Using Numerical Dynamic Analysis to Prevent Cascading Tower Failure

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***Abstract*—This paper presents a dynamic analysis-based design approach to prevent a transmission line from cascading failure under a specified ice storm. More specifically, it: 1) describes the development of finite-element model of a typical section of a 230 kV transmission line using software ADINA, 2) discusses the dynamic analysis results obtained from the numerical simulations in the event of ice storm and insulator string failure and 3) demonstrates how to utilize the dynamic analysis results in a line upgrading program to prevent cascading failure**

I. Introduction

Previous documented evidences and studies [1, 2, 3] have shown that sudden drop of conductor due to insulator string failure, sudden conductor failure or activation of a mechanical fuse could impose significant dynamic impact loads on the adjacent towers, resulting in line component damage or even cascading tower failure. Also, numerical simulations have been successful in predicting the dynamic load amplification on towers due to insulator string or conductor breakage.

The British Columbia Transmission Corporation (BCTC), through its Transmission Ice Risk Assessment Program, is studying the effect of both equal and unequal ice loading on its major transmission lines in southwest portion of the province and is in the process of upgrading the lines to specified target reliability and security levels. This paper focuses on the security requirement.

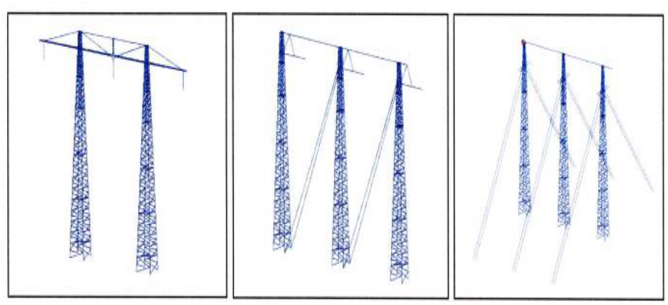
The objectives of the study are to quantify the dynamic loads, identify overloaded line components and to develop an anti-cascading strategy for a 230 kV line located in southern British Columbia, Canada.

A dynamic analysis was carried out to quantify the magnitude of dynamic impact loads. This paper addresses the dynamic loads associated with the sudden failure of insulator string only. Based on the dynamic loads obtained from numerical simulations, an anti-cascading reinforcement scheme was developed.

II. TRANSMISSION LINE DESCRIPTION

The transmission line under study was constructed in early 1950's. Steel lattice portal type tangent suspension towers (A tower), angle suspension towers (D tower) and dead-end towers (J tower) are used. Fig. 1 shows schematics of typical A, D and J towers.

The towers support 3 phases of 2-bundle Drake ACSR conductors, each having a diameter of 28.13 mm, area of 468.45 mm^2 and linear mass of 1.623 kg/m.



(A tower) (D tower) (J tower)

Fig.1. Typical A, D and J towers

III. DESIGN REQUIREMENTS

The line is to be upgraded to a reliability level corresponding to a 1:200 years return period of ice storm events. This requirement includes a maximum radial accumulation of ice of 40 mm on conductors.

The security requirement is to limit the propagation of a cascading failure of the line under ice loads.

IV. COMPUTER MODEL AND METHODOLOGY OF ANALYSIS

A typical 10-span line section of the 230 kV circuit was selected for the analysis, which includes eight tangent suspension towers (A tower, T1-T4 and T6-T9), one angle suspension tower (D tower, T5) and two dead-end towers (J tower, T0 and T10). The total length of the line section is 3055 m. The line section is illustrated in Fig. 2.

The line section was modeled using the ADINA software [4]. Forty two-node truss elements were used to model the three phase conductors in each span. All insulator strings, braces and guys of the tangent and angle tower were also modeled using truss elements. The masts and cross-arms of the towers were modeled using equivalent two-node 3-D beam elements. Non-linear behavior (tension only) was considered in the analysis for conductors and guys through specified strain-stress curves. To simplify the analysis, the 2 bundle conductors were modeled using an equivalent single conductor. Large displacements and small strains were selected for the kinematics to take into account geometry nonlinearity of the conductor displacements. Newmark integration was adopted with δ= 0.6 and α = 0.3025 and a time step of 0.001 seconds. The interaction between the dropping conductors and the ground surface was considered. A rigid contact surface was used to simulate the ground surface. By using only one contact surface, the ground profile was assumed flat, which is representative of the actual terrain conditions.

