Longitudinal Load and Cascading Failure Risk Assessment (CASE)

Volume I: Simplified Approach

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REPORT SUMMARY

This report documents an easy, accurate, and economical method to assess the cascading potential of a transmission line. Using this method, utilities can quickly identify lines or line sections that have a high potential to cascade and, therefore, a reduced level of reliability.

Background
A trend began in the 1950s in the utility industry to place less emphasis on the effect of unbalanced longitudinal loads caused by the failure of line components such as insulators, shield wires, and conductors. Better manufacturing methods and improved quality control for these components had significantly reduced the number of transmission line failures. As a result, it became commonly accepted that these types of failures were very rare and that the damage caused by these events was negligible. Consequently, utilities designed and constructed an increasing number of new transmission lines with a low level of longitudinal resistance to extreme event loads. Since the early 1960s, there have been numerous documented cases of multiple transmission structure failures. These longitudinal and transverse cascade failures caused utilities extremely high economic losses because they completely destroyed whole sections of transmission lines, requiring months of repair work.

Objectives
- To develop a method to easily predict unbalanced longitudinal loads acting on structures not adjacent to the insulator, shield wire, or conductor failure.
- To develop a method to assess the cascading potential of a transmission line by considering the energy dissipation at successive spans and supports.
- To develop a method to easily determine the effects of upgrading on the cascading potential of a transmission line

Approach
It is not economical for a utility to design, upgrade, or maintain an existing line system in a manner that provides sufficient strength to withstand high dynamic loads at every structure. A successful, economic line design or upgrade requires that the failure of a limited number of structures, based on the utility's design philosophy and targeted reliability levels, is acceptable if the overall system is protected from cascading. This study defines transmission line reliability levels using the simplified risk assessment

method developed during EPRI's Cascading FAilure RiSk AssEssment (CASE) project. The CASE project is an investigation into the nature of extreme loads that occur in cascading failures and the corresponding line response. The CASE investigation focused on the effects of a triggering event on a transmission line's integrity rather than the cause for the initial failure. Developed from analytical and experimental studies, the simplified CASE method predicts the magnitude of extreme event longitudinal loads.

Results

The study resulted in a cascading failure risk assessment that quickly and accurately determines extreme event unbalanced loads acting on a transmission line and identifies the cascading potential of a line subjected to different loading conditions. The CASE assessment method incorporates dynamic response and damping characteristics of the transmission line to determine unbalanced longitudinal loads at any structure within the containment boundary and at the critical containment structure. Utilities can easily identify effects of line changes or upgrades on line reliability.

EPRI Perspective

Industry emphasis has shifted to minimizing costs and maximizing use of existing facilities to reduce capital spending on upgrades and new construction. Consequently, the need to effectively apply reduced budgets to minimize system failures and to extend the life of existing facilities has increased in importance. The primary advantage of the CASE method is that containment boundaries can be defined or adjusted based on the importance of a given transmission line to the utility's operation. Thus, the longitudinal strength of a specific transmission line can now be calibrated to match a utility's target reliability level for a minimum cost. Having identified a line's current level of risk allows the utility to target system components of the line that are most critical to maintaining the system's primary function: delivery of electric power. As a result, the utility is able to implement cost-effective solutions to minimize outages while improving power transfer.

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Interest Categories

Overhead planning, analysis & design
Overhead construction, O & M

Keywords

Cascade failures
Transmission line failures
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Transmission lines

ABSTRACT

A cascading failure risk assessment method has been developed to quickly and accurately determine extreme event unbalanced loads acting on a transmission line and to identify the cascading potential of a line subjected to different loading conditions. While past investigations have focused on the magnitude of the unbalanced loads acting on the first structure from the initiating event, the simplified 'Cascading Failure Risk Assessment' (CASE) assessment method incorporates the dynamic response and damping characteristics of the transmission line to determine the unbalanced longitudinal loads at any structure away from the initiating failure event.

The CASE project constituted an investigation into the nature of the extreme loads that occur in a cascading failure and the corresponding line response. The goals of this investigation were:

- Develop a method to accurately predict unbalanced longitudinal loads acting on structures not adjacent to the broken insulator, shield wire, or conductor failure.

- Develop a method to assess the cascading potential of a transmission line by considering the energy dissipation at successive spans and supports.

- Develop a method to determine the effects of upgrading on the cascading potential of a transmission line.

The primary advantage of the CASE method is that containment boundaries can be defined based on the importance of the transmission line to the operation of the utility's electric grid. This flexibility allows the CASE assessment method to predict the unbalanced longitudinal loads at any structure within the containment boundary and at the critical containment structure. Unbalanced longitudinal loads at each structure are predicted by taking into account the energy dissipated at each structure and span along the transmission line. Consequently, the longitudinal strength of a specific transmission line can now be calibrated to match a utility's target reliability level for a minimum cost.

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INTRODUCTION

Deregulation and competition have changed the electric power industry business environment. The emphasis has shifted to minimizing costs and maximizing the use of existing facilities to reduce the capital spending on upgrades and new construction. Consequently, the need to effectively apply reduced budgets to minimize system failures and to extend the life of existing facilities has increased in importance.

A number of catastrophic transmission line failures occurred in the recent past whenever a multitude of support structures failed longitudinally or transversely along the line. These cascading failures (longitudinal or transverse cascades) of transmission lines caused the affected utilities extremely high economic losses because these failures have completely destroyed whole sections of transmission lines requiring months of repair work. During the repair time, the utilities experienced loss of revenue from the sale of power or increased cost of power delivered.

It is not economical for a utility to design, upgrade, uprate, or maintain an existing line system in a manner that provides sufficient strength to withstand the high dynamic loads at each structure. A successful and economic line design or upgrade requires that the failure of a limited number of structures is acceptable if the overall system is protected from cascading. The acceptable number of structural failures should be determined based on the utility's design philosophy and targeted reliability levels.

Consequently, it is important for a utility to assess the cascading risk of a line to implement a mitigation approach that maximizes reliability while minimizing cost. Having identified the line's current level of risk allows the utility to target the system components of the line that are most critical to maintaining the systems primary function, the delivery of electric power. As a result, the utility will be able to implement cost effective solutions to minimize outages while improving power transfer and quality on their transmission line systems.

In this study, transmission line reliability levels are defined using the simplified risk assessment method developed during the Electric Power Research Institute's (EPRI) 'Cascading Failure Risk Assessment' (CASE) project. The CASE project constituted an investigation into the nature of the extreme loads that occur in cascading failures and the corresponding line response. The CASE investigation focused on the effects of a triggering event on a transmission line's integrity rather than the cause for the initial failure. The goals of the project were to identify and/or develop a method to predict extreme event longitudinal load magnitudes and to assess the cascading potential of a line when subjected to such loads.

1.1 Background

Starting in the 1950's, a trend began in the utility industry to place less emphasis on the effect of unbalanced longitudinal loads caused by the failure of line components such as insulators, shield wires, and conductors. Better manufacturing methods and improved quality control in the production of these components in the preceding years had significantly reduced the number of failures observed on transmission lines. As a result of these improvements, it became commonly accepted that these types of failures were very rare and that the damage caused by these events was negligible.

Indicative of the general perception at the time, P.P. Bonar (1) stated in 1958 that "...the incidence of conductor failures on overhead lines is now much reduced because of improved materials and design and erection techniques...". Similarly, E. Comellini (2) indicated in an earlier publication that "...the failure of these elements should not be considered in tower design..." while an AIEE survey (3) conducted in 1960 concluded that "...the possibility of a broken conductor in these days of large conductors, lightning shielding, and fast relaying is so remote that it is uneconomical to design for broken conductors...".

Attempting to minimize the cost of line construction, the industry's focus shifted to designing transmission line structures to primarily resist transverse and longitudinal forces caused by wind and ice loading on the conductors and shield wires. The consensus of the industry centralized on the belief that it was uneconomical to design transmission structures to withstand extreme event loads. Consequently, an increasing number of new transmission lines were designed and constructed with negligible longitudinal resistance to extreme event loads.

Since the early 1960's there have been numerous documented cases of multiple transmission structure failures that can be directly related to the lack of nationally recognized or mandated design provisions for longitudinal strength. Records indicate at least 28 different cascading failures nationwide over a time period of 35 years resulted in a loss of more than 3000 transmission structures. While it is true that a number of these cascading failures were triggered by component failures as a result of significant wind or ice loads, it is apparent that a sizable amount of these cascades occurred under normal loading conditions. Consequently, it is evident that variations in the design of transmission lines exist which give rise to systems that may or may not be able to resist extreme loading events.

1.2 Objectives

A successful and economic line design or upgrade assumes that a limited number of structures will fail yet protect the overall system from cascading. Therefore, it is important to identify a utilitarian method to determine the magnitude of these extreme event loads and to assess the cascading potential of a transmission line. The goals of this investigation were:

- Develop a method to accurately predict unbalanced longitudinal loads acting on structures not adjacent to the broken insulator, shield wire, or conductor failure.

- Develop a method to assess the cascading potential of a transmission line by considering the energy dissipation at successive spans and supports.

- Develop a method to determine the effects of upgrading on the cascading potential of a transmission line.

2

CURRENT PRACTICE

There appears to be a large variation in the practices of electric utilities in designing transmission line structures to resist longitudinal loads from extreme loading events caused by broken insulators, shield wires, and conductors. These differences appear to exist because the governing standards that form the basis for the load determination process do not quantitatively address longitudinal load magnitudes or failure containment. Instead, the governing standards leave it to the transmission line designer to define the magnitude of the problem and to mitigate the effects. This is primarily due to the lack of direct solutions available that can determine the extreme event longitudinal loads that are suitable to the design environment.

Currently, there are two standards and one guideline that address the subject of longitudinal loads on transmission lines. Relevant sections of each of these documents are described in the following sections.

2.1 National Electric Safety Code (NESC) Standard

The purpose of the 1997 edition of the NESC C2 (4) code is to safeguard the public during the installation, operation, and maintenance of electric supply and communication lines and associated equipment. Consequently, the NESC code contains only basic provisions that are considered necessary for the safety of employees and the public, and its intent is not to be a design specification or an instruction manual. Based on this premise, the NESC code longitudinal load requirements are limited to the consideration of unbalanced longitudinal loads as a result of changes in the construction grade, insertion of dead ends, presence of unequal spans or vertical loads, and stringing loads.

Specifically, the NESC code requires that when sections of Grade B construction are required in lines of lower than Grade B construction the unbalanced longitudinal loads in the direction of the higher construction grade to be the larger of the following:

> 'The pull of two-thirds, but not less than two, of the conductors having a rated breaking strength of 13.3 kN (3000 lb.) or less. The conductors selected shall produce the maximum stress in the support.'

> 'The pull resulting from one conductor when there are eight or less conductors (including overhead ground wires) having a rated breaking strength of more than 13.3 kN (3000 lb.), and the pull of two conductors when there are more than eight conductors. The conductors selected shall produce the maximum stress in the support.'

Additionally, the NESC code lists a number of longitudinal load requirements that are targeted towards specific line components such as dead ends, specific line characteristics such as unequal spans, or particular construction situations such as stringing. These requirements are:

> 'The longitudinal load on a supporting structure at a dead end shall be an unbalanced pull equal to the tensions of all conductors and messengers (including overhead ground wires); except that with spans in each direction from the dead end structure, the unbalanced pull shall be the difference in tensions.'
>
> 'The structure should be capable of supporting the unbalanced longitudinal load created by the difference in tensions in the wires in adjacent spans caused by unequal vertical loads or unequal spans.'
>
> 'Consideration should be given to longitudinal loads that may occur on the structure during wire stringing operations.'
>
> 'It is recommended that structures having a longitudinal strength capability be provided at reasonable intervals along the line.'
>
> 'Where a combination of vertical, transverse, or longitudinal loads may occur simultaneously, the structure shall be designed to withstand the simultaneous application of these loads.'

Unfortunately, the NESC code neither provides guidance on how to determine the required longitudinal strength nor indicates what constitutes a reasonable interval. Consequently, the responsibility reverts back to the line designer to establish a rational approach to define the magnitude of the extreme event longitudinal loads and to identify an appropriate level of containment strength.

2.2 General Order 95 (GO 95) Standard

Similar to the NESC C2, General Order 95 (5) constitutes a set of rules for the State of California whose purpose is to formulate uniform requirements that will ensure the safety of persons engaged in the construction, maintenance, and operation or use of overhead electrical lines and the public in general. The rules contained in General Order 95 (GO 95) apply to all overhead electrical supply and communication lines within the jurisdiction of the State of California. GO 95's rules are not intended as complete construction specifications, but embody only the requirements that are most important from the standpoint of safety and service. GO 95 stipulates that all construction shall be in accordance with good practice for the given local conditions in all particulars not specified in the rules. Consequently, similar to the NESC C2, the GO 95 contains only basic provisions that are considered necessary for the safety of employees and the public. Its intent is not to be a design specification or an instruction manual. These provisions are:

> 'Poles, towers, or structures with longitudinal loads not normally balanced shall be of sufficient strength, or shall be guyed or braced, to withstand the total unbalanced load with the appropriate safety factors.'

Specifically, GO 95 requires that when sections of higher grade construction are located in lines of lower grade construction that the unbalanced longitudinal loads at each end support shall be equal to the pull of all conductors in the direction of the higher grade. The loads to be resisted are:

> 'For spans not exceeding 500 ft in length, where the pull in the direction of the higher grade section exceeds 30,000 lb., the loading requirements may be modified to consider 30,000 lb. plus one-fourth the excess above 30,000 lb., to a maximum of 50,000 lb.. The construction of the end supports (including poles, structures, towers, cross-arms, pins, insulators, conductor fastenings, and guys) of such sections shall be such as to withstand at all times the load specified with a safety factor at least equal to unity.'

Additionally, the GO 95 longitudinal load requirements address the loads acting on end supports of Grade A and B construction in lines of the same grade. These loads are:

> 'In Grades A or B construction the longitudinal load on each end support of crossings, conflicts or joint use, where located in lines of the same grade of construction, shall be taken as the unbalanced load equal to the tension of one-third of the total number of conductors (not including overhead ground wires), such one-third of the conductors being so selected as to produce the maximum stress in the supports.'

GO 95 does not address longitudinal loads as a result of extreme events such as broken insulators, conductors, or shield wires. However, there are a number of requirements in GO 95 applicable to Class E circuit support structures (i.e., 300-kV and above) that address the minimum longitudinal strength indirectly. Specifically, GO 95 requires that longitudinal guying shall be used unless the longitudinal strength of such a support structure equals the transverse strength. Furthermore, GO 95 addresses failure containment by requiring the line as a whole to be designed so that a failure of an individual support structure does not cause successive failures of more than ten additional support structures.

Similar to the NESC, GO 95 does not provide any guidance on how to determine the magnitude of these extreme event loads at successive structures away from the initiating event nor indicates the required longitudinal strength to contain the failure. Again, the responsibility lies with the line designer to establish a rational approach to define the magnitude of the extreme event longitudinal loads and to identify an appropriate level of containment strength.

2.3 American Society of Civil Engineers (ASCE) Recommendations

The purpose of the 1991 edition of the ASCE Manual 74 'Guidelines for Electrical Transmission Line Structural Loading' (6) is to present detailed guidelines and procedures to develop the structural loads acting on transmission lines. ASCE Manual 74 recognizes that alternative methods to develop the loads not presented in the document are acceptable wherever such alternatives have been established based on many years of successful operation.

ASCE Manual 74 (Section 3) addresses special loads such as unbalanced longitudinal loads caused by inequalities of wind and/or ice on adjacent spans and loads resulting from wire breakage or structural failures. The Manual suggests that the risk of cascading of transmission line structures can be reduced by one of three methods. These methods are:

> <u>Design All Structures for Broken Wire Loads:</u> Apply the residual static load (RSL) to a nominal one-third of the conductor support points or to one (or both) ground wire support point(s). These RSLs are to be applied in one direction only along with 50 percent or more of the wire vertical loads with no wind. Utilities in areas of known severe icing should consider an RSL at some iced condition.
>
> <u>Install Stop Structures at Specified Intervals:</u> Create stop or anchor structures at intervals along the line so that a cascading failure will be limited to the interval between the special structures. These special structures may often be ordinary suspension structures with extra longitudinal guys at sites where local conditions of soil or land use readily permit the installation.
>
> <u>Install Release Mechanisms:</u> Slip or release type suspension clamps can be used as fuses to limit the longitudinal loads that can be applied by the wires. The design of the slip or release mechanism must ensure consistent operation in any environmental condition.

