An Approach for Quantifying Structural Reliability of Overhead Structures and Its Application in Assessing Risk of Transmission Lines

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Abstract - **Estimation of probability of failure of a transmission overhead structure under extreme weather loading is an essential step for managing risk of a transmission line. A general approach based on structural reliability analysis to quantify the probability of failure of transmission overhead structures for a specific time window is presented. The approach allows quantification of risks in a scientific way, considering various uncertainties and failure modes. The analysis procedure and its application in risk assessment are demonstrated through a case study.**

I. NOMENCLATURE

Structural reliability analysis, steel lattice tower, probability of failure, risk assessment

II. INTRODUCTION

Risk assessment has become more and more important in today's engineering practice. The approach allows direct estimation of risk of an engineering system under certain events. The estimated risk usually expressed in dollars can then be used to determine the best remedial solution through a decision-making or so-called risk management process. A transmission line system could fail under extreme wind or ice loading as we observed during 1998 ice storm in North America. Over the last decade, risk assessment has been used by some utilities to evaluate the existing risks and to determine the best ice upgrading options for their transmission lines [1]. In the process of risk assessment of a transmission line, one has to quantify the probability of failure of the individual structures under certain event load conditions. The annual risk is calculated based on the probability of the event, probability of failure under the event and failure consequences. The approach currently used is mainly deterministic and judgmental, in which the probability of failure under certain event is assigned based on the ratio of structural load carrying capacity to the event load such as 500-year return ice load. For example, if the ratio is less than 1.0, 100% is assumed as the probability of failure and if the ratio is less than 1.0, probability of failure of 0% is assigned. Thus, this approach could result in either overestimate or underestimate of the actual risk. Ideally the estimation of the probability of failure under certain event should be done using structural reliability analysis rather than judgmental approach.

Over the last two decades, structural reliability methods have been studied and applied in the field of transmission and distribution engineering. Many contributions have been made towards reliability-based design and line upgrading, development of design guidelines and manuals and the calibration and assessment of existing structures [2, 3, 4]. In this paper, an approach using structural reliability analysis for risk assessment of transmission structures will be introduced, which permits the quantification of probability of failure of a transmission structure over a specific period of time, such as one year or 50 years considering the uncertainties involved in both structural withstand strength and applied loads.

III. STRUCTURAL RELIABILITY ANALYSIS

The reliability of an engineering system is defined as the probability that it will perform as required under the given conditions within a given period of time. The performance of a transmission overhead structure is normally controlled by several intervening variables such as material strength and applied loads. These variables are regarded as random and can be described in terms of mean values, standard deviations and distributions. The structural reliability analysis allows engineer to quantify the probability of failure of a component. The implementation of the analysis is based on a performance or limit-state function of interest (failure mode) G as follows:

$$G = C - D \quad \text{.......} \quad \mathbf{(1)}$$

where C is the function of material strength such as wood pole bending strength and D the function of load demand, such as groundline bending moment under wind and ice loads. If a combination of the random variables (eg, material strength, wind speed and ice thickness) results in $G < 0$, the structure is rated failure and the corresponding probability of such event, Prob($G < 0$), is called the probability of failure, P_f. Conversely, a combination of the random variables resulting in $G > 0$ will make the structure perform as required and the corresponding probability, Prob($G > 0$), is termed the reliability P_r. The condition when $G = 0$ is a limit-state that defines the boundary between failure and survival. The probability of failure is complimentary to the reliability:

$$P_r + P_f = 1 \quad \text{.........} \quad \mathbf{(2)}$$

The probability of failure can be obtained by calculating the probability of the event $G < 0$. Since, in general, there could be a number of random variables involved in G, the exact calculation requires the joint probability density function of all random variables and integration over the failure region $G < 0$, which can hardly be applied since the joint probability function f is unknown and very difficult to find. An alternative method is the straightforward, standard computer simulation (Monte Carlo method) which is simple to implement and can converge to the exact solution. However, it could be very computationally demanding, especially when dealing with a low probability of failure. A second alternative is the use of approximate methods that have been developed and widely used during the last three decades, such as the FORM/SORM procedures (First Order or Second Order Reliability Methods)[5]. The methods are based on the calculation of the reliability index β. From this index, the probability of failure P_f and the reliability P_r can be estimated approximately as shown in Equations (3) and (4), by use of the Standard Normal probability distribution function $\Phi(.)$.

$$P_f = \Phi(-\beta) \quad \text{.........} \quad \mathbf{(3)}$$

and

$$P_r = 1 - \Phi(-\beta) = \Phi(\beta) \quad \text{.........} \quad \mathbf{(4)}$$

The detailed procedure is presented below and illustrated through a case study, in which the annual probability of failure and the probability of failure over 50 years of a typical lattice steel tower were calculated for two load cases and different spans.

