

Equilibrium iterations use the full Newton method with stiffness updates at each iteration. Convergence criteria combine energy and displacement tolerances. The energy tolerance is assigned a value $\text{ETOL} = 10^{-8}$ and the displacement tolerance is $\text{DTOL} = 10^{-6}$. The tolerance for line search is set to $\text{STOL} = 0.5$. These convergence criteria are found to be adequate for the problem considered. Complete definitions of these parameters are given in [10].

The initial tension in the bare condition is given in Table 1. The self-weight application is performed in 10 load increments and the static load is then maintained until a fictitious time $t = 10$ s. Then, the element death option is activated in span #5 for the dynamic analysis at time $10$ s $+ \Delta t$ (that is at $t = 10.0015$ s). The material model is linear elastic in tension only.

### 3.4. Results

For each analysis performed, cable tensions at suspension points, insulator string rotations and the longitudinal reaction at supports are computed and saved. The axis convention used is as follows: The $X$-axis, $Y$-axis and the $Z$-axis correspond to the transverse, longitudinal and vertical directions, respectively.

Fig. 6 shows the conductor tension calculated in the uppermost phase of span #4, superimposed with the comparable results calculated with the two-dimensional model (Model 2D_CF). It is seen that the first and second peak tensions in the three-dimensional model are delayed with respect to the two-dimensional model and also have a longer duration. This is attributed to the fact that Model 3D includes the flexural and torsional flexibilities of the suspension structures and that the load is redistributed to the intact wires. Fig. 7 shows the important dynamic response of the intact shield wire in span #4. Space limitations prevent us from showing more results.

However, a last time history is shown in Fig. 8 in order to explain the observed line failure. It represents the torsional moment in the tower shaft at structures #3–5, at the panel section below the lower crossarms, close to the region where the failures were observed (Fig. 2). As expected, each curve of Fig. 8 has two distinct peaks, with the second representing the maximum calculated values. However, we need to focus on the results of the first peaks because this is when we think the

<table>
<thead>
<tr>
<th>Table 1: Cable properties (source: Hydro-Québec)</th>
<th>Conductor</th>
<th>Shield wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>CONDOR</td>
<td>CDG12C</td>
</tr>
<tr>
<td>Type</td>
<td>ACSR</td>
<td>Galvanized steel stranded cable</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>27.8</td>
<td>12.6</td>
</tr>
<tr>
<td>Area (mm$^2$)</td>
<td>455.1</td>
<td>96.5</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>64.5</td>
<td>178</td>
</tr>
<tr>
<td>Weight per unit length (N/m)</td>
<td>14.93</td>
<td>7.44</td>
</tr>
<tr>
<td>Mass per unit length (kg/m)</td>
<td>1.522</td>
<td>0.758</td>
</tr>
<tr>
<td>Initial horizontal tension (kN)</td>
<td>19.2</td>
<td>11.6</td>
</tr>
<tr>
<td>Rated tensile strength (kN)</td>
<td>127</td>
<td>114</td>
</tr>
</tbody>
</table>
failure happened. The true torsional resistance of the towers is unknown. The static torsional moment of 160 kNm shown in the figure (bold horizontal line) represents the maximum design value, thus a conservative lower bound estimate for the resistance. At the first peak, values at both structures #4 and #5 exceed the maximum design value. However, we assume that structure #5 resists this moment. As seen in the figure, the torsional moment at structure #5 decreases after this first peak while it continues to increase at structure #4. Clearly, after about 0.5 s following the initial cable rupture, structure #4 fails and the rest of the time history calculated is no longer realistic. Following the failure of structure #4, structure #3 is in turn subjected to large unbalanced longitudinal and torsional loads and fails.

Fig. 5. Variation of tension in a conductor element for meshes of 30 and 80 elements per span.

Fig. 6. Comparison of cable tensions calculated using two- and three-dimensional models.
3.5. Model limitations and future work

All analyses performed in this case study assume linear elastic materials. This is certainly an unrealistic assumption if analyses are carried out to explain failure mechanisms. In fact, the results shown indicate that torsional moments are very large in the shaft and plastic hinges or buckling mechanisms are susceptible to form. The addition of plasticity to the current model is complex, but feasible. Ongoing research is currently taking place at McGill University to include the effect of plasticity and buckling to detailed models of crossarms and complete lattice towers.

Another important shortcoming to the analysis of the results is that no data is available to quantify the dynamic resistance of power line components. The dynamic resistance of the conductor, the insulator strings and other accessories in the system could not be obtained because they are not known. The dynamic resistance of a component indeed differs from its static resistance as strain rates affect the elastic limit, the ultimate strength, and the modulus of elasticity of metals. In the analyses conducted, a component subjected to dynamic loads must resist varying loads with amplitudes of relatively short duration. It is reasonable to assume that the dynamic resistance would be greater than the...
static resistance. In absence of more appropriate resistance data, static values are used.

4. Conclusions

The paper has presented in detail a macroscopic modeling approach to study the dynamic response of line sections subjected to exceptional unbalanced loads such as those due to ruptured conductors. The approach is easily adaptable to study other problems like sudden ice-shedding effects from conductors or the sudden failure of other line components (tower member, suspension string). Improvements are needed to model the post-elastic response of components and strain rate effects on the material properties of the various line components. But most importantly, numerical models need validation with full scale physical test results.

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