Additionally, the ASCE Manual provides supplemental information on longitudinal loads resulting from stringing and broken wires while commenting on strength requirements to achieve failure containment. The manual concludes that successful containment of extreme event longitudinal loads requires the ability to reduce dynamic energy along the line through the successive failures of support structures. It stipulates that if the third structure away from the initiating event does not fail, there will be no cascade. Therefore, the manual concludes, that the important problem of failure containment reduces to that of determining the longitudinal static strength required at the third structure away from the failure after the failure of the first and second structure.

3

CASCADING FAILURE RISK ASSESSMENT (CASE)

The simplified CASE method was developed based on analytical and experimental studies (2, and 7 through 16) and predicts the magnitude of extreme event longitudinal loads caused by wire, hardware, or structural failures. Extreme event longitudinal loads are calculated readily at any structure along the direction of the transmission line. The magnitude of the extreme event longitudinal load is a function of the energy dissipating characteristics of the line, the load case to be investigated, the failure mode to be considered, and the number of structures permitted to fail to achieve failure containment. A more detailed description of the background and development of the simplified CASE method can be found in Volumes II, III, and IV (7, 8, and 9) due in 1997. Simplified CASE application examples are provided in Appendix A, B, and C.

3.1 Load Cases

The magnitude of the extreme event loads calculated using the CASE method strongly depends on the load case assumed to govern at the time of failure. Consequently, it is important to perform the CASE assessment for all load cases that are likely to exist at the time of failure. Load cases recommended to be considered in the CASE assessment include but are not limited to the everyday service load, cold temperature load (No Ice), NESC load, extreme wind load, and extreme ice load.

3.1.1 Service Loading

The service load (SL) condition addressed in this report constitutes everyday wire tension and sag at an ambient temperature of 60°F (no wind, no ice). The service load case constitutes the conditions present on the line for the majority of the time. Utilities should choose conditions for the service load case based on past experience or special local conditions for their service area.

3.1.2 Cold Temperature Loading

The cold temperature (CT) load condition addressed in this report constitutes wire tension and sag at an ambient temperature of 15°F with a 10 mph wind (no ice). The cold temperature load case simulates the conditions present on the line during the winter months. The cold temperature load case conditions are likely to be present on the line for extended periods of time. Again, utilities should choose conditions for the cold temperature load case based on past experience or special local conditions in their area.

3.1.3 NESC Loading

The NESC load case constitutes wire tension and sag at ambient temperatures ranging from 0 to 30°F, wind pressures ranging from 4 to 9 lb./ft^2 (psf), and radial ice deposits ranging from 0 to 0.5 inches. The NESC load case simulates the conditions present on the line during a severe winter storm or high wind event. Consequently, NESC load case conditions are likely to occur a small percentage of the year ranging anywhere from a few hours to a few days. Utilities may choose more stringent conditions than the applicable NESC load case based on past experience or special local conditions but it is suggested that the relevant NESC condition also be checked.

3.1.4 Extreme Wind Loading

The NESC extreme wind (EW) load case constitutes wire tension and sag at ambient temperatures of 60°F with wind speeds ranging from 70 to 110 mph (no ice). The NESC extreme wind load case simulates the conditions present on the line during a severe storm event with a 50 year return period. Utilities may choose more stringent conditions than the applicable NESC load case based on past experience or special local conditions.

3.1.5 Extreme Ice Loading

The extreme ice load (EI) condition addressed in this report constitutes wire tension and sag at an ambient temperature of 15°F with wind speeds equal to 40% of extreme wind speeds and 1.0 inch radial ice (ASCE Zone 3 Ice Loads). The extreme ice load case simulates the conditions present on the line during an extreme winter storm with a 50 year return period. The utility may choose different conditions for the extreme ice load case based on past experience or special local conditions based on their service area. Obviously, this criteria is not required in areas without icing events.

3.2 Limit States

Four distinctly different failure modes (Limit States) are considered in a CASE assessment. These limit states are ‘Broken Insulator’, ‘Broken Shield Wire’, ‘Broken Conductor’, and ‘Broken Structure’. A limit state defines acceptable or unacceptable structural behavior. Limit states are normally classified into three categories of serviceability, damage, and failure limit states. Damage and failure limit states include any type of partial or complete failures. Limit states included in the assessment are really representations of the dynamic response characteristics of the transmission line and do not focus on the failure of specific components. Consequently, the 'Broken Insulator' failure mode simulates the dynamic response of the system as a result of a broken insulator, broken support hardware such as clevisses or pins, and structural failures of support arms.

3.2.1 Broken Insulator

The 'Broken Insulator' (BI) limit state is included in the CASE assessment to evaluate the transmission line's response to an insulator failure at a suspension or light angle structure, failure of support hardware such as a clevis or pin, or failure of a structural component such as a cross-arm. In this limit state it is assumed that the previously supported shield wire or conductor remains intact. The 'Broken Insulator' limit state is representative of any failure of a component subjected to predominantly vertical loads prior to the initiating event.

3.2.2 Broken Shield Wire

The 'Broken Shield Wire' (BSW) limit state is included in each CASE assessment to evaluate a transmission line's response to a shield wire failure, failure of shield wire splice or dead end attachment hardware, or failure of a structural component such as a shield wire peak on an angle structure or dead end. The 'Broken Shield Wire' limit state is representative of any failure of a component that supports the shield wire subjected to predominantly longitudinal loads prior to the initiating event.

3.2.3 Broken Conductor

The 'Broken Conductor' (BC) limit state is included in the CASE assessment to evaluate a transmission line's response to a conductor failure, failure of a conductor splice or dead end attachment hardware, or failure of a structural component such as a cross arm on an angle structure or dead end. The 'Broken Conductor' limit state is representative of any failure of a conductor component that supports the conductor subjected to predominantly longitudinal loads prior to the initiating event.

3.2.4 Broken Structure

The 'Broken Structure' (BS) limit state is included in the CASE assessment to evaluate a transmission line's response to a 'Worst Case' loading scenario in which all shield and conductor wires are assumed to be severed at the same time or in which an angle or dead end structure fails. Representative failures for a 'Broken Structure' event may be caused by either the complete loss of any structure particularly an angle or dead end, the loss of all wires due to an aircraft, or the action of a tornado on individual structures.

3.3 Component Strengths

A transmission line is an integrated system consisting of shield wires, conductors, insulators, and support structures. In order to assess the cascading potential of such a system it is necessary to determine if and when the support structure fails. Failure of the support structure can occur as a result of excessive bending stresses, shear stresses, and axial tension or compression stresses. The ultimate load capacity of the structure is limited to the smaller of the three critical stresses.

The ultimate moment capacity, the ultimate shear capacity, and the ultimate axial load capacity of the support structure are required for the CASE assessment. The ultimate moment capacity (M_u) is defined as the maximum moment that the support structure can resist while supporting all vertically applied loads. The ultimate shear capacity (V_u) is defined as the maximum shear that the support structure can resist while supporting all vertically applied loads. The ultimate axial load capacity (P_u) is defined as the maximum axial load that the support structure can resist. The ultimate moment, shear, and axial capacity should be calculated based on ultimate tension or compression stresses using a strength reduction factor of unity.

3.4 Longitudinal Load Factors

Longitudinal load factors can be calculated for each combination of load case and limit state at each structure next to and removed from the initiating event. The magnitude of the longitudinal load factors depends on the span/sag and span/insulator ratio of the shield wire or conductor, the load case, the limit state, the structural flexibility of the supports, and the acceptable number of failed structures allowed to achieve containment. Longitudinal load factors are then multiplied by the horizontal wire tension prior to the initiating event to calculate the unbalanced longitudinal load acting on the chosen containment structure.

3.4.1 Span/Sag Ratio

The span/sag ratio (S/S) is the most critical parameter in the determination of the longitudinal load factor (LLF) and greatly influences the magnitude (i.e., 0 to 60%) of the unbalanced longitudinal load. The span/sag ratio is defined as the ratio of the span length to the sag. Sags of the shield wire or conductor should be calculated based on all of the loads acting on the wires at the applicable ambient temperature. Sags can be calculated using either the parabolic or hyperbolic formulation for a catenary wire.

3.4.2 Span/Insulator Ratio

The span/insulator ratio (S/I) has a noticeable effect (i.e., 0 to 15%) on the magnitude of the longitudinal load factor. The span/insulator ratio is defined as the ratio of span length to either I-string or V-string suspension insulator length.

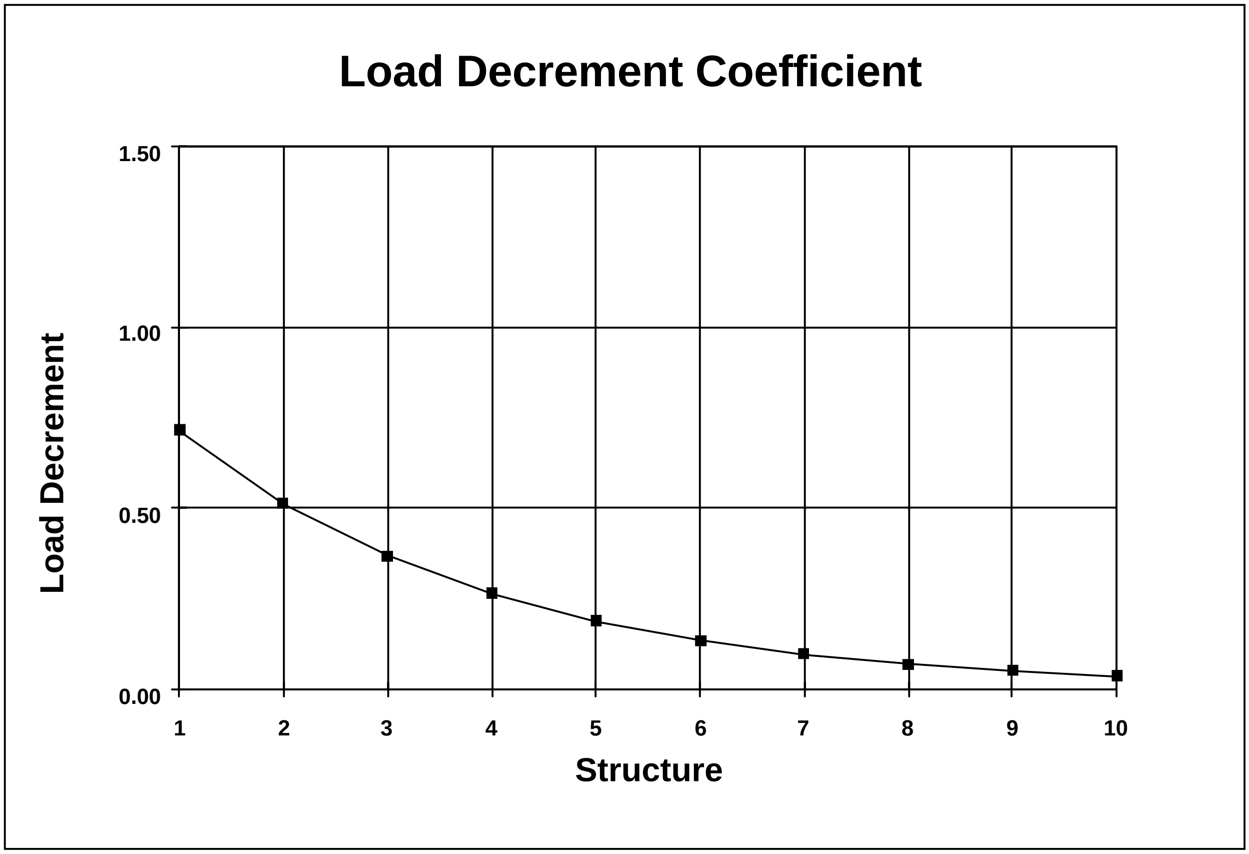

Figure 3-1
Load Decrement Coefficient

3.4.3 Load Decrement Coefficient

The load decrement coefficient (δ_N) is a function of the damping of the peak load amplitudes from one structure to the next along the direction of a transmission line. Figure 3-1 shows the variation of the load decrement as a function of the number of structures away from the initiating event. The load decrement coefficient for each structure away from the initial trigger event is independent of the number of structures that may fail to achieve containment. The load decrement coefficients are used to determine the response coefficients of each structure and can be calculated as:

$$\delta_N = e^{-(N/3)} \quad \text{(eq. 3-1)}$$

δ_N - Logarithmic Decrement

N - N_{th} Structure from Initiating Event (N = 1, 2, 3, ...)

The load decrement coefficient at each structure is proportional to the amount of energy transferred from the N_{th} structure to the N_{th}+1 structure along the transmission line counting from the initial failure. The amount of energy transferred decreases exponentially as the distance from the initial failure increases.

3.4.4 Response Coefficient

The response coefficient (Y_N) is a function of the logarithmic decrement. The response coefficient for the first structure away from the initiating event is constant (Y_0). Response coefficients are required to determine the longitudinal load factor on each support structure. The response coefficients for each structure equal:

$$Y_1 = Y_0 \quad \text{(eq. 3-2)}$$

$$Y_N = \frac{Y_0}{\left(e^{\delta_{N-1}}\right)!} \quad \text{(eq. 3-3)}$$

Y_0 - Response Amplification Constant (Y_0 = 100)

Y_N - Response Coefficient for N_{th} Structure

δ_{N-1} - Logarithmic Decrement

N - N_{th} Structure from Initiating Event (N = 2, 3, 4, ...)

Figure 3-2 shows the variation of the response coefficients as a function of the number of structures away from the initiating event. The response coefficient decreases rapidly for the first four structures; only negligible changes are realized for additional structures.

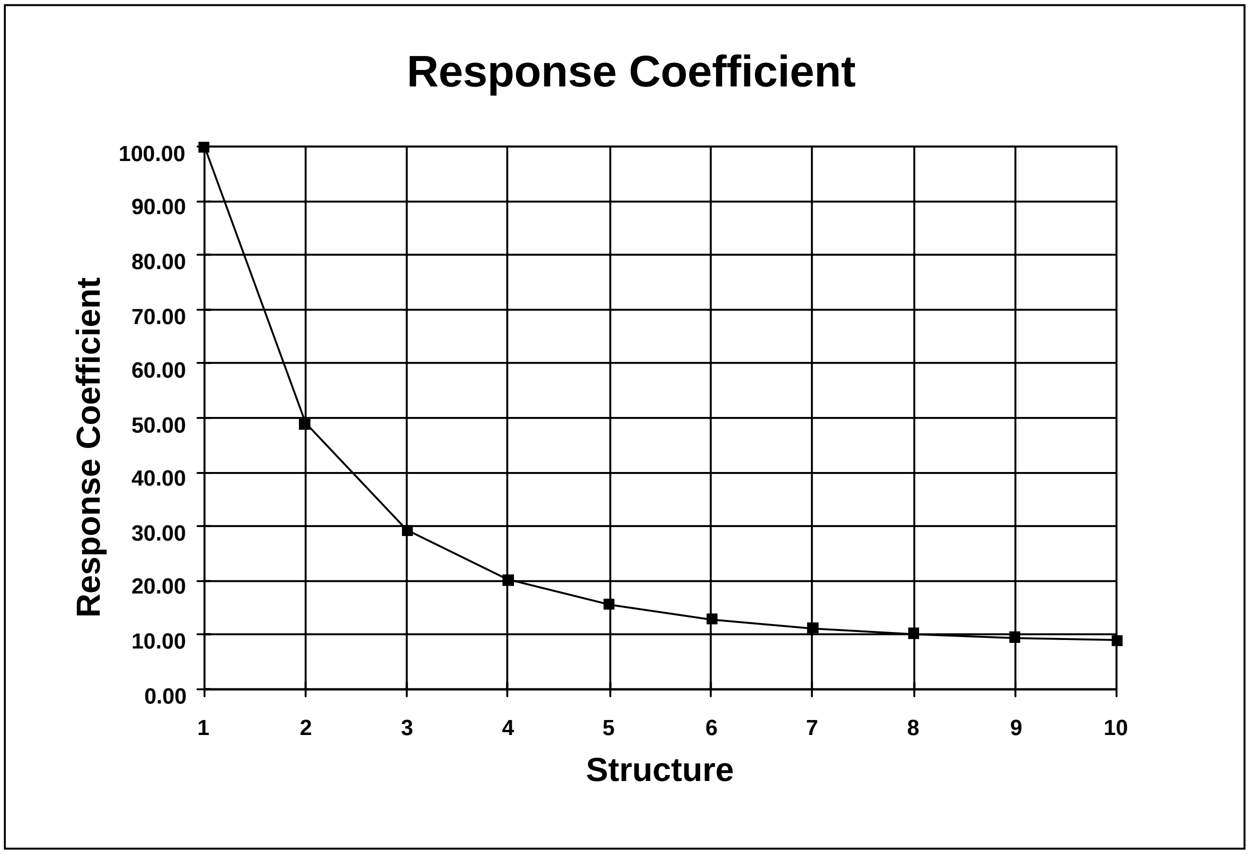

Figure 3-2
Load Response Coefficient

3.4.5 Longitudinal Load Factor

The longitudinal load factor (LLF) is a function of the response coefficient and the span/sag ratio. For a particular support structure the LLF decreases as the span/sag ratio increases. Additionally, the LLF decreases as the number of structures from the initiating event increases. LLFs are required to determine the unbalanced longitudinal load at each support structure. The LLFs at each structure equal:

$$(LLF)_N = \sqrt{\frac{Y_N}{\left(S/S\right)_N}} \qquad \text{(eq. 3-4)}$$

$(LLF)_N$ - Longitudinal Load Factor for N_{th} Structure

Y_N - Response Coefficient for N_{th} Structure

$(S/S)_N$ - Span/Sag Ratio for N_{th} Structure

N - N_{th} Structure from Initiating Event (N = 1, 2, 3, ...)