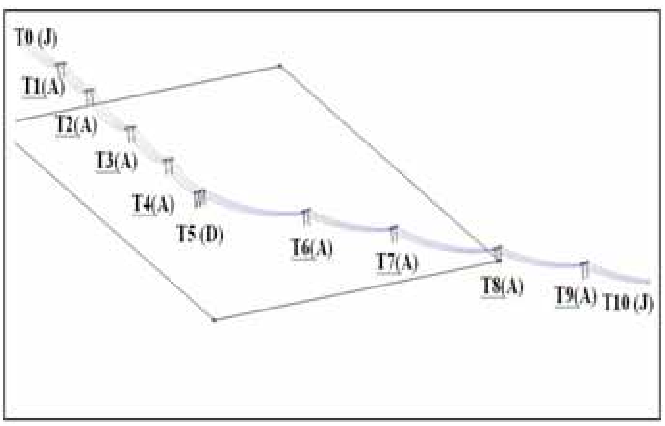


Fig.2. Finite element model of the line section

A static analysis was carried out to obtain the static responses and equilibrium configuration under the conductor weight, the ice load and the horizontal tension. Once the equilibrium configuration was reached, an insulator string failure was simulated by removing the insulator string on the right phase at tower T6 (worst case scenario) using the element-death option in ADINA. The time-history dynamic analysis was therefore triggered and performed for a duration of 7 seconds.

Using the maximum load amplification obtained during the dynamic analysis, a static analysis using PLS-Tower [5] is carried out in order to assess the tower strength and upgrades required at each tower.

A. Dynamic Analysis Results

Time-histories were obtained at all towers for insulator forces and corresponding longitudinal, transverse and vertical loads. Results for towers T0, T4, T5, T7 and T10 are summarized in Table 1. Figs. 3, 4, 5, 6, and 7 show the time history at the tower T0, T4, T5, T7 and T10 respectively.

From the results tabulated, the sudden drop of an insulator string from Tower T6 poses a significant dynamic impact on the adjacent towers and the two dead-end towers several spans away. The amplification factor ranges from 1.4 to 2.6. For tangent Tower T7, adjacent to Tower T6, the dynamic impact is mainly in vertical direction with amplification factor of 2.6. For angle suspension tower T5, the dynamic load amplification is mainly observed in the transverse and vertical direction with an amplification factor of 1.4 and 1.6 respectively. For dead-end towers T0 and T10, the dynamic load amplification is mainly in the longitudinal direction with amplification factor of 1.7 and 1.5, respectively.

In addition, a parallel analysis on a straight line segment (i.e. without angle suspension tower) showed that the dynamic load amplifications at tangent tower T4 and dead-end towers T0 and T10 is higher than those observed in Table 6. This suggests that upon an insulator string failure, an angle suspension tower reduces the dynamic impacts on the dead-end towers by changing the conductor swing direction.

B. Assessment of Tower Strength and Reinforcement Required

Based on the load amplifications obtained, a static analysis was carried out for tangent, angle and dead-end towers. The maximum dynamic load was applied to only one of the three phases with the others under initial static loads. The location of the dynamically loaded phase is alternated to obtain the worst load combination. The overloaded steel members and components under the maximum dynamic impact loads were identified. It was found that at towers T0, T5, and T6, T7 and T10, insulators, guys and steel members would be overloaded (ranging from 20% to 110% overload) under maximum dynamic loads.

TABLE 1
MAXIMUM DYNAMIC LOADS AND CORRESPONDING AMPLIFICATION FACTORS

Tower	Force/Loads (kN)	Initial (Static)	Max (Dynamic)	Amplification factor (Max/Initial)
T0-J tower	Longitudinal Load	196	340	1.7
	Transverse Load	0	0	-
	Vertical Load	29	49	1.7
T4-A tower	Longitudinal Load	0	14	-
	Transverse Load	0	0	-
	Vertical Load	59	85	1.4
T5-D tower	Longitudinal Load	0	24	-
	Transverse Load	82	114	1.4
	Vertical Load	58	94	1.6
T7-A tower	Longitudinal Load	0	29	-
	Transverse Load	0	0	-
	Vertical Load	60	156	2.6
T10-J tower	Longitudinal Load	196	292	1.5
	Transverse Load	0	0	-
	Vertical Load	25	39	1.6

Consequently, if an insulator string at Tower T6 (A tower) fails (the worst scenario), the immediately adjacent angle tower T5 (D tower) and suspension tower T7 (A tower) as well as the two dead-end towers would be damaged or possibly fail due to the dynamic impact loads. A cascade may therefore result from the failure of towers other than tower T6. However, if towers T5 (D tower), T4 or T6 (A tower) and the dead-end towers T0 and T10 (J tower) were reinforced to resist the dynamic impact loads, the potential cascading failure would be contained and would not pass an angle or a dead-end structure.

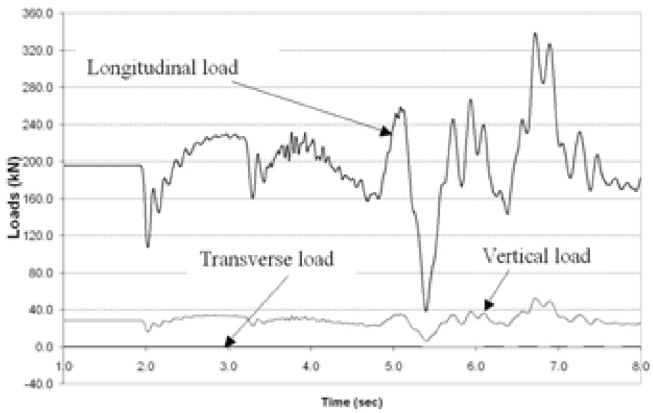


Fig.3. Time history of dynamic loads on Tower T0 (J tower)

