Reference 16

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Upgrading of a 230 kV Steel Transmission Line System Using Probabilistic Approach

Asim Haldar

Abstract: The paper presents a systematic approach to the upgrading of an existing 230 kV transmission line system using probabilistic method. The line system is located on a peninsula and consists of a number of steel and wood pole lines terminated at various substations. The line system extends over a severe icing zone known for glaze icing. A system approach was used in assessing the existing line reliability. The reliability analysis provided a "trend line" for the observed rate of failure. The original design ice load was updated based on the observed failure rate over a 30-year period. To ensure that the tower fails first before the conductor, a trapezoidal conductor specially designed with extra high strength steel core was used for the upgrading project. The existing suspension towers were reused with two special dead end towers designed to accommodate the increased conductor tension due to the revised ice load.

Three spans were considered in the upgrading study. The optimum upgrading option is presented for the steel transmission line system and is based on the cost risk model which used the ruling span (conductor tension) as one of the primary variables for optimization. Results show that the choice of the optimum span (tension) for upgrading the existing line system is not only sensitive to damage cost but also requires other considerations. One such criterion was to ensure that the suspension towers remaining in place were not subjected to uplift forces due to increased conductor tension under cold temperatures.

Keywords: Ice Load, Optimization, Probabilistic Upgrading, Risk Analysis, Strength Coordination, Structural Reliability, and Transmission Line.

I. INTRODUCTION

Newfoundland and Labrador Hydro operates two parallel transmission lines at 230 kV level between Sunnyside and St. John's (Figure 1). These lines are located on the Avalon Peninsula, eastern part of Newfoundland, which is characterized by a maritime regional climate and is affected by almost all low pressure systems that cross North America. Besides, the region is also affected by maritime systems passing along the eastern seaboard. Figure 2 depicts the transmission line system layout on the Avalon Peninsula. In general, the layout for these lines varies from flat to extremely rough and hilly terrain.

Transmission lines TL 203, TL 201 & TL 236 consist of H-framed wood pole structures while TL 237/207, TL 217 and TL 218 use lattice steel towers such as guyed V as suspension structures and self supported towers as heavy angle and dead end structures (Figure 3).

Since their commissioning in the 60's, these lines have experienced severe ice loadings almost every year. Several large ice accumulations have been observed and since 1965, there were at least four (4) major line failures on the peninsula. These failures occurred in 1970, 1984, 1988 and 1994 respectively. In 1990, one span in TL 217 had severe icing and the conductor came very close to the ground and had a severe burn mark. Figures 4 and 5 depict the observed glaze icing which caused line failures in 1984 and 1994 respectively.