Figure 3-3 shows the variation of the longitudinal load factors as a function of the span/sag ratio and the number of structures away from the initiating event. The longitudinal load factors decrease rapidly for the first five structures (LLF_1 through LLF_5); only small changes in the longitudinal load factor are realized for additional structures. As the number of structures away from the initial failure increases further, changes in the longitudinal load factor become negligible and the values approach a limiting value.

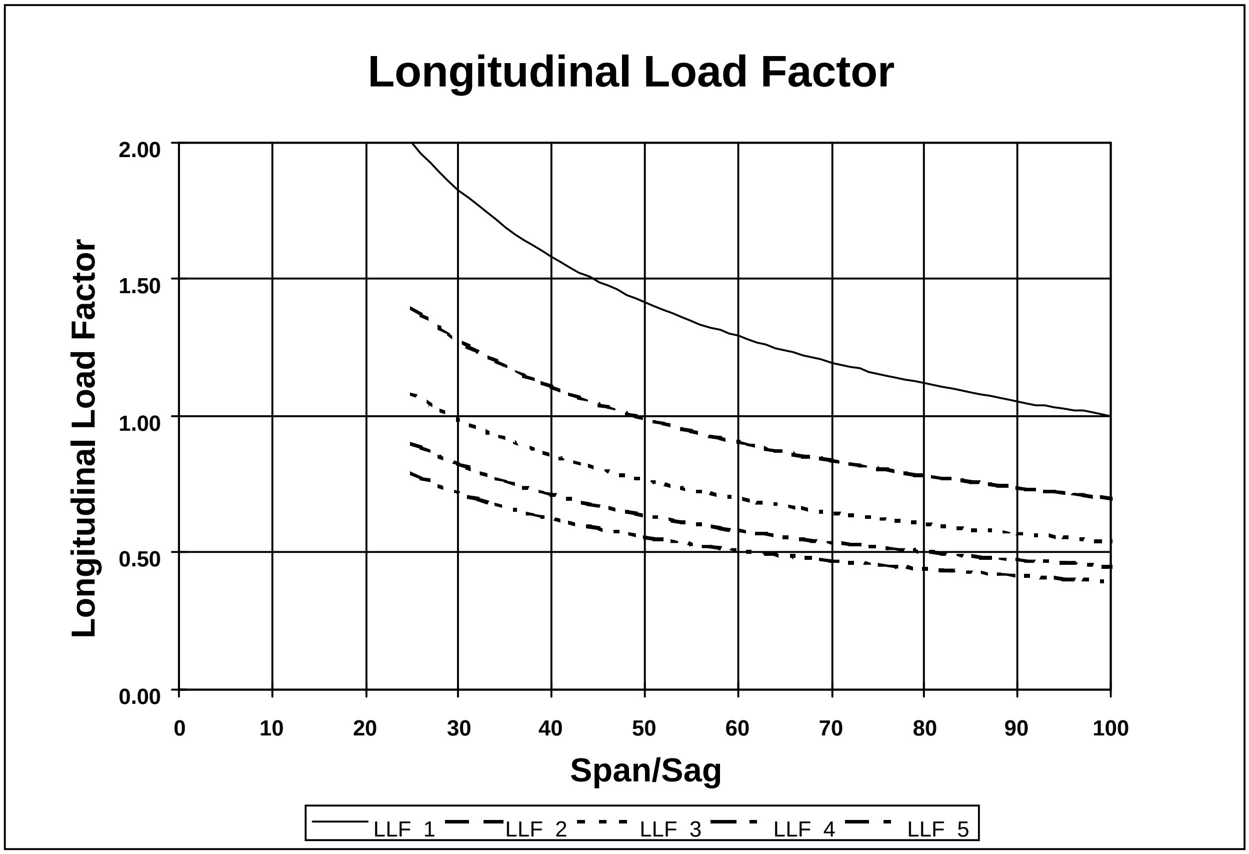

Figure 3-3
Longitudinal Load Factor

3.4.6 Span/Insulator Correction Factor

A correction may be made to the longitudinal load factor to account for the effect of the span/insulator ratio. The span/insulator ratio correction should only be used for I-string and V-string suspension insulators; post insulators and dead end insulator arrangements should not be corrected. The span/insulator ratio correction should not be made for shield wires. The S/I correction factor equals:

$$(CF_{S/I})_N = 1 \qquad \text{(Shield Wire)} \quad \text{(eq. 3-5)}$$

$$(CF_{S/I})_N = \left(1 - \frac{\left(S/I\right)_N}{2000}\right) \qquad \text{(Conductor)} \quad \text{(eq. 3-6)}$$

$(CF_{S/I})_N$ - Span/Insulator Correction Factor for N_{th} Structure

$(S/I)_N$ - Span/Insulator Ratio for N_{th} Structure ($(S/I)_{Max}$<500)

N - N_{th} Structure from Initiating Event (N = 1, 2, 3, ...)

Figure 3-4 shows the variation of the $(CF_{S/I})_N$ as a function of the span/insulator ratio. The $(CF_{S/I})_N$ equals 1.0 for a span/insulator ratio of 0.0 and the value of the $(CF_{S/I})_N$ decreases linearly to 0.75 for a span/insulator ratio of 500.

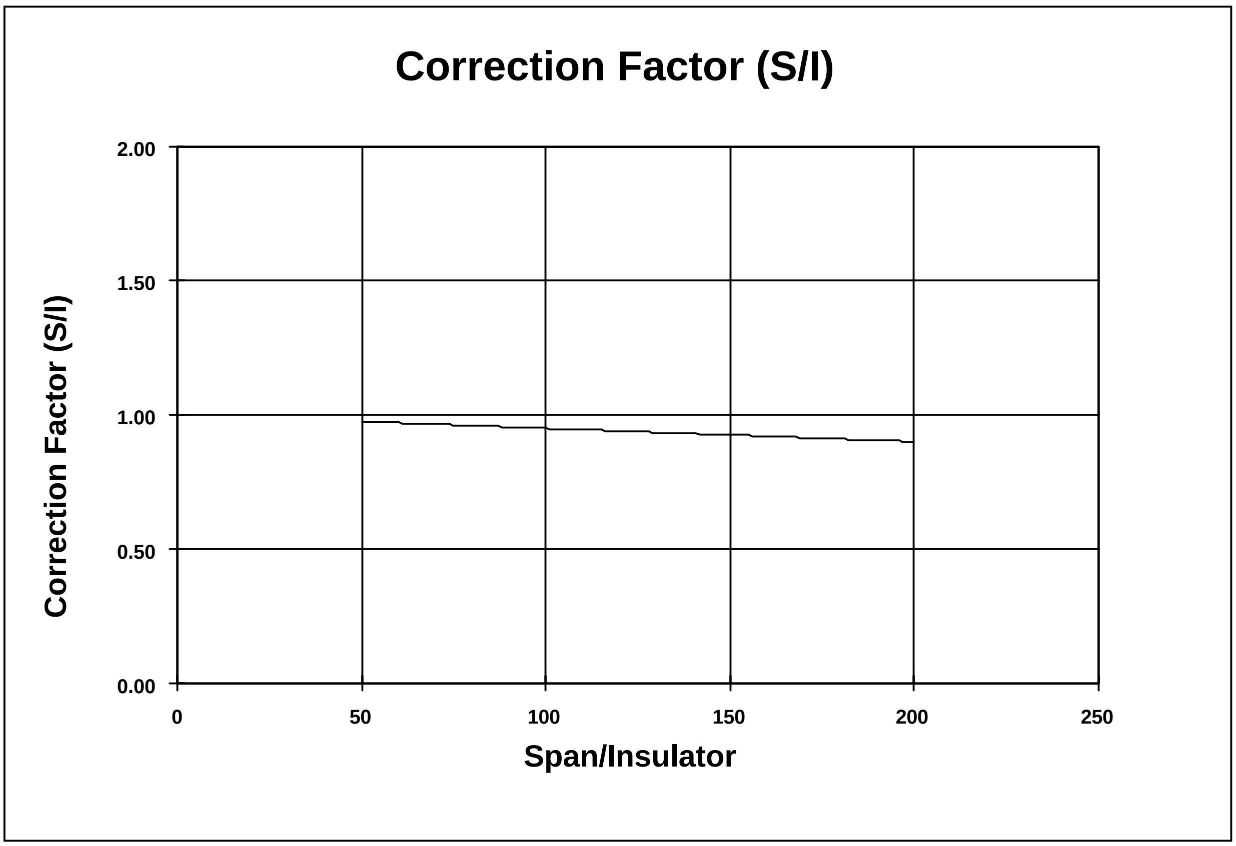

Figure 3-4
Correction Factor for Span/Insulator Ratio

3.4.7 Structural Flexibility Correction Factor

A correction may be made to the longitudinal load factor to account for the effect of the structural flexibility of the supports. The structural flexibility used in the calculation of the correction factor is calculated at the centroid of the shield wires and electrical conductors. The structural flexibility of a transmission structure is either determined by hand calculations or by using a finite element analysis program. Regardless of the analysis method, a unit load in the direction of the line is applied to the centroid of the shield wires and conductors to determine the corresponding displacement at that position. The structural flexibility of the structure is then calculated by dividing the displacement of the centroid in the longitudinal direction by the applied unit load. The magnitude of the applied unit load is arbitrary but should be selected in such a manner that the structure is stressed within the elastic range.

Structural flexibilities for most transmission structures range from 1 in/kip for heavy angle or lattice dead end structures to 75 in/kip for thin-walled tangent steel poles. Free-standing heavy angle and dead end lattice towers have structural flexibilities ranging from 1 in/kip to 6 in/kip; medium angle lattice structures range from 3 in/kip to 9 in/kip while light angle and tangent lattice structures have flexibilities ranging from 6 in/kip to 12 in/kip. Guyed lattice towers (excluding Chainettes) can be very stiff and flexibilities can be equivalent to values observed for free-standing dead end lattice structures.

Free-standing heavy angle and dead end steel poles and wood h-frames have structural flexibilities ranging from 0.5 in/kip to 6 in/kip; medium angle steel poles and wood h-frames range from 2 in/kip to 24 in/kip while light angle and tangent steel poles and wood h-frames have flexibilities ranging from 12 in/kip to 60 in/kip. Similar to lattice structures, guyed steel poles and wood h-frames are very stiff and flexibilities are typically equivalent to values observed for free-standing dead end structures.

The structural flexibility correction factor ranges from 1.0 for heavy angle and dead end lattice or steel pole structures to 0.7 for extremely flexible tangent steel poles. The structural flexibility correction factor equals:

$$(CF_{1/K})_N = e^{-\left((1/K)_N / 200\right)} \qquad \text{(eq. 3-7)}$$

$(CF_{1/K})_N$ - Structural Flexibility Correction Factor for N_{th} Structure

$(1/K)_N$ - Structural Flexibility of N_{th} Structure (in/kip)

N - N_{th} Structure from Initiating Event (N = 1, 2, 3, ...)

Figure 3-5 shows the variation of the $(CF_{1/K})_N$ as a function of the structural flexibility of the wire supports. The $(CF_{1/K})_N$ equals 1.0 for a structural flexibility of 0.0 in/kip and the value of the $(CF_{1/K})_N$ decreases exponentially to 0.36 for a structural flexibility of 200 in/kip. $(CF_{1/K})_N$ factors of less than 0.7 are rarely justified and should be verified.

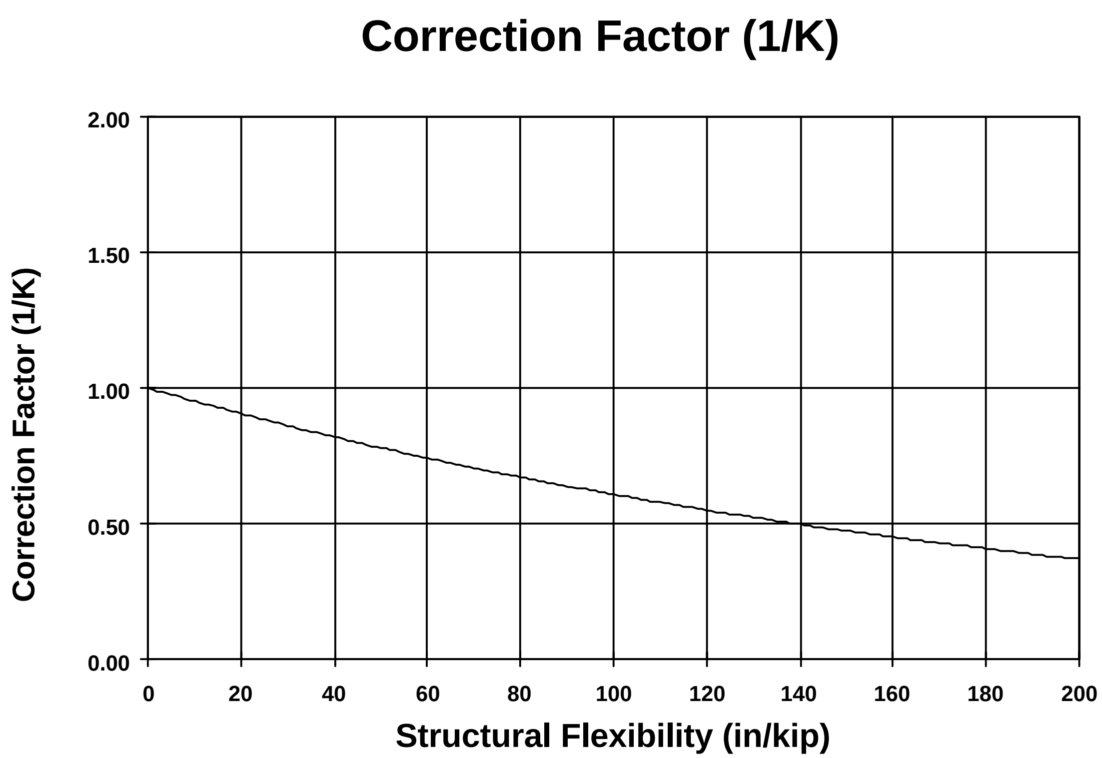

Figure 3-5
Correction Factor for Support Structure Flexibility

3.5 Unbalanced Longitudinal Loads

Unbalanced longitudinal loads (H_{UL}) are calculated as a function of the initial horizontal tension and the applicable longitudinal load factor for each load case and limit state. The calculated H_{UL} is the unbalanced horizontal tension acting on the support structure in the direction away from the initiating failure event. The effects of the calculated H_{UL} on the support structure should be considered to act concurrently with the effects of any permanently applied load imbalance. It is recommended that the calculated H_{UL} be applied to any one, or preferably to one-third, of all wire support points of a single circuit transmission line. For a double circuit line with two shield wires it is recommended to apply the calculated H_{UL} to any two conductor phases, two shield wire supports, or one conductor phase and shield wire support. Phases consisting of bundled conductors are treated similarly to single conductor phases and it is assumed that all of the wires in a bundle fail simultaneously.