A. Procedure Of The Reliability Analysis For A General Transmission Structure

1) Establishment Of Performance Functions Or Limit States:

Based on various failure modes of the structure, performance functions must be first established. These failure modes may include, for example, yielding and buckling of steel leg members and arm members of a lattice tower, bending failure at groundline of a wood pole. The established limit states are used in the reliability analysis to estimate the probability of failure in the corresponding failure modes.

2) Statistical Analysis Of Weather Loading And Material Strength:

For a selected structure, ideally localized historical weather statistical data such maximum wind speed and ice thickness should be obtained and analyzed to derive required statistics for the analysis such as mean value, standard deviation and distribution. If the weather data are not available, the 50-year return loads as shown in the weather maps of CSA C22.3 or NESC C2 can be used to estimate the required statistics [6]. The statistical data of material strength such as steel yield strength and wood pole bending strength should be also collected, which in general are available or can be obtained from carrying out laboratory testing.

3) Structural Analysis:

To carry out the reliability analysis, a structural analysis model is required to calculate various structural responses such as compression force of a steel member of a lattice tower and bending moment of a wood pole. Depending on the complication of the structure, finite element based numerical approach can be used for lattice tower while close form formulation can be used for a simple structure such as single wood pole.

4) Structural Reliability Analysis:

Reliability analysis software or simplified approach can then be integrated with the structural analysis discussed above to calculate the probability of failure.

B. Case Study: Reliability Of A Typical Lattice Steel Tower

A typical suspension lattice steel tower was chosen for the case study for illustration purpose (see Fig. 1). Six conductors are attached and the leg member is considered as the critical component, assuming that failure of the leg member will cause failure of the entire structure. Compression force of the leg member is considered in the limit-state function for the reliability analysis. The objective of this application is to find the probability of failure of the leg member under wind only and wind during ice load case for a given period of time.

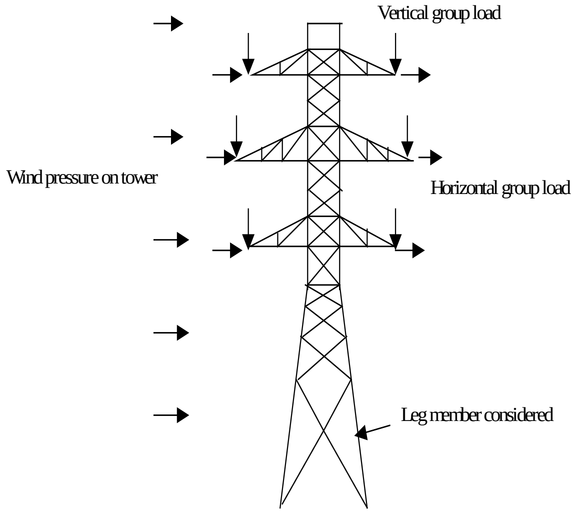

Fig. 1: The suspension lattice steel tower

In the reliability analysis, an analytical structural analysis model formulated either as a close-form equation or as a computational program is needed to evaluate the effect of loads considered in the limit-state functions, such as deflection, bending moment and compression force. For this case study, it is assumed that the tower has a linear behavior in compression, thus the influence coefficient (effect of unit loads) can be used to calculate the structural response. To obtain the influence coefficient, structural analysis software

ATADS [7] was used to calculate the effect (compression force of the leg member) of the unit vertical group loads and unit horizontal group loads as well as unit wind pressure.

For the reliability calculations, the limit state functions corresponding to compression failure of the leg member are written as follows, considering two load cases:

Wind + ice:

$$G_1 = R\ A - effect\ of\left[TS + \left(V + D\right)\right]S\rho + d + P \quad \text{.......}\mathbf{(5)}$$

Wind only:

$$G_2 = RA - effect\ of\left(TS + DS\rho + d + P\right) \quad \text{..................}\mathbf{(6)}$$

where

S = wind span

T = transverse load (function of wind velocity and /or ice thickness) per unit length of conductor

ρ = ratio of weight span to wind span

V = vertical load (function of ice thickness) per unit length of conductor

D = dead load per unit length contributed by the weight of conductors

d = dead load contributed by the weight of members

P = wind pressure applied on the structure

RA = compression capacity, taking the slenderness function into account

The effect is the compression force of the leg member. Three random variables are considered: compression capacity RA, wind velocity, and ice thickness. If a combination of wind load and ice load results in $G_1 < 0$ or $G_2 < 0$, the structure would fail.

For a specified wind span S, the probability of failure for a given period of time can be calculated using RELAN [8], a reliability analysis software program.

Weather statistics of wind velocity and ice thickness for the tower location were assumed as shown in Table I. The compression capacity (treated as random variable) of the leg member was also assumed for this case study.