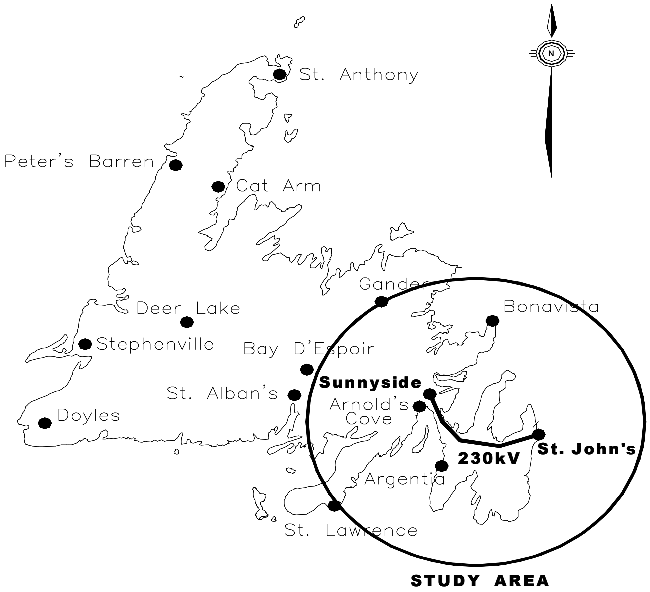

Figure 1. Study Area

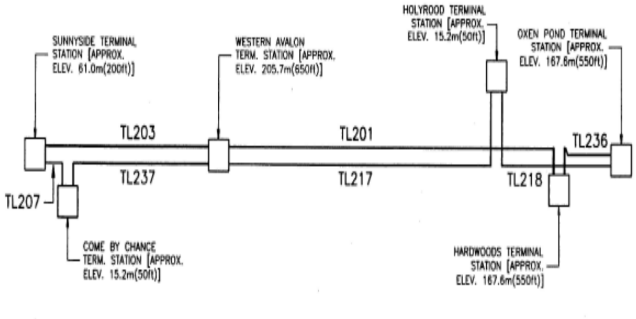

Figure 2. Typical Line Layout Diagram

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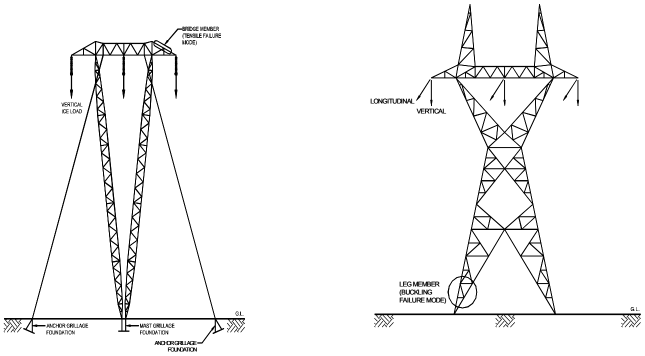

Figure 3. Typical Tower Layout Diagram

Figure 6 presents the failure of a forged eyebolt on a wood pole dead end structure (TL 201, Figure 2) near Western Avalon terminal station in 1994. This failure caused a cascading event in which seven structures failed. The failure cost was approximately $500,000 dollars. A failure investigation study in [5] concluded that the observed failure rate based on many events over a 30-year operational life could be modeled with an annual rate of 0.1 for the entire Avalon region. This information was used later to revise the original design ice load.

Figure 4. Observed Icing on April 8, 1984

II. ORIGINAL DESIGN CRITERIA

The original design wind and ice loads for these lines was based on CSA (Canadian Standards Association) heavy load in [2] and was 12.5 mm glaze ice combined with 117-km/hr wind. Upon review of the pertinent information available at the time, two basic load conditions evolved**:** Normal Zone with 25.4 mm radial glaze ice and Ice Zone with 38 mm radial glaze ice. The ice zone was used for a small section of the line system. The overload factor for steel tower design was 1.33.

III. FAILURE INVESTIGATION STUDY

In all cases, original design loads were exceeded several times during the operational life (30 years) indicating the need for a better prediction of ice and wind loads on these lines [5]. A method developed earlier in [4] to predict the extreme ice load taking into account the observed failure events was used to revise the ice load. From all the reported failures, the conductor hardware assembly and the conductor itself appeared to be the "weak link" once the design load is exceeded.

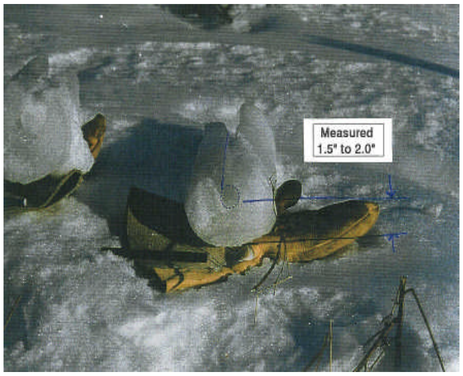

Figure 5. Observed Icing on December 9, 1994

In reviewing the observed ice load on conductor, it is noted that 38 mm to 50 mm of equivalent radial glaze ice was found to be on conductor and /or guy wires in many instances (Figure 5).