The unbalanced longitudinal load H_{UL} is a function of the load case, the limit state, the type of wire (i.e., conductor or shield wire), and the horizontal tension in the wire prior to the initiating failure event. The H_{UL} for a specific load case and limit state at the Nth structure away from the initial failure equals:

$$\left[(H_{UL})_{LS}^{LC}\right]_N = \left[(H)_{LS}^{LC}\right]_N \cdot \left[(LLF)_{LS}^{LC}\right]_N \cdot \left(CF_{S/I}\right)_N \cdot \left(CF_{1/K}\right)_N \qquad \text{(eq. 3-8)}$$

$(H_{UL})_N$ - Unbalanced Longitudinal Load at N_{th} Structure

$(H)_N$ - Horizontal Tension at N_{th} Structure

$(LLF)_N$ - Longitudinal Load Factor for N_{th} Structure

$(CF_{S/I})_N$ -Span/Insulator Correction Factor for N_{th} Structure

$(CF_{1/K})_N$ -Structural Flexibility Correction Factor for N_{th} Structure

N - N_{th} Structure from Initiating Event (N = 1, 2, 3, ...)

LC - Load Case (LC = SL, CT, NESC, EW, EI)

LS - Limit State (LS = BI, BC, BSW, BS)

The complete evaluation of the equation for all relevant load cases and limit states produces a matrix of unbalanced longitudinal loads for the N_{th} structure away from the initiating failure event. Similar matrices can be developed for the $N\text{-}1_{th}$ and the $N\text{+}1_{th}$ structure away from the initial failure. Each entry in the matrix constitutes the unbalanced longitudinal load for a specific load case and limit state. The unbalanced longitudinal load matrix $[H_{UL}]_N$ for the N_{th} structure from the initiating failure event is:

$$[H_{UL}]_N = \begin{bmatrix} (H_{UL})_{BI}^{SL} & (H_{UL})_{BI}^{CT} & (H_{UL})_{BI}^{NESC} & (H_{UL})_{BI}^{EW} & (H_{UL})_{BI}^{EI} \\ (H_{UL})_{BC}^{SL} & (H_{UL})_{BC}^{CT} & (H_{UL})_{BC}^{NESC} & (H_{UL})_{BC}^{EW} & (H_{UL})_{BC}^{EI} \\ (H_{UL})_{BSW}^{SL} & (H_{UL})_{BSW}^{CT} & (H_{UL})_{BSW}^{NESC} & (H_{UL})_{BSW}^{EW} & (H_{UL})_{BSW}^{EI} \\ (H_{UL})_{BS}^{SL} & (H_{UL})_{BS}^{CT} & (H_{UL})_{BS}^{NESC} & (H_{UL})_{BS}^{EW} & (H_{UL})_{BS}^{EI} \end{bmatrix}_N \qquad \text{(eq. 3-9)}$$

3.6 Evaluation of Cascading Potential

To evaluate the cascading potential of a transmission line it is necessary to identify the unbalanced longitudinal load(s) acting on each of the structures away from the initial failure to determine if the applied loads will cause a failure at any of the support structures. Consequently, it is important to determine if the first structure from the initiating event will fail. If the first structure from the initiating event does not fail, a cascade will not occur. If the first structure fails, the potential for a cascade is dependent on the performance of the second structure. The evaluation process is repeated for the next structure until no further failures occur.

Therefore, the evaluation of the cascading potential of a line reduces to the structural evaluation of the individual support structures subjected to the unbalanced longitudinal loads determined using the methods outlined in the previous sections. The goal of the evaluation is to identify the first structure in the line that is capable of resisting all unbalanced longitudinal loads without failure.

3.6.1 Identification of Critical Containment Structure

The first structure in the line that is capable to resist all unbalanced longitudinal loads without failure is defined as the critical containment structure. Depending on the structural characteristics, ultimate strengths, and unbalanced longitudinal loads the critical containment structure can be any structure along the line. However, if none of the structures along the line are capable of resisting the unbalanced longitudinal loads, a cascade is very likely to occur. To determine if containment will occur and to identify the containment boundaries it is necessary to identify the first structure from the initiating event at which the ultimate strengths of the supports exceed the effects of the unbalanced longitudinal loads. It is necessary to identify the structure at which:

$$[R_U]_N - \left[(F_{UL})_{LS}^{LC}\right]_N \geq \{0\} \qquad \text{(eq. 3-10)}$$

$[R_U]_N$ - Ultimate Axial Load, Shear Force, and Overturning Moment Resistance of N_{th} Structure

$[F_{UL}]_N$ - Unbalanced Axial Load, Shear Force, and Overturning Moment on N_{th} Structure for a Specific Load Case and Limit State

$[R_U]_N$ is a vector consisting of the ultimate component strength values discussed previously and $[F_{UL}]_N$ is a vector consisting of the corresponding parameters calculated based on the unbalanced longitudinal load determined for a specific load case and limit state. The individual components of these vectors are:

$$\left[\left(R_U\right)_{LS}^{LC}\right]_N = \begin{bmatrix} P_U \\ V_U \\ M_U \\ T_U \end{bmatrix}_N \quad \text{(eq. 3-11)}$$

$$\left[\left(F_{UL}\right)_{LS}^{LC}\right]_N = \begin{bmatrix} \left(P_{UL}\right)_{LS}^{LC} \\ \left(V_{UL}\right)_{LS}^{LC} \\ \left(M_{UL}\right)_{LS}^{LC} \\ \left(T_{UL}\right)_{LS}^{LC} \end{bmatrix}_N \quad \text{(eq. 3-12)}$$

If the purpose of the investigation is to assess the cascading potential of a transmission line upgrade or new line construction, it is required to define an appropriate level of containment in accordance with the utility's reliability targets. Factors that are typically taken into consideration in the definition of the containment boundaries are the importance of the line to the operation of the transmission grid, the number of replacement structures maintained in inventory, and the maximum downtime that a utility is willing to accept for a particular line in the event of a cascade.

Once acceptable containment boundaries have been defined (i.e., N is the index of the critical containment structure), it is necessary to calculate the expected unbalanced loads acting on the N_{th} structure. Next, the critical containment structure is analyzed and designed for each load case and limit state combination. An initiating failure event will not cause a cascade if the N_{th} structure is capable of resisting the calculated unbalanced loads. However, a cascading failure is very likely to occur if the N_{th} structure is not capable of resisting the calculated unbalanced loads.

3.6.2 Determination of Security Level

The security level (SL) of a transmission line is a function of the energy dissipating characteristics of the line, the load case, and the limit state. Similar to a reliability index, the security level provides a qualitative parameter that is indicative of the inherent resistance of a line to a cascading failure. A 'high' security level indicates a low probability that a cascading failure will occur while a 'low' security level indicates a high probability that a cascading failure will occur. Since security levels are a function of the load case and limit state, it may be acceptable to have a significantly lower security level for a load case with a very small probability of occurrence, while the security level should be significantly higher for a load case with a high probability of occurrence such as service loads.

The security level is defined as the logarithmic decrement of the critical force ratios at any two successive structures from the initial failure event. The critical force ratio $(CF)_N$ is defined as the maximum ratio of $[F_{UL}]_N$ (i.e., Strength Factor = 1.0) divided by $[R_U]_N$ with $(CF)_N$ ranging from zero to one. $(CF)_N$ can not exceed one since the structure is not capable of resisting loads in excess of its capacity. If $(CF)_N$, $(CF)_{N-1}$, and $(CF)_{N-2}$ all equal one, the security level of the transmission line is zero and the probability that a cascading failure occurs is extremely high. If $(CF)_N$, $(CF)_{N-1}$, and $(CF)_{N-2}$ are all less than one, the security level of the transmission line is a value between zero and one and the probability of a cascading failure is lower. The $(SL)_I$ for a specified containment boundary, load case, and limit state equals:

$$\left[(SL)_{LS}^{LC}\right]_I = \frac{1}{I-1} \cdot \sum_{N=1}^{I-1} \ln\left(\frac{\left((CF)_{LS}^{LC}\right)_N}{\left((CF)_{LS}^{LC}\right)_{N+1}}\right) \qquad \text{(eq. 3-13)}$$

$(CF)_N$ - Critical Force Ratio at N_{th} Structure (i.e., $[F_{UL}]_N / [R_U]_N$)

I - Critical Containment Structure (i.e., Critical Structure at which Cascade is to be Contained) (I = 2, 3, 4, ...)

N - N_{th} Structure from Initiating Event (N = 1, 2, 3, ...)

Similar to the case of the unbalanced longitudinal loads, the complete evaluation of the equation for all relevant limit states and load cases produces a matrix of security levels. Similar matrices can be developed for the $I\text{-}1_{th}$ and the $I\text{+}1_{th}$ structure away from the initial failure. Each entry in the matrix constitutes the security level for a specific limit state and load case. The security level matrix $[SL]_I$ for the I_{th} structure from the initiating failure event is:

$$[SL]_I = \begin{bmatrix} (SL)_{BI}^{SL} & (SL)_{BI}^{CT} & (SL)_{BI}^{NESC} & (SL)_{BI}^{EW} & (SL)_{BI}^{EI} \\ (SL)_{BC}^{SL} & (SL)_{BC}^{CT} & (SL)_{BC}^{NESC} & (SL)_{BC}^{EW} & (SL)_{BC}^{EI} \\ (SL)_{BSW}^{SL} & (SL)_{BSW}^{CT} & (SL)_{BSW}^{NESC} & (SL)_{BSW}^{EW} & (SL)_{BSW}^{EI} \\ (SL)_{BS}^{SL} & (SL)_{BS}^{CT} & (SL)_{BS}^{NESC} & (SL)_{BS}^{EW} & (SL)_{BS}^{EI} \end{bmatrix}_I \qquad \text{(eq. 3-14)}$$

3.6.3 Interpretation of Security Level

Security level matrices vary as a function of the containment boundaries, the load case being considered, and the limit state analyzed. For a given containment strategy (i.e., number of structures accepted to fail) it is quite obvious that the security level calculated for the most severe load case and limit state is lower than the security level calculated for the least severe load case and limit state. However, the probability of occurrence for the most severe load case and limit state combination is much lower than the probability for the least severe combination. Consequently, the evaluation of security levels should be performed with regard to utility experiences and/or meteorological data.

To evaluate specific security levels between zero and one it is necessary to identify a specific cutoff value that conclusively separates high risk from low risk transmission lines (relative to cascading at the specified conditions). However, the cascading potential of a steel pole line with a security level of 0.31 is not likely to be the same as the cascading potential of a wood frame line with the same security level. Essentially, the statistical variation of the ultimate strength of wood structures is significantly larger than the statistical variation of the ultimate strength of manufactured steel poles. For example, if the ultimate strength of a steel pole can be predicted with an accuracy of plus or minus ten percent, it is likely that the steel pole fails for critical force ratios between 0.9 to 1.0. Similarly, if the ultimate strength of a wood frame can be predicted with an accuracy of plus or minus thirty percent, it is likely that a wood frame failure occurs for critical force ratios between 0.7 to 1.0. Consequently, the security level cutoff value for a wood frame line is larger than the corresponding value for a steel pole line.

Based on EPRI test experience on over 100 different structures, the ultimate strength of a steel pole can be predicted with an accuracy of plus or minus ten percent, the ultimate strength of a lattice tower can be predicted with an accuracy of plus or minus fifteen percent, and the ultimate strength of a wood frame line can be predicted with an accuracy of plus or minus thirty percent. Consequently, the minimum security level required to avoid a cascading failure on a steel structure transmission line, a steel lattice structure line, or a wood structure line are 0.03, 0.04, or 0.08, respectively.

As a result of the uncertainties involved in the prediction of the ultimate strength of a transmission structure and the magnitude of the unbalanced longitudinal load it may be advantageous to define broader ranges of cascading risk to group transmission lines with similar cascading potential. For example, security level ranges of varying risks (i.e., 'Low', 'Medium', 'High', and 'Extreme') can be defined as a function of the support structure material and construction (i.e., 'Lattice', 'Tubular Steel', and 'Wood'). At the same time, group security level ranges are dependent on the size of the containment boundary. An example of such a broad based grouping of security levels based on containment of a cascade at the third structure is shown in Table 3-1.

Table 3-1
Cascading Potential Classification for Third Structure

Structure Type	Cascading Potential			
	'Low'	'Medium'	'High'	'Extreme'
Wood	.32-1.00	.16-.32	.08-.16	.00-.08
Tubular Steel	.12-1.00	.06-.12	.03-.06	.00-.03
Lattice	.16-1.00	.08-.16	.04-.08	.00-.04

4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusion

A cascading failure risk assessment method has been developed to quickly and accurately determine extreme event unbalanced loads acting on a transmission line and to identify the cascading potential of a line subjected to different loading conditions. While past investigations have focused on the magnitude of the unbalanced loads acting on the first structure from the initiating event, the CASE assessment method incorporates the dynamic response and damping characteristics of the transmission line to determine the unbalanced longitudinal loads at any structure away from the initiating failure event.

The primary advantage of the CASE method is that containment boundaries can be defined based on the importance of the transmission line to the operation of the utility's electric grid. This flexibility allows the CASE assessment method to predict the unbalanced longitudinal loads at any structure within the containment boundary and at the critical containment structure. Unbalanced longitudinal loads at each structure are predicted by taking into account the energy dissipated at each structure and span along the transmission line. The longitudinal strength of a specific transmission line can now be calibrated to match a utility's target reliability level for a minimum cost.

4.2 Recommendations

Once the cascading potential of a specific transmission line has been identified as extremely high, it becomes important to the transmission designer to mitigate the existing problem. While traditional mitigation techniques such as storm guys and stop structures have been used extensively in the past, right-of-way limitations and public opposition have made it increasingly difficult to employ such mitigation measures. At the same time, the effectiveness of storm guys and stop structures has been questioned based on past experiences. Consequently, it may be appropriate to develop energy dissipating mitigation devices for use on limited right-of-ways and in upgrade situations.

Currently, probability based methods which are commonly used to determine wind and ice load magnitudes and return periods are not available to predict longitudinal load magnitudes and return periods. Probability based return periods should be developed for standard longitudinal load cases and limit states to predict transmission service life capital cost more accurately. In addition, probability based return periods will make it possible to match system reliability levels with respect to longitudinal loads to system reliability levels for wind and ice loading.