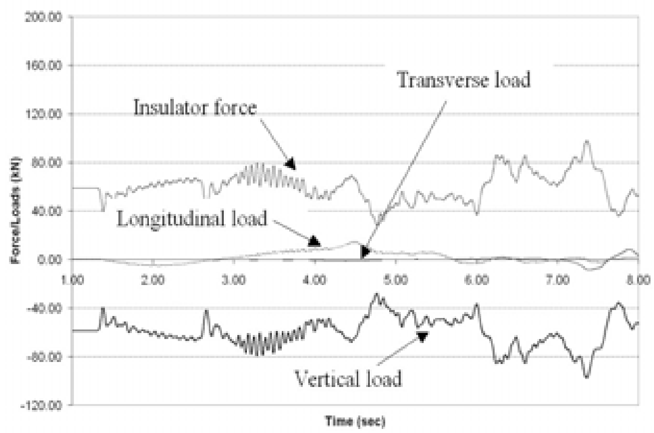


Fig.4. Time history of dynamic loads on Tower T4 (A tower)

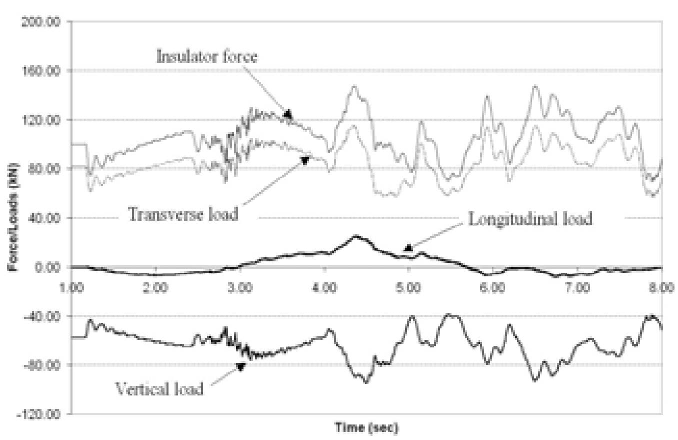


Fig.5. Time history of dynamic loads on Tower T5 (D tower)

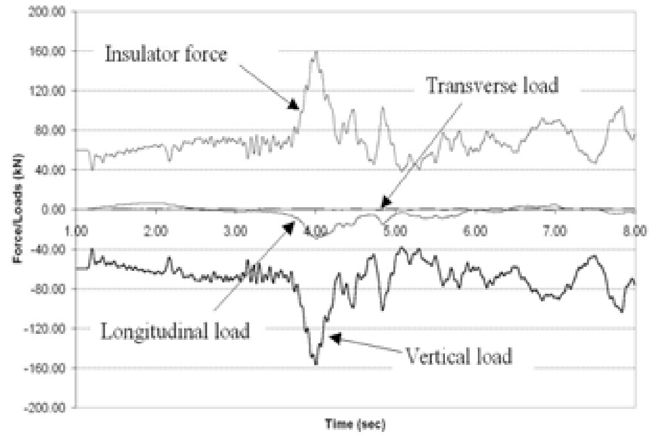


Fig.6. Time history of dynamic loads on Tower T7 (A tower)

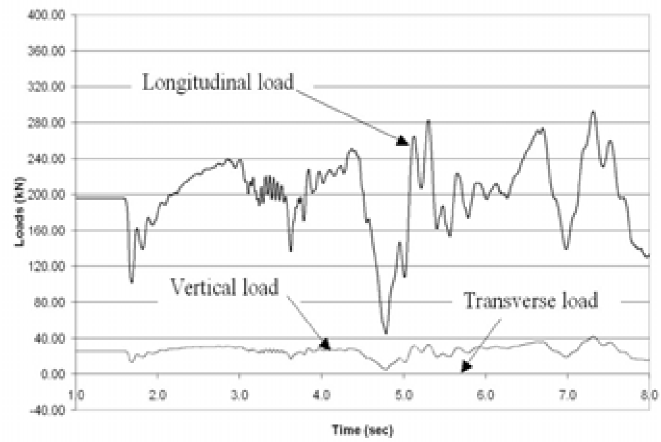


Fig.7. Time history of dynamic loads on Tower T10 (J tower)

V. ANTI-CASCADING REINFORCEMENT SCHEME

To avoid potential cascade of the line, the following anti-cascading scheme is suggested.

- Stop the propagation of a cascade at angle and dead-end towers;
- Reinforce angle and dead-end towers;
- Reinforce tangent towers adjacent to the angle tower.

In addition, the following items are recommended for study to complement the proposed anti-cascading reinforcement scheme:

- Eliminate potential cascading failure triggers by identifying / replacing damaged or defective components through inspection of line components;
- Ensure that potential cascading failure triggers are eliminated by continuing to perform regular inspections as part of a maintenance program;
- Study the dynamic strength of line components such as insulator strings and hardware through mechanical tests in order to study their dynamic behavior and determine their dynamic strength.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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