Figure 6. Failure of a forged eyebolt on a Wood Pole Dead End Structure - 1994

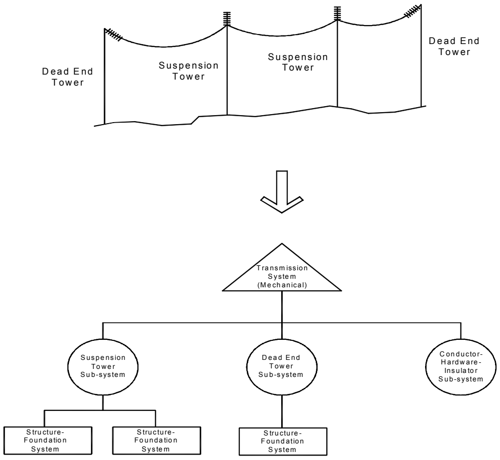

Figure 7. Series System Model For Strength Coordination

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In the industry, there is a general consensus that suspension tower should be the "weakest component" in a line to ensure that the tower fails first before any other components fail. It is well understood that the conductor subsystem failure has a severe consequence with respect to cascading of a line and could cause a long outage. Figure 7 depicts a "series" system model for strength coordination.

Therefore, a re-conductoring option with an extra high strength steel (EHSS) conductor (804 kcmil-TW wires for aluminum strands) equivalent in diameter to existing "DRAKE" conductor (795 kcmil with 28 mm diameter) was considered to alter the sequence of failure [5]. The rated tensile strength (RTS) of the trapezoidal conductor (RTS = 284kN) was twice that of the "DRAKE" conductor while the self-weight (21.5 N/m) was 34% more compared to the weight of the "DRAKE" conductor.

IV. METHODOLOGY

To carry out the upgrading study of the transmission line system based on probabilistic approach, the reliability of the existing system needed to be evaluated first. This implied assessing the reliability of major line components in the existing system such as conductor, suspension tower, dead end tower etc. The line could be modeled as a "series" system (Figure 7) where the "weakest" component governs the design. Although the actual line layout would have many different tower heights because of the rolling terrain profile, it was assumed that a flat terrain model with a fixed ruling span for a typical section of a line would provide a reasonable insight to the line reliability analysis with particular reference to strength coordination.

For the existing system with "DRAKE" conductor, the reliabilities of various components such as the suspension tower, conductor and dead end tower were evaluated under a vertical ice load. The ruling span for a typical section of a line was 427 m. Under vertical ice load at the suspension points, this gave a tensile failure mode for the bridge member and the conductor (Figure 3). A buckling failure mode for the dead end tower leg member was also considered (Figure 3). Although many other failure modes are possible, this simple failure mode was used for initial strength coordination. Using a first order bound presented in [1], the system failure probability was estimated for the existing line under vertical ice load.

Next, the ice load was updated using [4], based on the observed failure events in [5]. The system reliability was also assessed for 804 kcmil conductor where three different spans (152m, 305m and 427m) were considered. In each case, the system reliability was obtained along with the associated cost of upgrading. Finally a cost optimization procedure was adopted where the upgrading cost was balanced against the risk, which included the failure probability and the cost of failure presented in [2]-[5]. Final selection of the span was based not only on the reliability based optimization but also based on the constraint that the suspension towers which would not be relocated would not be subjected to uplift forces under extreme cold temperatures. This could be encountered if one chooses to use very high conductor tension (large span) to minimize the relocation of existing towers in place.

The five major steps included: (1) Re-estimation of ice load based on historical failure information;(2) Estimation of mean conductor tension under existing and revised ice loads and its variation; (3) Reliability assessment of line components (such as conductor, suspension tower and dead end tower using strength as log normal distribution and load effect as Gumbel distribution; (4) Span (tension) optimization for various cost risk scenarios; and (5) Final selection of the optimum design span based on reliability as well as other effects such as no uplift on existing towers remaining in place. All computations in the present study were done in "MATLAB" environment [6]. In the original upgrading project, reliability calculation was based on log normal distributions. This present work is an extension to the earlier work.