5

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A

CASE ASSESSMENT OF A TUBULAR STEEL POLE

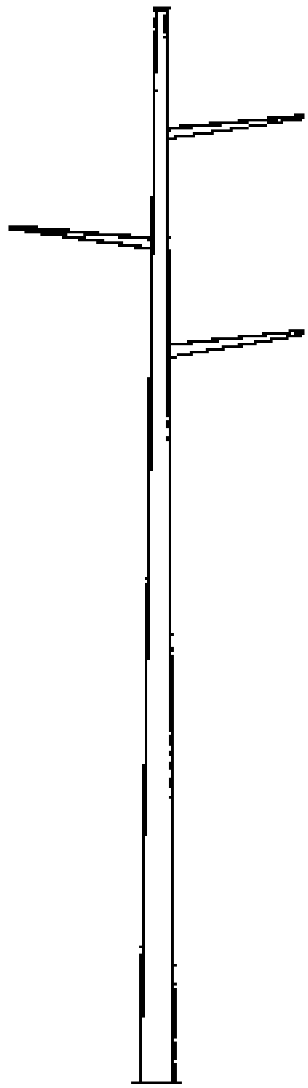

Table A-1
Input Parameters Required for CASE Assessment

Load Parameters		
Basic Wind Speed		70 mph
Basic Ice Thickness		1 inch
Average Daily Temperature		60°F
Extreme Wind Temperature		30°F
Extreme Ice Temperature		15°F

Wire Parameters		
Conductor:	795-kcmil ACSR 'Drake'	
	Diameter	1.108 inch
	Weight	1.094 lb./ft
	Rated Strength	31,500 lb.
Shield Wire:	3/8 Inch EHS Wire	
	Diameter	0.360 inch
	Weight	0.273 lb./ft
	Rated Strength	15,400 lb.
Sag/Tension:	Shield Wire	Table (A-2)
	Conductor	Table (A-3)
Insulators:	I-String	10 ft

Line Parameters		
Tangent Structure:	Front Span	1000 ft
	Back Span	1100 ft
	Horizontal Line Angle	0°
	Vertical Line Angle	0°

Structure Parameters		
Tangent Structure:	Dodecagonal (65 ksi)	
	Pole Top Diameter	8 inch
	Pole Bottom Diameter	18 inch
	Pole Length	105 ft
	Embedment Depth	12 ft
	Wall Thickness	0.1875 inch
	Structural Flexibility	50 in/kip

Some of the information required for a typical simplified CASE assessment is shown above. Additional information that is required are the structural flexibility of the tangent and dead end structures and the component strengths (i.e., ultimate moment,

shear, axial load, etc.). Structural flexibility and ultimate component strengths can be determined either by hand calculations or by a detailed structural analysis using a commercially available finite element program. The restraining effect of the wires (i.e., shield wires and conductors) on the structure should be neglected in the calculation of the structural flexibility and ultimate strength.

Table A-2
Sag-Tensions of 3/8 Inch EHS Shield Wire

3/8 - inch EHS Shield Wire

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
-30	0	0	0	0	None	8.53	4003	9.37	3645
-15	0	0	0	0	None	8.90	3838	9.79	3488
-15	1.0	0	0	0	None	30.35	8131	30.35	8131
30	0	12.5	0	0	None	14.58	3980	15.63	3715
0	0.5	4.0	0.3	0	None	24.14	6370	24.79	6205
15	0	0	0	0	None	9.70	3520	10.71	3188
30	0	0	0	0	None	10.14	3368	11.21	3047
45	0	0	0	0	None	10.60	3221	11.73	2911
60	0	0	0	20.0	Initial	11.09	3080	12.28	2782
75	0	0	0	0	None	11.60	2945	12.84	2659
90	0	0	0	0	None	12.13	2816	13.43	2543
105	0	0	0	0	None	12.68	2694	14.04	2434

Table A-3
Sag-Tensions of ACSR 'DRAKE' Conductor

795 - kcmil ACSR 'DRAKE'

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
-30	0	0	0	0	None	16.72	8192	19.98	6861
-15	0	0	0	0	None	17.52	7818	21.00	6528
-15	1.0	0	0	0	None	30.04	15535	30.04	15535
30	0	12.5	0	0	None	22.99	8673	26.01	7672
0	0.5	4.0	0.3	0	None	25.98	12115	27.44	11472
15	0	0	0	0	None	19.18	7143	23.01	5959
30	0	0	0	0	None	20.04	6840	24.00	5715
45	0	0	0	0	None	20.90	6559	24.97	5494
60	0	0	0	20.0	Initial	21.76	6300	25.93	5293
75	0	0	0	0	None	22.63	6060	26.87	5109
90	0	0	0	0	None	23.49	5839	27.79	4941
105	0	0	0	0	None	24.35	5634	28.57	4807

Sag and tension values for the conductor and shield wire are typically determined by means of an analysis program for a variety of temperature and loading conditions. Sags shown in Table A-2 and A-3 were determined with SAG/T for 20 % of UTS Final at temperatures ranging from -30 to 105 °F.

Table A-4
Critical Sag Values for CASE Assessment

Structure from Failure	Line Component	**Tangent Structure Sags**				
		SL Sag (ft)	CT Sag (ft)	NESC Sag (ft)	EW Sag (ft)	EI Sag (ft)
1 to 10	SW C	12.28 25.93	10.71 23.01	24.79 27.44	15.63 26.01	30.35 30.04

Table A-5
Critical Conductor and Shield Wire Tensions for CASE Assessment

Structure from Failure	Line Component	**Tangent Structure Tensions**				
		SL Tension (lb.)	CT Tension (lb.)	NESC Tension (lb.)	EW Tension (lb.)	EI Tension (lb.)
1 to 10	SW C	2782 5293	3188 5959	6205 11472	3715 7672	8131 15535

Table A-6
Critical Span/Sag Ratios for CASE Assessment

Structure from Failure	Line Component	**Tangent Structure Span/Sag Ratios**				
		(S/S) SL (ft)	(S/S) CT (ft)	(S/S) NESC (ft)	(S/S) EW (ft)	(S/S) EI (ft)
1 to 10	SW C	81.43 38.57	93.37 43.46	40.34 36.44	63.98 38.45	32.95 33.29

Critical sag values used in the CASE assessment for the conductor and shield wire are shown in Table A-4. Table A-5 shows a summary of the critical conductor and shield wire tensions used in the CASE assessment while Table A-6 summarizes calculated span/sag ratios. Critical sags and span/sag ratios for this particular example are identical at all ten structures because it was assumed that the span length is constant and that the horizontal and vertical line angles are zero (i.e., average span concept). Different assumptions may require the calculation of critical sags and span/sag ratios at each structure to accurately predict the unbalanced longitudinal loads at each structure from the initiating failure event. Similarly, structural flexibilities may have to be calculated at each structure to include the effects of varying support elevations.

Table A-7
Longitudinal Load Factors

Structure from Failure	Line Component	Tangent Structure Longitudinal Load Factors				
		LLF SL	LLF CT	LLF NESC	LLF EW	LLF EI
1	SW	1.11	1.03	1.57	1.25	1.74
	C	1.61	1.52	1.66	1.61	1.73
2	SW	0.77	0.72	1.10	0.87	1.22
	C	1.13	1.06	1.16	1.13	1.21
3	SW	0.60	0.56	0.85	0.68	0.94
	C	0.87	0.82	0.90	0.87	0.94
4	SW	0.50	0.47	0.71	0.56	0.78
	C	0.72	0.68	0.75	0.73	0.78
5	SW	0.44	0.41	0.62	0.49	0.69
	C	0.63	0.60	0.65	0.64	0.68
6	SW	0.40	0.37	0.56	0.45	0.62
	C	0.58	0.54	0.59	0.58	0.62
7	SW	0.37	0.35	0.53	0.42	0.58
	C	0.54	0.51	0.56	0.54	0.58
8	SW	0.35	0.33	0.50	0.40	0.56
	C	0.51	0.48	0.53	0.52	0.55
9	SW	0.34	0.32	0.49	0.39	0.54
	C	0.50	0.47	0.51	0.50	0.53
10	SW	0.33	0.31	0.47	0.38	0.52
	C	0.48	0.46	0.50	0.49	0.52

Longitudinal load factors are calculated at each structure from the initiating event. Table A-7 shows a summary of all longitudinal load factors as a function of the load case and distance (i.e., Number of Structures) from the initiating event for the conductor and shield wire. Considering the data summarized in the table it is possible to see the reduction in the magnitude of the longitudinal load factor from one structure to the next. Based on the data it is easily recognized that the largest reduction in the longitudinal load factors occurs within the first 5 structures while only small reductions in the load factors are realized at any subsequent structure.

Longitudinal load factors increase as the mass per unit length of the conductor or shield wire increases because of a decreasing span/sag ratio. Therefore, longitudinal load factors for the NESC load case (i.e., 0.5 inch Radial Ice) or the Extreme Ice load case (i.e., 1.0 inch Radial Ice) are significantly larger than load factors for the other load cases at comparable temperatures.

Longitudinal load factors increase slightly as the temperature of the conductor or shield wire increases because of small changes in the span/sag ratio. Table A-7 shows that large changes in the temperature of the conductor or shield wire cause only small changes in the magnitude of the longitudinal load factors regardless of the distance (i.e., Number of Structures) of the structure from the initial failure.

Unbalanced longitudinal loads are shown in Table A-8 for all four limit states and five load cases. For example, the unbalanced longitudinal loads acting on the fifth structure away from the initiating failure event at service loads are 2262 lb., 947 lb., 2486 lb., and 9352 lb. for the broken insulator, broken shield wire, broken conductor, and broken structure limit state. Similarly, the unbalanced longitudinal loads are shown for the first through fourth structure and the sixth through tenth structure away from the initiating event. Essentially, if a cascading failure is to be arrested within five structures, each tangent structure should be able to resist the forces acting on the fifth structure.

Unbalanced longitudinal loads shown in Table A-8 can be used to assess the required longitudinal load strength in an upgrading situation or new construction. For example, if the failure of two structures is acceptable in the event of a single shield wire or conductor breakage at service loads, the minimum longitudinal strength to be provided is 1298 lb. and 3409 lb. for the shield wire and conductor, respectively. Similarly, the minimum longitudinal strength to be provided in the event of a single shield wire or conductor breakage at extreme ice loads is 5964 lb. and 10770 lb., respectively. The significantly higher loads are a result of the increased mass of the wire with the ice attached and the resulting changes in the span/sag ratio and initial tension. The worst case scenario (i.e., loss of a complete structure at extreme ice loads) indicates that the third structure away from the initiating event has to resist an unbalanced longitudinal load of 5964 lb. (i.e., assuming 1 shield wire) and three times 10770 lb. (i.e., single circuit configuration) to avoid a cascading failure.

While, the combination of extreme ice loads coupled with the loss of a structure (or all phases) occurs infrequently in most areas this combination may be critical in other areas. Although either service loads or cold temperature loading are likely to be present nearly all the time, the worst case scenario of extreme ice coupled with a structural failure may occur only once every 50 years (however, typically with devastating results). Utility experience and specialized weather conditions are likely to have some influence on the probability that will be associated with each load case - failure mode combination.

Table A-8
Unbalanced Longitudinal Loads for All Limit States

Structure Number	Limit State	Tangent Structure Unbalanced Longitudinal Loads				
		UL SL (lb.)	UL CT (lb.)	UL NESC (lb.)	UL EW (lb.)	UL EI (lb.)
1	BI	4407	4674	9826	6398	13923
	BSW	2401	2569	7609	3617	11032
	BC	6306	6688	14060	9154	19921
	BS	23720	25202	57397	34697	81827
2	BI	3409	3616	7602	4949	10770
	BSW	1678	1796	5318	2528	7710
	BC	4407	4674	9826	6398	13923
	BS	16578	17614	40114	24250	57188
3	BI	2837	3008	6324	4118	8961
	BSW	1298	1389	4114	1956	5964
	BC	3409	3616	7602	4949	10770
	BS	12824	13626	31032	18759	44240
4	BI	2486	2637	5543	3609	7854
	BSW	1080	1156	3422	1627	4962
	BC	2837	3008	6324	4118	8961
	BS	10670	11336	25818	15607	36807
5	BI	2262	2399	5044	3284	7147
	BSW	947	1013	3000	1426	4350
	BC	2486	2637	5543	3609	7854
	BS	9352	9937	22630	13680	32262
6	BI	2114	2242	4714	3069	6679
	BSW	861	922	2730	1298	3958
	BC	2262	2399	5044	3284	7147
	BS	8509	9041	20591	12447	29355
7	BI	2014	2136	4491	2924	6363
	BSW	805	861	2551	1213	3699
	BC	2114	2242	4714	3069	6679
	BS	7953	8450	19243	11633	27434
8	BI	1945	2063	4337	2824	6146
	BSW	767	821	2430	1155	3524
	BC	2014	2136	4491	2924	6363
	BS	7576	8050	18333	11082	26136
9	BI	1898	2012	4231	2755	5994
	BSW	741	793	2347	1116	3403
	BC	1945	2063	4337	2824	6146
	BS	7317	7775	17707	10704	25243
10	BI	1850	1962	4124	2685	5843
	BSW	722	773	2290	1088	3320
	BC	1898	2012	4231	2755	5994
	BS	7138	7584	17271	10441	24623

Table A-9
Critical Force Ratios

Structure Number	Limit State	Tangent Structure Critical Force Ratios CF SL	CF CT	CF NESC	CF EW	CF EI
1	BI	1.00	1.00	1.00	1.00	1.00
	BSW	0.71	0.76	1.00	1.00	1.00
	BC	1.00	1.00	1.00	1.00	1.00
	BS	1.00	1.00	1.00	1.00	1.00
2	BI	0.90	0.95	1.00	1.00	1.00
	BSW	0.49	0.53	1.00	0.74	1.00
	BC	1.00	1.00	1.00	1.00	1.00
	BS	1.00	1.00	1.00	1.00	1.00
3	BI	0.75	0.79	1.00	1.00	1.00
	BSW	0.38	0.41	1.00	0.58	1.00
	BC	0.90	0.95	1.00	1.00	1.00
	BS	1.00	1.00	1.00	1.00	1.00
4	BI	0.65	0.69	1.00	0.95	1.00
	BSW	0.32	0.34	1.00	0.48	1.00
	BC	0.75	0.79	1.00	1.00	1.00
	BS	1.00	1.00	1.00	1.00	1.00
5	BI	0.60	0.63	1.00	0.86	1.00
	BSW	0.28	0.30	0.88	0.42	1.00
	BC	0.65	0.69	1.00	0.95	1.00
	BS	1.00	1.00	1.00	1.00	1.00
6	BI	0.56	0.59	1.00	0.81	1.00
	BSW	0.25	0.27	0.80	0.38	1.00
	BC	0.60	0.63	1.00	0.86	1.00
	BS	1.00	1.00	1.00	1.00	1.00
7	BI	0.53	0.56	1.00	0.77	1.00
	BSW	0.24	0.25	0.75	0.36	1.00
	BC	0.56	0.59	1.00	0.81	1.00
	BS	1.00	1.00	1.00	1.00	1.00
8	BI	0.51	0.54	1.00	0.74	1.00
	BSW	0.23	0.24	0.71	0.34	1.00
	BC	0.53	0.56	1.00	0.77	1.00
	BS	1.00	1.00	1.00	1.00	1.00
9	BI	0.50	0.53	1.00	0.72	1.00
	BSW	0.22	0.23	0.69	0.33	1.00
	BC	0.51	0.54	1.00	0.74	1.00
	BS	1.00	1.00	1.00	1.00	1.00
10	BI	0.49	0.52	1.00	0.71	1.00
	BSW	0.21	0.23	0.67	0.32	0.98
	BC	0.50	0.53	1.00	0.72	1.00
	BS	1.00	1.00	1.00	1.00	1.00

Critical force ratios (i.e., Ratio of Unbalanced Loads to Ultimate Resistances as defined in Section 3.6.1) are shown in Table A-9 for each load case and limit state combination at each structure away from the initiating failure event. For example, the critical load ratio at the third structure away from the initiating event for a broken conductor at cold temperature loads is 0.95. This indicates that the unbalanced loads are very close to the ultimate resistance of the third structure away from the initiating event.

It should be noted that the accuracy of the critical force ratio strongly depends on the accuracy of the predictions made for the unbalanced longitudinal load and the structural resistance. Because there are many uncertainties involved in the modeling and prediction it is recommended to consider the consequences of these uncertainties.

For example, slight variations in the unbalanced loads or ultimate strengths may change the critical force ratio at the third structure from the initial event to 1.00 which of course would be indicative of the failure of the third structure. Therefore, a more advantageous and conservative approach would be to assume that the third structure will fail. Based on the critical force ratio of the fourth structure (i.e., 0.79) from the initial event it is unlikely that the unbalanced load will exceed the ultimate strength and it can be assumed that the fourth structure is not going to fail.

Cascading Failure Security Levels are shown in Table A-10 for each load case and limit state combination as a function of the expected number of structural failures. The expected number of structural failures is equal to the number of structures that are assumed to fail (i.e., equal to the number of structures a utility is willing to lose in an extreme event load case) in the containment of an initiating event. For example, if a utility is willing to lose two structures in a broken shield wire event at the service load condition, the security level of the particular tangent structure used in this example for the particular scenario is 0.31 on a scale ranging from 0 to 1.0. Of course, a security level of zero is indicative of a cascading failure while a security level of one indicates that a cascading failure is extremely unlikely to occur. Similarly, if a utility is willing to lose two structures in a broken conductor event at the service load condition, the security level is 0.05 which indicates a high risk of cascading based on the groups outlined in Section 3.6.3.