TABLE I:
STATISTICS OF RANDOM VARIABLES FOR AN AREA WHERE THE STRUCTURE IS LOCATED

Component	Mean	COV	Type
Compression capacity RA	890 kN	0.10	Lognormal
Annual extreme wind speed	100 km/h	0.15	Gumbel
Wind during ice	65 km/h	0.4	Gumbel
Annual maximum ice (radial thickness)	9 mm	0.7	Gumbel

The probability of failure was first calculated for each load case and each of specified spans. Both annual and 50-year period were considered. The reliability indexes and the corresponding annual probability of failure are shown in Table II. The combined probability of failure was also calculated using system reliability method [9] considering both wind only load and wind during ice load cases.

Similar approach could be used to calculate the probability of failure for other types of the transmission overhead structures such as H-frame wood poles and steel poles.

TABLE II
ANNUAL RELIABILITY INDEX AND CORRESPONDING ANNUAL PROBABILITY FAILURE

Span (m)	Wind only		Wind and ice		Combined	
	Reliability index	Probability of failure	Reliability index	Probability of failure	Reliability index	Probability of failure
100	2.511	0.623×10^{-2}	2.273	0.115×10^{-1}	2.109	0.0175
200	1.866	0.310×10^{-1}	1.821	0.343×10^{-1}	1.522	0.1465
300	1.357	0.873×10^{-1}	1.508	0.658×10^{-1}	1.052	0.1465
400	0.931	0.176	1.270	0.102	0.650	0.2578

TABLE III
RELIABILITY INDEX AND CORRESPONDING ANNUAL PROBABILITY FAILURE FOR 50 YEARS

Span (m)	Wind only		Wind and ice		Combined	
	Reliability index	Probability of failure	Reliability index	Probability of failure	Reliability index	Probability of failure
100	0.710	0.239	1.920	0.0274	0.648	0.2585
200	-0.538	0.705	1.336	0.091	-0.603	0.7269
300	-1.602	0.945	0.935	0.175	-1.668	0.9523
400	-2.498	0.994	0.624	0.266	-2.564	0.9948

C. *Application In The Risk Assessment Of A Transmission Line*

To domenstrate how the reliability analysis results can be used for risk assessment, an event sub tree was created for the same tower as shown in Fig.1, assuming the tower has a wind span of 300 m. Two load cases wind only and wind with ice were considered. Based on above case study, the probabilities of failure for a span of 300 m can be directly used for each of the brances as shown in Fig. 2. Given the consequence of the tower failure, the risks in dolloars for a specific period of time can be calculated as following:

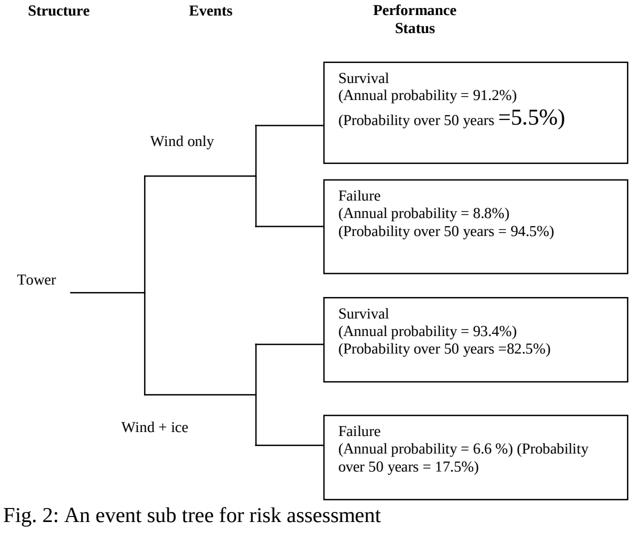

Fig. 2: An event sub tree for risk assessment

Annual Risk = Consequence × combined annual probability of failure due to either wind only or wind during ice.

Risk in 50 years = Consequence × combined probability of failure over 50 years due to either wind only or wind with ice.

If we assume the consequence of the failure is $1.0M, then the total annual risk and risk in 50 years would be $150K and $950 K respectively.

It should be noted that the event tree discussed above is a sub tree used only for demonstration of how the reliability analysis results are plugged into a risk assessment model. A more comprehensive event tree should be used for the actual application, which may require the system reliability analysis of a tower considering the failure modes of all the critical members under various load cases.

IV. SUMMARY AND DISCUSSIONS

A structural reliability-based approach is presented in this paper. Instead of determining the conditional probability of failure under a certain return load event using deterministic or judgmental method, this approach allows quantification of the probability of failure for a specified period of time, taking into account uncertainties involved in both material properties and loads. The obtained results can be directly used in a risk assessment and management model. The general procedure presented in the paper can also be applied to any transmission structures such as tower, wood pole and steel pole to evaluate if an existing structure meets the target reliability specified in the relevant reliability based design documents [10].

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