V. EXISTING LINE RELIABILITY

Annual Ice Load Estimation

To assess the annual reliability of the existing line, we had to determine the mean annual ice thickness and the coefficient of variation of ice thickness. Since the original design assumed a 25.4 mm radial ice thickness as lifetime load (50 year service life), it was assumed that it was a 50-year load. Further, a coefficient of variation of 0.70 was also assumed to estimate the mean annual ice thickness. The relationship for a 50-year return period is

$$t_{50} = \bar{t}(1 + 2.59\,\mathrm{cov}) \tag{1}$$

where t_{50} = 25.4 mm radial glaze ice thickness. Based on this, the mean annual ice thickness, $\bar{t}$ was estimated as 9.02 mm.

Conductor Tension

Using the state equation in Appendix A, the conductor tensions under various ice thicknesses were obtained and presented in Figure 8. The initial stringing tension was assumed to be 20% of the rated tensile strength (RTS) of the conductor. A linear relationship with high correlation was found based on regression analysis. It is also noted that 45 mm ice load is the limit load for the conductor. This was also validated by field observations with respect to conductor subsystem failure (Figure 5).

Conductor Reliability

In the reliability analysis, the load effect, Q was considered to be a function of the basic variables (wind speed, ice thickness, etc) and was related to these basic variables via some transfer function (linear or non linear). Normally, the basic variables typically follow a Gumbel distribution while the strength of the component R normally follows either a normal or a log normal distribution. The nominal strength could represent the rated strength of the conductor, buckling strength of the tower member etc; the probability of failure is the shaded area shown in Figure 9.

The limit state expression for the existing conductor was given by

$$LS = R_n - 2385t_i - 20260 \qquad (2)$$

where R_n was the nominal rated strength of the conductor and was assumed to follow a log normal distribution while t_i was the ice thickness which followed the Gumbel distribution.

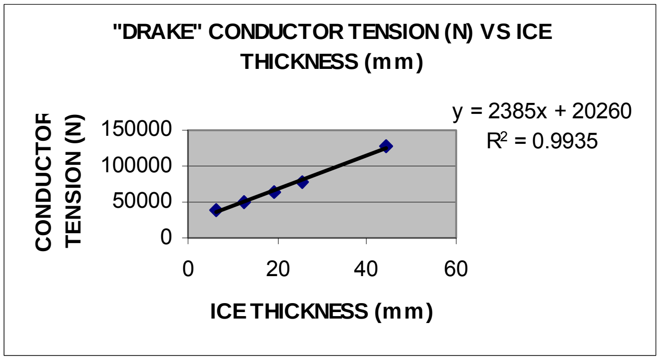

Figure 8: Regression Plot For 795 Conductor

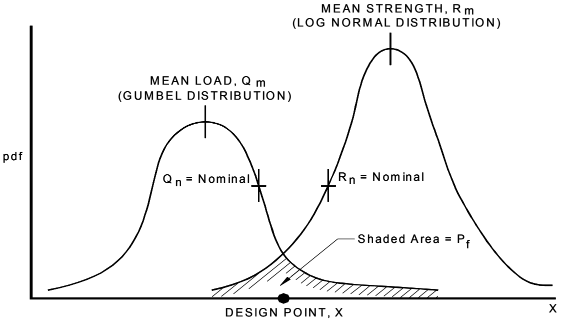

Figure 9 Probability of Failure Diagram

LS $\leq$ 0.0 implied failure while LS > 0.0 meant it was safe. The computation method for reliability analysis for linear and/or non-linear function with non-normal variables is given in APPENDIX B based on [8]. Following the methodology, we obtained the conductor reliability index, β = 3.40 (pf = 3.32E-04)