Table A-10
Cascading Failure Security Levels

Expected Number of Failed Structures	Limit State	Tangent Structure Security Levels Load Case (SL)	Load Case (CT)	Load Case (NESC)	Load Case (EW)	Load Case (EI)
0	BI	N/A	N/A	N/A	N/A	N/A
	BSW	N/A	N/A	N/A	N/A	N/A
	BC	N/A	N/A	N/A	N/A	N/A
	BS	N/A	N/A	N/A	N/A	N/A
1	BI	0.11	0.05	0.00	0.00	0.00
	BSW	0.36	0.36	0.00	0.30	0.00
	BC	0.00	0.00	0.00	0.00	0.00
	BS	0.00	0.00	0.00	0.00	0.00
2	BI	0.15	0.12	0.00	0.00	0.00
	BSW	0.31	0.31	0.00	0.28	0.00
	BC	0.05	0.02	0.00	0.00	0.00
	BS	0.00	0.00	0.00	0.00	0.00
3	BI	0.14	0.12	0.00	0.02	0.00
	BSW	0.27	0.27	0.00	0.25	0.00
	BC	0.10	0.08	0.00	0.00	0.00
	BS	0.00	0.00	0.00	0.00	0.00
4	BI	0.13	0.11	0.00	0.04	0.00
	BSW	0.23	0.23	0.03	0.22	0.00
	BC	0.11	0.09	0.00	0.01	0.00
	BS	0.00	0.00	0.00	0.00	0.00
5	BI	0.12	0.11	0.00	0.04	0.00
	BSW	0.21	0.21	0.04	0.19	0.00
	BC	0.10	0.09	0.00	0.03	0.00
	BS	0.00	0.00	0.00	0.00	0.00
6	BI	0.11	0.10	0.00	0.04	0.00
	BSW	0.18	0.18	0.05	0.17	0.00
	BC	0.10	0.09	0.00	0.04	0.00
	BS	0.00	0.00	0.00	0.00	0.00
7	BI	0.10	0.09	0.00	0.04	0.00
	BSW	0.16	0.16	0.05	0.15	0.00
	BC	0.09	0.08	0.00	0.04	0.00
	BS	0.00	0.00	0.00	0.00	0.00
8	BI	0.09	0.08	0.00	0.04	0.00
	BSW	0.15	0.15	0.05	0.14	0.00
	BC	0.08	0.08	0.00	0.04	0.00
	BS	0.00	0.00	0.00	0.00	0.00
9	BI	0.08	0.07	0.00	0.04	0.00
	BSW	0.13	0.13	0.04	0.13	0.00
	BC	0.08	0.07	0.00	0.04	0.00
	BS	0.00	0.00	0.00	0.00	0.00

To evaluate specific security levels between zero and one it is necessary to identify a specific cutoff value that conclusively separates high risk from low risk transmission lines (relative to cascading at the specified conditions). However, the cascading potential of a steel pole line with a security level of 0.31 is not likely to be the same as the cascading potential of a wood frame line with the same security level. Essentially, the statistical variation of the ultimate strength of wood structures is significantly larger than the statistical variation of the ultimate strength of manufactured steel poles. For example, if the ultimate strength of a steel pole can be predicted with an accuracy of plus or minus ten percent, it is likely that the steel pole fails for critical force ratios between 0.9 to 1.0. Similarly, if the ultimate strength of a wood frame can be predicted with an accuracy of plus or minus thirty percent, it is likely that a wood frame failure occurs for critical force ratios between 0.7 to 1.0. Consequently, the security level cutoff value for a wood frame line is larger than the corresponding value for a steel pole line.

Based on experience, the ultimate strength of a steel pole can be predicted with an accuracy of plus or minus ten percent, the ultimate strength of a lattice tower can be predicted with an accuracy of plus or minus fifteen percent, and the ultimate strength of a wood frame line can be predicted with an accuracy of plus or minus thirty percent. Consequently, the minimum security level required to avoid a cascading failure on a steel structure transmission line, a steel lattice structure line, or a wood structure line range from 0.03, 0.04, or 0.08.

B

CASE ASSESSMENT OF A WOOD H-FRAME LINE

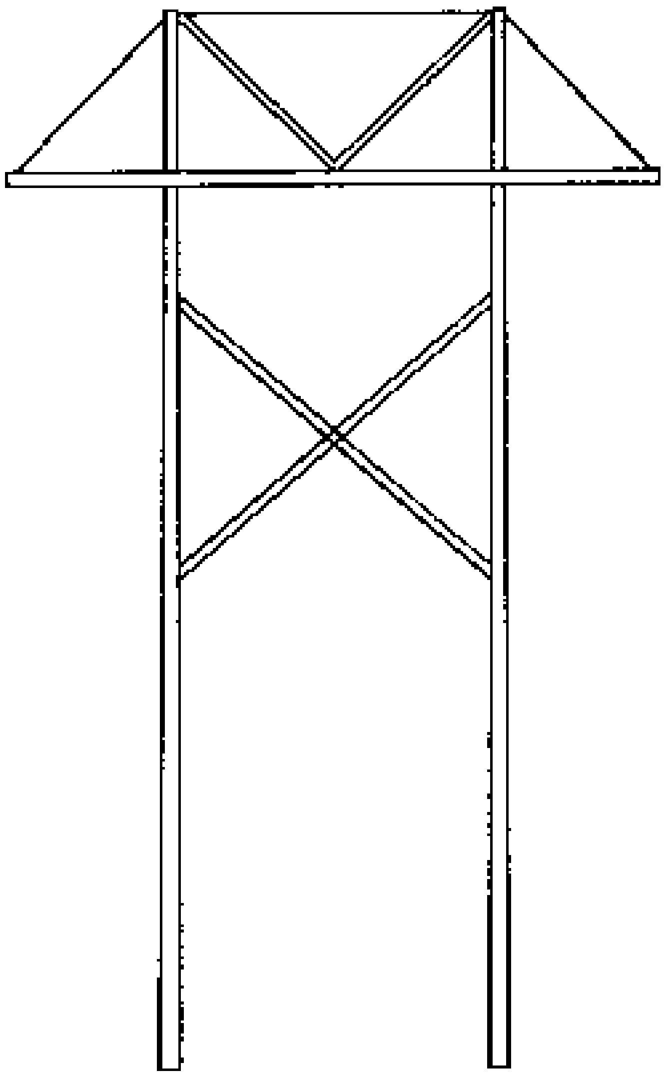

Table B-1
Input Parameters Required for CASE Assessment

Load Parameters		
Basic Wind Speed		70 mph
Basic Ice Thickness		1 inch
Average Daily Temperature		60°F
Extreme Wind Temperature		30°F
Extreme Ice Temperature		15°F

Wire Parameters		
Conductor:	795-kcmil ACSR 'Drake'	
	Diameter	1.108 inch
	Weight	1.094 lb./ft
	Rated Strength	31,500 lb.
Shield Wire:	3/8 Inch EHS Wire	
	Diameter	0.360 inch
	Weight	0.273 lb./ft
	Rated Strength	15,400 lb.
Sag/Tension:	Shield Wire	Table (B-2)
	Conductor	Table (B-3)
Insulators:	I-String	10 ft

Line Parameters		
Tangent Structure:	Front Span	1000 ft
	Back Span	1100 ft
	Horizontal Line Angle	0°
	Vertical Line Angle	0°

Structure Parameters		
Tangent Structure:	Douglas Fir (Class 2)	
	Cross-Brace (bxd, L)	6"x6.75", 36'
	Cross-Arm (bxd, L)	5.5"x7.5", 54'
	Pole Length	70 ft
	Embedment Depth	10 ft
	Shield-Arm (bxd, L)	3.6"x9.5", 34'
	Structural Flexibility	25 in/kip

Some of the information required for a typical simplified CASE assessment is shown above. Additional information that is required are the structural flexibility of the tangent and dead end structures and the component strengths (i.e., ultimate moment,

shear, axial load, etc.). Structural flexibility and ultimate component strengths can be determined either by hand calculations or by a detailed structural analysis using a commercially available finite element program. The restraining effect of the wires (i.e., shield wires and conductors) on the structure should be neglected in the calculation of the structural flexibility and ultimate strength.

Table B-2
Sag-Tensions of 3/8 Inch EHS Shield Wire

3/8 - inch EHS Shield Wire

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
-30	0	0	0	0	None	8.53	4003	9.37	3645
-15	0	0	0	0	None	8.90	3838	9.79	3488
-15	1.0	0	0	0	None	30.35	8131	30.35	8131
30	0	12.5	0	0	None	14.58	3980	15.63	3715
0	0.5	4.0	0.3	0	None	24.14	6370	24.79	6205
15	0	0	0	0	None	9.70	3520	10.71	3188
30	0	0	0	0	None	10.14	3368	11.21	3047
45	0	0	0	0	None	10.60	3221	11.73	2911
60	0	0	0	20.0	Initial	11.09	3080	12.28	2782
75	0	0	0	0	None	11.60	2945	12.84	2659
90	0	0	0	0	None	12.13	2816	13.43	2543
105	0	0	0	0	None	12.68	2694	14.04	2434

Table B-3
Sag-Tensions of ACSR 'DRAKE' Conductor

795 - kcmil ACSR 'DRAKE'

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
-30	0	0	0	0	None	16.72	8192	19.98	6861
-15	0	0	0	0	None	17.52	7818	21.00	6528
-15	1.0	0	0	0	None	30.04	15535	30.04	15535
30	0	12.5	0	0	None	22.99	8673	26.01	7672
0	0.5	4.0	0.3	0	None	25.98	12115	27.44	11472
15	0	0	0	0	None	19.18	7143	23.01	5959
30	0	0	0	0	None	20.04	6840	24.00	5715
45	0	0	0	0	None	20.90	6559	24.97	5494
60	0	0	0	20.0	Initial	21.76	6300	25.93	5293
75	0	0	0	0	None	22.63	6060	26.87	5109
90	0	0	0	0	None	23.49	5839	27.79	4941
105	0	0	0	0	None	24.35	5634	28.57	4807

Table B-4
Critical Sag Values for CASE Assessment

Structure from Failure	Line Component	Tangent Structure Sags				
		SL Sag (ft)	CT Sag (ft)	NESC Sag (ft)	EW Sag (ft)	EI Sag (ft)
1 to 10	SW C	12.28 25.93	10.71 23.01	24.79 27.44	15.63 26.01	30.35 30.04

Table B-5
Critical Conductor and Shield Wire Tensions for CASE Assessment

Structure from Failure	Line Component	Tangent Structure Tensions				
		SL Tension (lb.)	CT Tension (lb.)	NESC Tension (lb.)	EW Tension (lb.)	EI Tension (lb.)
1 to 10	SW C	2782 5293	3188 5959	6205 11472	3715 7672	8131 15535

Table B-6
Critical Span/Sag Ratios for CASE Assessment

Structure from Failure	Line Component	Tangent Structure Span/Sag Ratios				
		(S/S) SL (ft)	(S/S) CT (ft)	(S/S) NESC (ft)	(S/S) EW (ft)	(S/S) EI (ft)
1 to 10	SW C	81.43 38.57	93.37 43.46	40.34 36.44	63.98 38.45	32.95 33.29

Critical sag values used in the CASE assessment for the conductor and shield wire are shown in Table B-4. Table B-5 shows a summary of the critical conductor and shield wire tensions used in the CASE assessment while Table B-6 summarizes calculated span/sag ratios. Critical sags and span/sag ratios for this particular example are identical at all ten structures because it was assumed that the span length is constant and that the horizontal and vertical line angles are zero (i.e., average span concept). Different assumptions may require the calculation of critical sags and span/sag ratios at each structure to accurately predict the unbalanced longitudinal loads at each structure from the initiating failure event. Similarly, structural flexibilities may have to be calculated at each structure to include the effects of varying support elevations.

Table B-7
Longitudinal Load Factors

Structure from Failure	Line Component	Tangent Structure Longitudinal Load Factors				
		LLF SL	LLF CT	LLF NESC	LLF EW	LLF EI
1	SW	1.11	1.03	1.57	1.25	1.74
	C	1.61	1.52	1.66	1.61	1.73
2	SW	0.77	0.72	1.10	0.87	1.22
	C	1.13	1.06	1.16	1.13	1.21
3	SW	0.60	0.56	0.85	0.68	0.94
	C	0.87	0.82	0.90	0.87	0.94
4	SW	0.50	0.47	0.71	0.56	0.78
	C	0.72	0.68	0.75	0.73	0.78
5	SW	0.44	0.41	0.62	0.49	0.69
	C	0.63	0.60	0.65	0.64	0.68
6	SW	0.40	0.37	0.56	0.45	0.62
	C	0.58	0.54	0.59	0.58	0.62
7	SW	0.37	0.35	0.53	0.42	0.58
	C	0.54	0.51	0.56	0.54	0.58
8	SW	0.35	0.33	0.50	0.40	0.56
	C	0.51	0.48	0.53	0.52	0.55
9	SW	0.34	0.32	0.49	0.39	0.54
	C	0.50	0.47	0.51	0.50	0.53
10	SW	0.33	0.31	0.47	0.38	0.52
	C	0.48	0.46	0.50	0.49	0.52

Longitudinal load factors are calculated at each structure from the initiating event. Table B-7 shows a summary of all longitudinal load factors as a function of the load case and distance (i.e., Number of Structures) from the initiating event for the conductor and shield wire. Considering the data summarized in the table it is possible to see the reduction in the magnitude of the longitudinal load factor from one structure to the next. Based on the data it is easily recognized that the largest reduction in the longitudinal load factors occurs within the first 5 structures while only small reductions in the load factors are realized at any subsequent structure.

Longitudinal load factors increase as the mass per unit length of the conductor or shield wire increases because of a decreasing span/sag ratio. Therefore, longitudinal load factors for the NESC load case (i.e., 0.5 inch Radial Ice) or the Extreme Ice load case (i.e., 1.0 inch Radial Ice) are significantly larger than load factors for the other load cases at comparable temperatures.

Table B-8
Unbalanced Longitudinal Loads for All Limit States

Structure Number	Limit State	Tangent Structure Unbalanced Longitudinal UL SL (lb.)	UL CT (lb.)	UL NESC (lb.)	UL EW (lb.)	UL EI (lb.)
1	BI	4994	5296	11135	7250	15776
	BSW	2721	2912	8622	4099	12501
	BC	7146	7578	15932	10373	22573
	BS	26878	28558	65039	39317	92722
2	BI	3863	4097	8614	5608	12204
	BSW	1901	2035	6026	2865	8737
	BC	4994	5296	11135	7250	15776
	BS	18785	19959	45455	27478	64802
3	BI	3214	3409	7166	4666	10154
	BSW	1471	1574	4661	2216	6759
	BC	3863	4097	8614	5608	12204
	BS	14532	15440	35164	21257	50131
4	BI	2817	2988	6282	4090	8900
	BSW	1224	1310	3878	1844	5623
	BC	3214	3409	7166	4666	10154
	BS	12090	12846	29256	17686	41708
5	BI	2563	2719	5715	3721	8098
	BSW	1073	1148	3399	1616	4929
	BC	2817	2988	6282	4090	8900
	BS	10597	11260	25643	15502	36558
6	BI	2396	2541	5341	3478	7568
	BSW	976	1045	3093	1470	4485
	BC	2563	2719	5715	3721	8098
	BS	9642	10245	23332	14105	33263
7	BI	2282	2421	5089	3313	7210
	BSW	912	976	2891	1374	4191
	BC	2396	2541	5341	3478	7568
	BS	9011	9575	21806	13182	31087
8	BI	2204	2338	4915	3200	6964
	BSW	869	930	2754	1309	3993
	BC	2282	2421	5089	3313	7210
	BS	8585	9121	20774	12558	29616
9	BI	2150	2280	4794	3121	6793
	BSW	839	898	2660	1264	3856
	BC	2204	2338	4915	3200	6964
	BS	8292	8810	20064	12129	28604
10	BI	2096	2223	4673	3043	6621
	BSW	819	876	2594	1233	3762
	BC	2150	2280	4794	3121	6793
	BS	8088	8593	19571	11831	27901

Longitudinal load factors increase slightly as the temperature of the conductor or shield wire increases because of small changes in the span/sag ratio. Table B-7 shows that large changes in the temperature of the conductor or shield wire cause only small changes in the magnitude of the longitudinal load factors regardless of the distance (i.e., Number of Structures) of the structure from the initial failure.

Unbalanced longitudinal loads are shown in Table B-8 for all four limit states and five load cases. For example, the unbalanced longitudinal loads acting on the fifth structure away from the initiating failure event at service loads are 2563 lb., 1073 lb., 2817 lb., and 10597 lb. for the broken insulator, broken shield wire, broken conductor, and broken structure limit state. Similarly, the unbalanced longitudinal loads are shown for the first through fourth structure and the sixth through tenth structure away from the initiating event. Essentially, if a cascading failure is to be arrested within five structures, each tangent structure should be able to resist the forces acting on the fifth structure.

Unbalanced longitudinal loads shown in Table B-8 can be used to assess the required longitudinal load strength in an upgrading situation or new construction. For example, if the failure of two structures is acceptable in the event of a single shield wire or conductor breakage at service loads, the minimum longitudinal strength to be provided is 1471 lb. and 3863 lb. for the shield wire and conductor, respectively. Similarly, the minimum longitudinal strength to be provided in the event of a single shield wire or conductor breakage at extreme ice loads is 6759 lb. and 12204 lb., respectively. The significantly higher loads are a result of the increased mass of the wire with the ice attached and the resulting changes in the span/sag ratio and initial tension. The worst case scenario (i.e., loss of a complete structure at extreme ice loads) indicates that the third structure away from the initiating event has to resist an unbalanced longitudinal load of two times 6759 lb. (i.e., for 2 shield wires) and three times 12204 lb. (i.e., single circuit configuration) to avoid a cascading failure.

While, the combination of extreme ice loads coupled with the loss of a structure (or all phases) occurs infrequently in most areas this combination may be critical in other areas. Although either service loads or cold temperature loading are likely to be present nearly all the time, the worst case scenario of extreme ice coupled with a structural failure may occur only once every 50 years (however, typically with devastating results). Utility experience and specialized weather conditions are likely to have some influence on the probability that will be associated with each load case - failure mode combination.

Critical force ratios (i.e., Ratio of Unbalanced Loads to Ultimate Resistances as defined in Section 3.6.1) are shown in Table B-9 for each load case and limit state combination at each structure away from the initiating failure event. For example, the critical load ratio at the third structure away from the initiating event for a broken conductor at NESC loading is 0.98. This indicates that the unbalanced loads are very close to the ultimate resistance of the third structure away from the initiating event.

Table B-9
Critical Force Ratios

Structure Number	Limit State	Tangent Structure Critical Force Ratios CF SL	CF CT	CF NESC	CF EW	CF EI
1	BI	0.57	0.60	1.00	0.82	1.00
	BSW	0.39	0.42	1.00	0.59	1.00
	BC	0.81	0.86	1.00	1.00	1.00
	BS	1.00	1.00	1.00	1.00	1.00
2	BI	0.44	0.47	0.98	0.64	1.00
	BSW	0.27	0.29	0.86	0.41	1.00
	BC	0.57	0.60	1.00	0.82	1.00
	BS	1.00	1.00	1.00	1.00	1.00
3	BI	0.37	0.39	0.81	0.53	1.00
	BSW	0.21	0.22	0.67	0.32	0.97
	BC	0.44	0.47	0.98	0.64	1.00
	BS	1.00	1.00	1.00	1.00	1.00
4	BI	0.32	0.34	0.71	0.46	1.00
	BSW	0.17	0.19	0.55	0.26	0.80
	BC	0.37	0.39	0.81	0.53	1.00
	BS	1.00	1.00	1.00	1.00	1.00
5	BI	0.29	0.31	0.65	0.42	0.92
	BSW	0.15	0.16	0.49	0.23	0.70
	BC	0.32	0.34	0.71	0.46	1.00
	BS	1.00	1.00	1.00	1.00	1.00
6	BI	0.27	0.29	0.61	0.40	0.86
	BSW	0.14	0.15	0.44	0.21	0.64
	BC	0.29	0.31	0.65	0.42	0.92
	BS	1.00	1.00	1.00	1.00	1.00
7	BI	0.26	0.28	0.58	0.38	0.82
	BSW	0.13	0.14	0.41	0.20	0.60
	BC	0.27	0.29	0.61	0.40	0.86
	BS	1.00	1.00	1.00	1.00	1.00
8	BI	0.25	0.27	0.56	0.36	0.79
	BSW	0.12	0.13	0.39	0.19	0.57
	BC	0.26	0.28	0.58	0.38	0.82
	BS	1.00	1.00	1.00	1.00	1.00
9	BI	0.24	0.26	0.54	0.35	0.77
	BSW	0.12	0.13	0.38	0.18	0.55
	BC	0.25	0.27	0.56	0.36	0.79
	BS	0.99	1.00	1.00	1.00	1.00
10	BI	0.24	0.25	0.53	0.35	0.75
	BSW	0.12	0.13	0.37	0.18	0.54
	BC	0.24	0.26	0.54	0.35	0.77
	BS	0.97	1.00	1.00	1.00	1.00

It should be noted that the accuracy of the critical force ratio strongly depends on the accuracy of the predictions made for the unbalanced longitudinal load and the structural resistance. Because there are many uncertainties involved in the modeling and prediction it is recommended to consider the consequences of these uncertainties.

For example, slight variations in the unbalanced loads or ultimate strengths may change the critical force ratio at the third structure from the initial event to 1.00 which of course would be indicative of the failure of the third structure. Therefore, a more advantageous and conservative approach would be to assume that the third structure will fail. Based on the critical force ratio of the fourth structure (i.e., 0.81) from the initial event it is less likely that the unbalanced load will exceed the ultimate strength and it can be assumed that the fourth structure is not going to fail.

Cascading Failure Security Levels are shown in Table B-10 for each load case and limit state combination as a function of the expected number of structural failures. The expected number of structural failures is equal to the number of structures that are assumed to fail (i.e., equal to the number of structures a utility is willing to lose in an extreme event load case) in the containment of an initiating event. For example, if a utility is willing to lose two structures in a broken shield wire event at the service load condition, the security level of the particular tangent structure used in this example for the particular scenario is 0.31 on a scale ranging from 0 to 1.0. Of course, a security level of zero is indicative of a cascading failure while a security level of one indicates that a cascading failure is extremely unlikely to occur. Similarly, if a utility is willing to lose two structures in a broken conductor event at the service load condition, the security level is also 0.31 which again indicates a low risk of cascading based on the groups outlined in Section 3.6.3.

To evaluate specific security levels between zero and one it is necessary to identify a specific cutoff value that conclusively separates high risk from low risk transmission lines (relative to cascading at the specified conditions). However, the cascading potential of a steel pole line with a security level of 0.31 is not likely to be the same as the cascading potential of a wood frame line with the same security level. Essentially, the statistical variation of the ultimate strength of wood structures is significantly larger than the statistical variation of the ultimate strength of manufactured steel poles. For example, if the ultimate strength of a steel pole can be predicted with an accuracy of plus or minus ten percent, it is likely that the steel pole fails for critical force ratios between 0.9 to 1.0. Similarly, if the ultimate strength of a wood frame can be predicted with an accuracy of plus or minus thirty percent, it is likely that a wood frame failure occurs for critical force ratios between 0.7 to 1.0. Consequently, the security level cutoff value for a wood frame line is larger than the corresponding value for a steel pole line.

Table B-10
Cascading Failure Security Levels

Expected Number of Failed Structures	Limit State	Tangent Structure Security Levels				
		Load Case (SL)	Load Case (CT)	Load Case (NESC)	Load Case (EW)	Load Case (EI)
0	BI	N/A	N/A	N/A	N/A	N/A
	BSW	N/A	N/A	N/A	N/A	N/A
	BC	N/A	N/A	N/A	N/A	N/A
	BS	N/A	N/A	N/A	N/A	N/A
1	BI	0.26	0.26	0.02	0.26	0.00
	BSW	0.36	0.36	0.15	0.36	0.00
	BC	0.36	0.36	0.00	0.19	0.00
	BS	0.00	0.00	0.00	0.00	0.00
2	BI	0.22	0.22	0.10	0.22	0.00
	BSW	0.31	0.31	0.20	0.31	0.02
	BC	0.31	0.31	0.01	0.23	0.00
	BS	0.00	0.00	0.00	0.00	0.00
3	BI	0.19	0.19	0.11	0.19	0.00
	BSW	0.27	0.27	0.20	0.27	0.07
	BC	0.27	0.27	0.07	0.21	0.00
	BS	0.00	0.00	0.00	0.00	0.00
4	BI	0.17	0.17	0.11	0.17	0.02
	BSW	0.23	0.23	0.18	0.23	0.09
	BC	0.23	0.23	0.08	0.19	0.00
	BS	0.00	0.00	0.00	0.00	0.00
5	BI	0.15	0.15	0.10	0.15	0.03
	BSW	0.21	0.21	0.16	0.21	0.09
	BC	0.21	0.21	0.09	0.17	0.02
	BS	0.00	0.00	0.00	0.00	0.00
6	BI	0.13	0.13	0.09	0.13	0.03
	BSW	0.18	0.18	0.15	0.18	0.09
	BC	0.18	0.18	0.08	0.15	0.03
	BS	0.00	0.00	0.00	0.00	0.00
7	BI	0.12	0.12	0.08	0.12	0.03
	BSW	0.16	0.16	0.13	0.16	0.08
	BC	0.16	0.16	0.08	0.14	0.03
	BS	0.00	0.00	0.00	0.00	0.00
8	BI	0.11	0.11	0.08	0.11	0.03
	BSW	0.15	0.15	0.12	0.15	0.07
	BC	0.15	0.15	0.07	0.13	0.03
	BS	0.00	0.00	0.00	0.00	0.00
9	BI	0.10	0.10	0.07	0.10	0.03
	BSW	0.13	0.13	0.11	0.13	0.07
	BC	0.13	0.13	0.07	0.12	0.03
	BS	0.00	0.00	0.00	0.00	0.00

Based on experience, the ultimate strength of a steel pole can be predicted with an accuracy of plus or minus ten percent, the ultimate strength of a lattice tower can be predicted with an accuracy of plus or minus fifteen percent, and the ultimate strength of a wood frame line can be predicted with an accuracy of plus or minus thirty percent. Consequently, the minimum security level required to avoid a cascading failure on a steel structure transmission line, a steel lattice structure line, or a wood structure line range from 0.03, 0.04, or 0.08.

C

CASE ASSESSMENT OF A LATTICE STEEL TOWER LINE

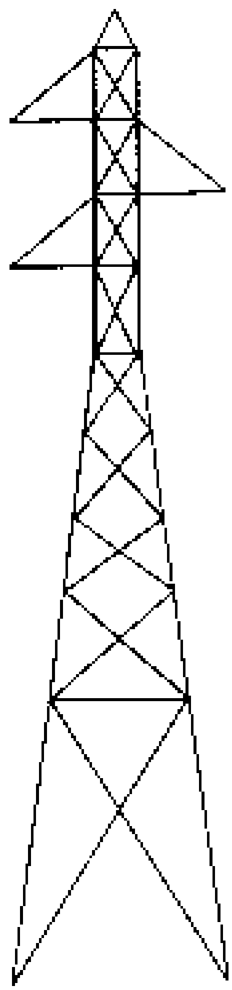

Table C-1
Input Parameters Required for CASE Assessment

Load Parameters		
Basic Wind Speed		70 mph
Basic Ice Thickness		1 inch
Average Daily Temperature		60°F
Extreme Wind Temperature		30°F
Extreme Ice Temperature		15°F

Wire Parameters		
Conductor:	795-kcmil ACSR 'Drake'	
	Diameter	1.108 inch
	Weight	1.094 lb./ft
	Rated Strength	31,500 lb.
Shield Wire:	3/8 Inch EHS Wire	
	Diameter	0.360 inch
	Weight	0.273 lb./ft
	Rated Strength	15,400 lb.
Sag/Tension:	Shield Wire	Table (C-2)
	Conductor	Table (C-3)
Insulators:	I-String	10 ft

Line Parameters		
Tangent Structure:	Front Span	1000 ft
	Back Span	1100 ft
	Horizontal Line Angle	0°
	Vertical Line Angle	0°

Structure Parameters		
Tangent Structure:	Steel Lattice (A36)	
	Single Circuit Delta	
	Tower Height	115 ft
	Width at Base	30 ft
	Structural Flexibility	6 in/kip

Some of the information required for a typical simplified CASE assessment is shown above. Additional information that is required are the structural flexibility of the tangent and dead end structures and the component strengths (i.e., ultimate moment,

shear, axial load, etc.). Structural flexibility and ultimate component strengths can be determined either by hand calculations or by a detailed structural analysis using a commercially available finite element program. The restraining effect of the wires (i.e., shield wires and conductors) on the structure should be neglected in the calculation of the structural flexibility and ultimate strength.

Table C-2
Sag-Tensions of 3/8 Inch EHS Shield Wire

3/8 - inch EHS Shield Wire

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial		Final	
						Sag (ft)	Tension (lb.)	Sag (ft)	Tension (lb.)
-30	0	0	0	0	None	8.53	4003	9.37	3645
-15	0	0	0	0	None	8.90	3838	9.79	3488
-15	1.0	0	0	0	None	30.35	8131	30.35	8131
30	0	12.5	0	0	None	14.58	3980	15.63	3715
0	0.5	4.0	0.3	0	None	24.14	6370	24.79	6205
15	0	0	0	0	None	9.70	3520	10.71	3188
30	0	0	0	0	None	10.14	3368	11.21	3047
45	0	0	0	0	None	10.60	3221	11.73	2911
60	0	0	0	20.0	Initial	11.09	3080	12.28	2782
75	0	0	0	0	None	11.60	2945	12.84	2659
90	0	0	0	0	None	12.13	2816	13.43	2543
105	0	0	0	0	None	12.68	2694	14.04	2434

Table C-3
Sag-Tensions of ACSR 'DRAKE' Conductor

795 - kcmil ACSR 'DRAKE'

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial		Final	
						Sag (ft)	Tension (lb.)	Sag (ft)	Tension (lb.)
-30	0	0	0	0	None	16.72	8192	19.98	6861
-15	0	0	0	0	None	17.52	7818	21.00	6528
-15	1.0	0	0	0	None	30.04	15535	30.04	15535
30	0	12.5	0	0	None	22.99	8673	26.01	7672
0	0.5	4.0	0.3	0	None	25.98	12115	27.44	11472
15	0	0	0	0	None	19.18	7143	23.01	5959
30	0	0	0	0	None	20.04	6840	24.00	5715
45	0	0	0	0	None	20.90	6559	24.97	5494
60	0	0	0	20.0	Initial	21.76	6300	25.93	5293
75	0	0	0	0	None	22.63	6060	26.87	5109
90	0	0	0	0	None	23.49	5839	27.79	4941
105	0	0	0	0	None	24.35	5634	28.57	4807

Sag and tension values for the conductor and shield wire are typically determined by means of an analysis program for a variety of temperature and loading conditions. Sags shown in Table C-2 and C-3 were determined with SAG/T for 20 % of UTS Final at temperatures ranging from -30 to 105 °F.