Suspension Tower Reliability -Bridge Member

To estimate the tower reliability under vertical ice load, Q, the limit state equation was defined as

$$LS = R - Q = R - [0.0277 * t_I (d + t_I) + w_C] * span \qquad (3)$$

where R is the nominal capacity of the bridge hanger member following a log normal distribution; Q, the vertical ice load in (kN/m), is a function of ice thickness, t_i (mm) which follows a Gumbel distribution. w_c is the self-weight of the conductor and d is the conductor diameter (mm). Again, the reliability analysis was carried out to determine the reliability index, β = 4.01 (pf =3E-05)

Based on this analysis, it is shown that the tower has almost one order higher reliability compared to conductor. Therefore, under extreme ice loading, failure observations support the conclusions drawn from this analysis. Later the existing line system will be reanalyzed with the revised ice load based on observed failure events.

Dead End Tower Reliability – Leg Member

The reliability of the dead end tower was based on the leg member capacity under a buckling failure mode. This was calculated assuming three phase longitudinal loads on one side of the tower, due to the load from all broken conductors under ice.

The force in the leg member was calculated based on the influence coefficients under longitudinal conductor tensions as well as the vertical ice loads on three phases. After simplification, the force under compression was given as,

$$Q = Ht_i^2 + Kt_i + L \qquad (4)$$

where H is a function of vertical influence coefficients and span length. K is a function of longitudinal influence coefficients, conductor regression coefficients and diameter of the conductor. The term L contains contribution from self-weight and influences coefficients.

The limit state equation for the tower leg member was

$$LS = R_n - Ht_i^2 - Kt_i - L \qquad (5)$$

where R_n is the nominal leg capacity in compression. The reliability index for the leg member was found to be β = 6.55 (pf = 2.74 E-11).

System Reliability-Existing Line

The system reliability was obtained following [1] as

$$\max P_{f_i} \leq System Failure\,Probability \leq \sum_{1}^{n} P_{f_i} \qquad (6)$$

where P_i is the probability of failure of ith element. Table 1 presents the two bounds for the existing line.

Table 1 System Failure Probability Bounds -Existing Line With "DRAKE" Conductor

Member	β	$P_{f_i} = \phi(-\beta_i)$	Lower Bound	Upper Bound
Conductor	3.40	3.32E-04	0.000332	0.00036
Suspension Tower	4.01	3.0E-05		
Dead End Tower	6.55	2.74 E-11		

VI. UPGRADING WITH 804 CONDUCTOR

Revised Mean Annual Ice Thickness

The maximum ice thickness for a 10-year return period, X_{10}, could be related to any other return period, X_T as

$$X_T = X_{10}[1-0.78*\{2.30+\ln(\ln(\frac{T}{T-1}))\}V_{10}] \qquad (7)$$

where T is the return period. A 25-year return period load based on observed ice thickness of 50 mm (10-year return period) was 63 mm .The selection of a 25-year return period was based on the assumption that the load will be exceeded once during the remaining life of the line (also 25 years) as it is normally assumed in the new design. The 50-year load was 75 mm radial glaze ice. The coefficient of variations for 25-year return period and 50-year return period ice were used as 0.40 and 0.267 respectively. This provided a mean annual ice thickness of 21.6 mm with a coefficient of variation of 0.96. Based on this relationship, the original design ice load, 25.4 mm radial ice, will have an approximate return period of 2.8 years.

System Reliability With 804 Conductor

Three spans were considered to study the reliability based upgrading scenarios. Figure 10 presents the results for all three spans. It is seen in all cases that the tower failure probability is considerably higher compared to that of the conductor thus providing a desired coordination of strength. The failure probability for a 427 m span was approximately three times that of the 305 m span.