Table C-4
Critical Sag Values for CASE Assessment

Structure from Failure	Line Component	**Tangent Structure Sags**				
		SL Sag (ft)	CT Sag (ft)	NESC Sag (ft)	EW Sag (ft)	EI Sag (ft)
1 to 10	SW C	12.28 25.93	10.71 23.01	24.79 27.44	15.63 26.01	30.35 30.04

Table C-5
Critical Conductor and Shield Wire Tensions for CASE Assessment

Structure from Failure	Limit State	**Tangent Structure Tensions**				
		SL Tension (lb.)	CT Tension (lb.)	NESC Tension (lb.)	EW Tension (lb.)	EI Tension (lb.)
1 to 10	SW C	2782 5293	3188 5959	6205 11472	3715 7672	8131 15535

Table C-6
Critical Span/Sag Ratios for CASE Assessment

Structure from Failure	Limit State	**Tangent Structure Span/Sag Ratios**				
		(S/S) SL (ft)	(S/S) CT (ft)	(S/S) NESC (ft)	(S/S) EW (ft)	(S/S) EI (ft)
1 to 10	SW C	81.43 38.57	93.37 43.46	40.34 36.44	63.98 38.45	32.95 33.29

Critical sag values used in the CASE assessment for the conductor and shield wire are shown in Table C-4. Table C-5 shows a summary of the critical conductor and shield wire tensions used in the CASE assessment while Table C-6 summarizes calculated span/sag ratios. Critical sags and span/sag ratios for this particular example are identical at all ten structures because it was assumed that the span length is constant and that the horizontal and vertical line angles are zero (i.e., average span concept).

Different assumptions may require the calculation of critical sags and span/sag ratios at each structure to accurately predict the unbalanced longitudinal loads at each structure from the initiating failure event. Similarly, structural flexibilities may have to be calculated at each structure to include the effects of varying support elevations.

Table C-7
Longitudinal Load Factors

Structure from Failure	Line Component	**Tangent Structure Longitudinal Load Factors**				
		LLF SL	LLF CT	LLF NESC	LLF EW	LLF EI
1	SW	1.11	1.03	1.57	1.25	1.74
	C	1.61	1.52	1.66	1.61	1.73
2	SW	0.77	0.72	1.10	0.87	1.22
	C	1.13	1.06	1.16	1.13	1.21
3	SW	0.60	0.56	0.85	0.68	0.94
	C	0.87	0.82	0.90	0.87	0.94
4	SW	0.50	0.47	0.71	0.56	0.78
	C	0.72	0.68	0.75	0.73	0.78
5	SW	0.44	0.41	0.62	0.49	0.69
	C	0.63	0.60	0.65	0.64	0.68
6	SW	0.40	0.37	0.56	0.45	0.62
	C	0.58	0.54	0.59	0.58	0.62
7	SW	0.37	0.35	0.53	0.42	0.58
	C	0.54	0.51	0.56	0.54	0.58
8	SW	0.35	0.33	0.50	0.40	0.56
	C	0.51	0.48	0.53	0.52	0.55
9	SW	0.34	0.32	0.49	0.39	0.54
	C	0.50	0.47	0.51	0.50	0.53
10	SW	0.33	0.31	0.47	0.38	0.52
	C	0.48	0.46	0.50	0.49	0.52

Longitudinal load factors are calculated at each structure from the initiating event. Table C-7 shows a summary of all longitudinal load factors as a function of the load case and distance (i.e., Number of Structures) from the initiating event for the conductor and shield wire. Considering the data summarized in the table it is possible to see the reduction in the magnitude of the longitudinal load factor from one structure to the next. Based on the data it is easily recognized that the largest reduction in the longitudinal load factors occurs within the first 5 structures while only small reductions in the load factors are realized at any subsequent structure.

Longitudinal load factors increase as the mass per unit length of the conductor or shield wire increases because of a decreasing span/sag ratio. Therefore, longitudinal load factors for the NESC load case (i.e., 0.5 inch Radial Ice) or the Extreme Ice load case (i.e., 1.0 inch Radial Ice) are significantly larger than load factors for the other load cases at comparable temperatures.

Longitudinal load factors increase slightly as the temperature of the conductor or shield wire increases because of small changes in the span/sag ratio. Table C-7 shows that large changes in the temperature of the conductor or shield wire cause only small changes in the magnitude of the longitudinal load factors regardless of the distance (i.e., Number of Structures) of the structure from the initial failure.

Unbalanced longitudinal loads are shown in Table C-8 for all four limit states and five load cases. For example, the unbalanced longitudinal loads acting on the fifth structure away from the initiating failure event at service loads are 2819 lb., 1180 lb., 3098 lb., and 11653 lb. for the broken insulator, broken shield wire, broken conductor, and broken structure limit state. Similarly, the unbalanced longitudinal loads are shown for the first through fourth structure and the sixth through tenth structure away from the initiating event. Essentially, if a cascading failure is to be arrested within five structures, each tangent structure should be able to resist the forces acting on the fifth structure.

Unbalanced longitudinal loads shown in Table C-8 can be used to assess the required longitudinal load strength in an upgrading situation or new construction. For example, if the failure of two structures is acceptable in the event of a single shield wire or conductor breakage at service loads, the minimum longitudinal strength to be provided is 1618 lb. and 4248 lb. for the shield wire and conductor, respectively. Similarly, the minimum longitudinal strength to be provided in the event of a single shield wire or conductor breakage at extreme ice loads is 7432 lb. and 13421 lb., respectively. The significantly higher loads are a result of the increased mass of the wire with the ice attached and the resulting changes in the span/sag ratio and initial tension. The worst case scenario (i.e., loss of a complete structure at extreme ice loads) indicates that the third structure away from the initiating event has to resist an unbalanced longitudinal load of 7432 lb. (i.e., assuming 1 shield wire) and three times 13421 lb. (i.e., single circuit configuration) to avoid a cascading failure.

Table C-8
Unbalanced Longitudinal Loads for All Limit States

Structure Number	Limit State	Tangent Structure Unbalanced Longitudinal Loads				
		UL SL (lb.)	UL CT (lb.)	UL NESC (lb.)	UL EW (lb.)	UL EI (lb.)
1	BI	5492	5824	12244	7972	17349
	BSW	2992	3202	9481	4507	13747
	BC	7858	8333	17520	11407	24823
	BS	29557	31404	71521	43236	101962
2	BI	4248	4506	9472	6167	13421
	BSW	2091	2238	6626	3150	9607
	BC	5492	5824	12244	7972	17349
	BS	20657	21948	49985	30217	71260
3	BI	3535	3749	7881	5131	11166
	BSW	1618	1731	5126	2437	7432
	BC	4248	4506	9472	6167	13421
	BS	15980	16979	38668	23376	55126
4	BI	3098	3286	6908	4497	9787
	BSW	1346	1440	4265	2027	6183
	BC	3535	3749	7881	5131	11166
	BS	13295	14126	32171	19448	45864
5	BI	2819	2990	6285	4092	8905
	BSW	1180	1262	3738	1777	5420
	BC	3098	3286	6908	4497	9787
	BS	11653	12382	28199	17047	40201
6	BI	2634	2794	5874	3824	8322
	BSW	1073	1149	3401	1617	4931
	BC	2819	2990	6285	4092	8905
	BS	10603	11266	25658	15510	36578
7	BI	2510	2662	5596	3643	7929
	BSW	1003	1073	3179	1511	4609
	BC	2634	2794	5874	3824	8322
	BS	9910	10529	23979	14496	34185
8	BI	2424	2571	5405	3519	7658
	BSW	956	1023	3028	1440	4391
	BC	2510	2662	5596	3643	7929
	BS	9440	10030	22844	13810	32567
9	BI	2364	2508	5272	3433	7470
	BSW	923	988	2925	1390	4241
	BC	2424	2571	5405	3519	7658
	BS	9118	9688	22064	13338	31455
10	BI	2305	2444	5139	3346	7281
	BSW	900	963	2853	1356	4137
	BC	2364	2508	5272	3433	7470
	BS	8894	9450	21521	13010	30682

While, the combination of extreme ice loads coupled with the loss of a structure (or all phases) occurs infrequently in most areas this combination may be critical in other areas. Although either service loads or cold temperature loading are likely to be present nearly all the time, the worst case scenario of extreme ice coupled with a structural failure may occur only once every 50 years (however, typically with devastating results). Utility experience and specialized weather conditions are likely to have some influence on the probability that will be associated with each load case - failure mode combination.

Critical force ratios (i.e., Ratio of Unbalanced Loads to Ultimate Resistances as defined in Section 3.6.1) are shown in Table C-9 for each load case and limit state combination at each structure away from the initiating failure event. For example, the critical load ratio at the fourth structure away from the initiating event for a broken conductor at extreme ice loading is 0.94. This indicates that the unbalanced loads are very close to the ultimate resistance of the fourth structure away from the initiating event.

It should be noted that the accuracy of the critical force ratio strongly depends on the accuracy of the predictions made for the unbalanced longitudinal load and the structural resistance. Because there are many uncertainties involved in the modeling and prediction it is recommended to consider the consequences of these uncertainties.

For example, slight variations in the unbalanced loads or ultimate strengths may change the critical force ratio at the third structure from the initial event to 1.00 which of course would be indicative of the failure of the third structure. Therefore, a more advantageous and conservative approach would be to assume that the fourth structure will fail. Based on the critical force ratio of the fifth structure (i.e., 0.83) from the initial event it is unlikely that the unbalanced load will exceed the ultimate strength and it can be assumed that the fifth structure is not going to fail.

Cascading Failure Security Levels are shown in Table C-10 for each load case and limit state combination as a function of the expected number of structural failures. The expected number of structural failures is equal to the number of structures that are assumed to fail (i.e., equal to the number of structures a utility is willing to lose in an extreme event load case) in the containment of an initiating event. For example, if a utility is willing to lose two structures in a broken shield wire event at the service load condition, the security level of the particular tangent structure used in this example for the particular scenario is 0.31 on a scale ranging from 0 to 1.0. Of course, a security level of zero is indicative of a cascading failure while a security level of one indicates that a cascading failure is extremely unlikely to occur. Similarly, if a utility is willing to lose two structures in a broken conductor event at the service load condition, the security level is also 0.31 which again indicates a low risk of cascading based on the groups outlined in Section 3.6.3.

Table C-9
Critical Force Ratios

Structure Number	Limit State	Tangent Structure Critical Force Ratios CF SL	CF CT	CF NESC	CF EW	CF EI
1	BI	0.46	0.49	1.00	0.67	1.00
	BSW	0.28	0.30	0.88	0.42	1.00
	BC	0.66	0.71	1.00	0.97	1.00
	BS	1.00	1.00	1.00	1.00	1.00
2	BI	0.36	0.38	0.80	0.52	1.00
	BSW	0.19	0.21	0.61	0.29	0.89
	BC	0.46	0.49	1.00	0.67	1.00
	BS	1.00	1.00	1.00	1.00	1.00
3	BI	0.30	0.32	0.67	0.43	0.94
	BSW	0.15	0.16	0.47	0.22	0.69
	BC	0.36	0.38	0.80	0.52	1.00
	BS	1.00	1.00	1.00	1.00	1.00
4	BI	0.26	0.28	0.58	0.38	0.83
	BSW	0.12	0.13	0.39	0.19	0.57
	BC	0.30	0.32	0.67	0.43	0.94
	BS	0.94	1.00	1.00	1.00	1.00
5	BI	0.24	0.25	0.53	0.35	0.75
	BSW	0.11	0.12	0.35	0.16	0.50
	BC	0.26	0.28	0.58	0.38	0.83
	BS	0.82	0.87	1.00	1.00	1.00
6	BI	0.22	0.24	0.50	0.32	0.70
	BSW	0.10	0.11	0.31	0.15	0.46
	BC	0.24	0.25	0.53	0.35	0.75
	BS	0.75	0.80	1.00	1.00	1.00
7	BI	0.21	0.23	0.47	0.31	0.67
	BSW	0.09	0.10	0.29	0.14	0.43
	BC	0.22	0.24	0.50	0.32	0.70
	BS	0.70	0.74	1.00	1.00	1.00
8	BI	0.21	0.22	0.46	0.30	0.65
	BSW	0.09	0.09	0.28	0.13	0.41
	BC	0.21	0.23	0.47	0.31	0.67
	BS	0.67	0.71	1.00	0.97	1.00
9	BI	0.20	0.21	0.45	0.29	0.63
	BSW	0.09	0.09	0.27	0.13	0.39
	BC	0.21	0.22	0.46	0.30	0.65
	BS	0.64	0.68	1.00	0.94	1.00
10	BI	0.20	0.21	0.43	0.28	0.62
	BSW	0.08	0.09	0.26	0.13	0.38
	BC	0.20	0.21	0.45	0.29	0.63
	BS	0.63	0.67	1.00	0.92	1.00

Table C-10
Cascading Failure Security Levels

Expected Number of Failed Structures	Limit State	**Tangent Structure Security Levels** Load Case (SL)	Load Case (CT)	Load Case (NESC)	Load Case (EW)	Load Case (EI)
0	BI	N/A	N/A	N/A	N/A	N/A
	BSW	N/A	N/A	N/A	N/A	N/A
	BC	N/A	N/A	N/A	N/A	N/A
	BS	N/A	N/A	N/A	N/A	N/A
1	BI	0.26	0.26	0.22	0.26	0.00
	BSW	0.36	0.36	0.36	0.36	0.12
	BC	0.36	0.36	0.00	0.36	0.00
	BS	0.00	0.00	0.00	0.00	0.00
2	BI	0.22	0.22	0.20	0.22	0.03
	BSW	0.31	0.31	0.31	0.31	0.19
	BC	0.31	0.31	0.11	0.31	0.00
	BS	0.00	0.00	0.00	0.00	0.00
3	BI	0.19	0.19	0.18	0.19	0.06
	BSW	0.27	0.27	0.27	0.27	0.19
	BC	0.27	0.27	0.14	0.27	0.02
	BS	0.02	0.00	0.00	0.00	0.00
4	BI	0.17	0.17	0.16	0.17	0.07
	BSW	0.23	0.23	0.23	0.23	0.17
	BC	0.23	0.23	0.13	0.23	0.05
	BS	0.05	0.03	0.00	0.00	0.00
5	BI	0.15	0.15	0.14	0.15	0.07
	BSW	0.21	0.21	0.21	0.21	0.16
	BC	0.21	0.21	0.13	0.21	0.06
	BS	0.06	0.05	0.00	0.00	0.00
6	BI	0.13	0.13	0.12	0.13	0.07
	BSW	0.18	0.18	0.18	0.18	0.14
	BC	0.18	0.18	0.12	0.18	0.06
	BS	0.06	0.05	0.00	0.00	0.00
7	BI	0.12	0.12	0.11	0.12	0.06
	BSW	0.16	0.16	0.16	0.16	0.13
	BC	0.16	0.16	0.11	0.16	0.06
	BS	0.06	0.05	0.00	0.00	0.00
8	BI	0.11	0.11	0.10	0.11	0.06
	BSW	0.15	0.15	0.15	0.15	0.12
	BC	0.15	0.15	0.10	0.15	0.05
	BS	0.05	0.05	0.00	0.01	0.00
9	BI	0.10	0.10	0.09	0.10	0.05
	BSW	0.13	0.13	0.13	0.13	0.11
	BC	0.13	0.13	0.09	0.13	0.05
	BS	0.05	0.04	0.00	0.01	0.00

To evaluate specific security levels between zero and one it is necessary to identify a specific cutoff value that conclusively separates high risk from low risk transmission lines (relative to cascading at the specified conditions). However, the cascading potential of a steel pole line with a security level of 0.31 is not likely to be the same as the cascading potential of a wood frame line with the same security level. Essentially, the statistical variation of the ultimate strength of wood structures is significantly larger than the statistical variation of the ultimate strength of manufactured steel poles. For example, if the ultimate strength of a steel pole can be predicted with an accuracy of plus or minus ten percent, it is likely that the steel pole fails for critical force ratios between 0.9 to 1.0. Similarly, if the ultimate strength of a wood frame can be predicted with an accuracy of plus or minus thirty percent, it is likely that a wood frame failure occurs for critical force ratios between 0.7 to 1.0. Consequently, the security level cutoff value for a wood frame line is larger than the corresponding value for a steel pole line.

Based on experience, the ultimate strength of a steel pole can be predicted with an accuracy of plus or minus ten percent, the ultimate strength of a lattice tower can be predicted with an accuracy of plus or minus fifteen percent, and the ultimate strength of a wood frame line can be predicted with an accuracy of plus or minus thirty percent. Consequently, the minimum security level required to avoid a cascading failure on a steel structure transmission line, a steel lattice structure line, or a wood structure line range from 0.03, 0.04, or 0.08.