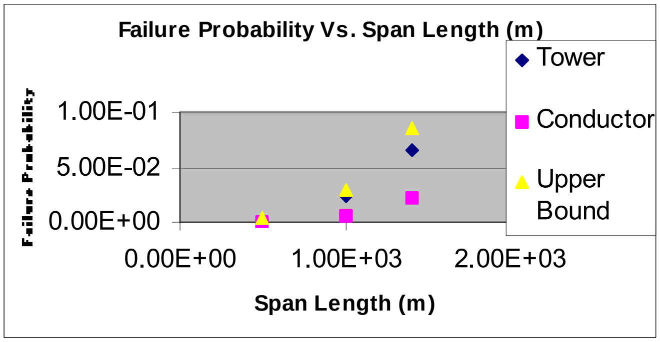

Figure 10 Failure Probability Vs. Span

The existing line system was also reanalyzed with the revised ice load and it was noted that the "DRAKE" conductor annual failure probability was 0.1315 (1 in 8 years). This was very similar to the assumed rate of failure 0.1 per year over a 30-year operational life of the line. The present methodology provided a reasonable calibration of the revised ice load, which was used in the upgrading project.

VII. COST OPTIMIZATION

The cost optimization study was illustrated for a 5 km line section. Additional suspension towers were not required when the reconductoring option was chosen based on the existing 427 m ruling span because all suspension towers would remain in place. We only needed to replace the two existing dead end towers with stronger towers because the rated strength of the conductor was twice that of the existing conductor.

For a 305 m span, 6 new towers were needed and 6 existing towers required relocation. Five towers will remain in place. For a 152 m span, 18 new towers were needed. The failure cost was assumed to be $2 million dollars. Figure 11 presents the results and shows 305m span option is economical. However if the failure cost was reduced to $ 0.5million dollars, the 427m span option would also be economical. The total cost was sensitive to the failure cost assumed.

Besides this, the existing line layout information indicated that the revised spotting of the line using a 305m option would ensure existing suspension towers remaining in-place would not encounter uplift force under cold temperatures. This was not the case if one had to use the cold curve based on 427 m span. Many towers with shorter heights were under uplift situation because of the significant higher tension under cold temperature. This implied that additional tower extensions and/or dead end towers would be needed in many places to meet this option. Also, the cost for the containment tower is proportional to the design tension used under ice load. These costs were not included in the simple optimization model but it was obvious that the overall cost of upgrading the line system with 427 m span would be higher. Therefore, the 305 m option was chosen in the final design. This option also provided a reasonable line reliability.

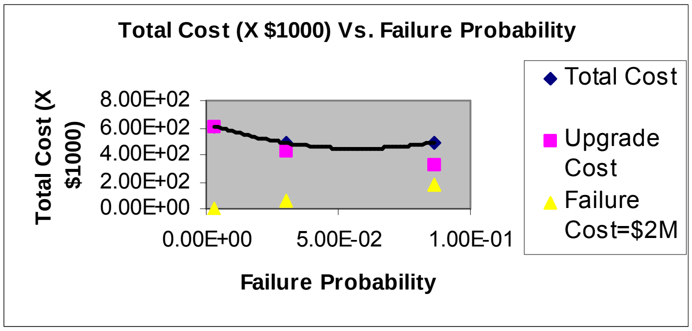

Figure 11 Cost Optimization Plot

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VIII. SUMMARY & CONCLUSIONS

The paper presents a systematic approach for upgrading a steel transmission line system using the probabilistic method. Probabilistic ice load was revised based on observed failure events over a 30-year period. To ensure that the tower fails first before the conductor, a trapezoidal conductor specially designed with extra high strength steel was used with the existing suspension tower arrangement.

The assessment of existing line reliability confirmed the observed rate of failure. For the new EHSS –TW conductor, three different spans were considered. The optimization results indicated that the total cost was sensitive to the assumed value of the failure cost. In the final analysis, 305 m span was chosen for the upgrading project to ensure that the suspension towers remaining in place would not encounter uplift forces under cold temperatures. Also, the 305 m option based on a simple "series" model provided a reasonable failure probability for the overall system.

IX APPENDIX A

Conductor Tension Estimation

The ice weight of the conductor is estimated from

$$w_i = [0.0277 * t_I (d + t_I) + w_C] \qquad \text{(A1)}$$

where

w_i = ice weight of the conductor per unit length, w_C = self-weight of the conductor and t_i = ice thickness in mm.

Assuming that the conductor tension under every day condition as 20% of the rated strength, the conductor tension under any given ice load can be estimated from the following equation

$$f = H^3 - H^2 H_{initial} + H^2 (A_0) - B_0 = 0 \qquad \text{(A3)}$$

where H = final tension under ice load, $H_{initial}$ = initial tension under every day condition

$$A_0 = \left[\frac{span^2 * w_C{}^2 * EA}{24} + \alpha * DELTA * EA\right] \qquad \text{(A4a)}$$

$$B_0 = \left[\frac{span^2 * w_I{}^2 * EA}{24}\right] \qquad \text{(A4b)}$$

where EA = axial rigidity, α = thermal expansion coefficient and DELTA = temperature rise or drop in ^{0}C.

Since the above equation is nonlinear, Newton method is used to solve H in an iterative manner

$$H_{\mathrm{mod}} = H_{init} - \frac{f}{f'}; \qquad \text{(A5)}$$

and

$$\text{the TOL} = \left(\frac{H_{\mathrm{mod}} - H_{init}}{H_{init}}\right); \qquad \text{(A6)}$$

The convergence is rapid and typical output from a full sag tension run is compared in Table A1

Table A1
Comparison of Tensions (427 m span)

Conductor	Ice Thickness (mm)	Tension (N) based on Equation (A3)	Tension (N) based on SAG-TENSION Program	Difference
DRAKE Conductor	25.4	81402	77917	4%

X APPENDIX B

Reliability Computation [8]

The normalized variables are defined as

$$u_i = \frac{x_i - \bar{x}_i}{\sigma_{X_i}} \qquad \text{(B1)}$$

and the limit state function $g(x_1,..x_n)$ becomes

$$g(u_1\sigma_{x_1} + \bar{x}_1, ...u_n\sigma_{X_n} + \bar{x}_n) = 0 \qquad \text{(B2)}$$

and the gradient becomes

$$\frac{\partial g}{\partial u_i} = \frac{\partial g}{\partial x_i}\frac{\partial x_i}{\partial u_i} = \frac{\partial g}{\partial x_i}\sigma_i\,. \qquad \text{(B3)}$$

Using a first order Taylor Series expansion of g (.)=0 around the design point u^* and approximating $u^* = u^0 + \Delta u$, it can be shown

$$g(u^*) \cong g(u^0) + \nabla g(u^0)^T [\lambda \nabla (g(u^0) - u^0] \qquad \text{(B4)}$$

where λ is a scalar multiplier. At the design point, u^* should satisfy the following

$$u^* = \lambda \nabla g(u^*) \qquad \text{(B5)}$$

Equating $g(u^*) = 0.0$,

$$\lambda = \frac{\nabla g(u^0)^T u^0 - g(u^0)}{\nabla g(u^0)^T \nabla g(u^0)} \qquad \text{(B6)}$$

An iterative algorithm can be set up with initial values of u_i and the reliability index, β, which defines the minimum distance from the origin can be obtained as

$$\beta^{i+1} = \sqrt{(u^{i+1})^T u^{i+1}} \qquad \text{(B7)}$$

$P_f = \varphi(-\beta)$ which is obtained from the normal table where u^{i+1} can be obtained from

$$u^{i+1} = \nabla g(u^i) \frac{\nabla g(u^i)^T u^i - g(u^i)}{\nabla g(u^i)^T \nabla g(u^i)}; \qquad \text{(B8)}$$

The convergence in β is obtained when

$$\left|\beta_{i+1} - \beta_i\right| \le 10^{-3}; \qquad \text{(B9)}$$

The unit normal vector α is obtained as

$$\alpha = -\frac{\nabla g(u^*)}{\left|\nabla g(u^*)\right|} \quad u^* = \alpha\beta; \qquad \text{(B10)}$$

Since the basic variable, ice thickness t_i is non-normal, a simple transformation from t_i to u_i space (zero mean and unit standard deviation) is done using

$$\varphi(u_i) = F(t_i) \qquad \text{(B11)}$$

where F (.) is the cumulative distribution for a non-normal variable.

Since the variable follows Gumbel distribution

$$F(t) = \exp(-\exp(-a(t-b))) \qquad \text{(B12)}$$

where

$$a = \frac{\pi}{\sqrt{6}\sigma} \text{ and } b = \mu - \frac{0.5772}{a}; \qquad \text{(B13)}$$

In the tail approximation, the distribution and density functions of the non-normal variables are matched based on the following equations

$$\varphi\left(\frac{t - \bar{t}_i}{\sigma_{t_i}}\right) = F_x(t_i) \qquad \text{(B14)}$$

The limit state equation R- Q = 0 is used as an example where R follows a normal distribution and Q follows a Gumbel distribution. Reference [7] presented the failure probability results for various central safety factors with V_R

$$\frac{1}{\sigma_{t_i}} \phi\left(\frac{t - \bar{t}_i}{\sigma_{t_i}}\right) = f_x(t_i) \qquad \text{(B15)}$$

=0.1 for strength and V_Q = 0.3 for load respectively. Figure B1 depicts the comparison and the agreement was excellent. The software was developed in "MATLAB" environment. [6].

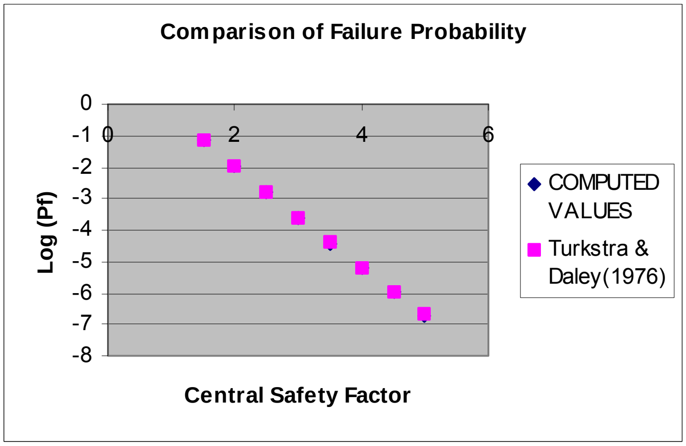

Figure B1 Comparison of Failure Probability

XI. REFERENCES

[1] C. A. Cornell. "Bounds on the Reliability of Structural System", J. ASCE Structural Division. 93,171-200, 1967.
[2] Canadian Standard Association (CSA), "Overhead System", 2001
[3] Haldar. "Optimum Reliability Based Design of Transmission Lines", 16th_INTER-RAM Conference for The Electric Power Industry, Monterey, California, pp. 422-426, 1989.
[4] Haldar. "Failure of a Transmission Line Due to Ice in Newfoundland", Proc. 5TH International Workshop for Atmospheric Icing of Structures (IWAIS), Tokyo, November, 6p, 1990.
[5] Haldar. "Reliability Study of Transmission Lines On The Avalon and Connaigre Peninsulas", Report Prepared for Engineering Design, TRO Division, Newfoundland and Labrador Hydro, Report # 3-2-54, 160p, 1995.
[6] MATLAB 2005 Windows Version, The Mathworks Inc. USA
[7] Turrkstra, and M. J. Daley. "Two moment Structural Safety Analysis", Can. J. of Civil Engineering, Vol. 5, pp: 414-426, 1976.
[8] J. Sorensen. "Note 1+2: Structural Reliability", Aalborg University, Denmark, 2004.

XII. BIOGRAPHY

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