Longitudinal Load and Cascading Failure Risk Assessment (CASE)

Tennessee Valley Authority's 161-kV
Lowndes-West Point Transmission Line

TR-108479

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REPORT SUMMARY

EPRI's Cascading Failure Risk Assessment (CASE) methodology was used to determine extreme event, unbalanced loads on Tennessee Valley Authority's (TVA) 161-kV, single circuit, Lowndes-West Point transmission line. CASE also identified the line's cascading potential under different loading conditions.

Background

Analysts used CASE to assess TVA's 161-kV, single circuit, Lowndes-West Point transmission line. Other cascading assessment methods primarily focus on the magnitude of unbalanced loads acting on the first structure from the initiating event. EPRI's CASE assessment method incorporates the dynamic response and damping characteristics of the transmission line to determine unbalanced longitudinal loads at any structure away from the initiating failure event. One primary advantage of the CASE method is that containment boundaries are based on the line's importance to the operation of TVA's electric grid. The CASE method predicts the unbalanced longitudinal loads at any structure within the containment boundary and at the critical containment structure. The critical containment structure is the first structure away from the initiating failure event that is not lost to a cascading failure.

Objectives

- To quantify unbalanced longitudinal loads acting on structures adjacent to the broken insulator, shield wire, or conductor failure as well as downline structures.
- To assess the cascading potential of the Lowndes-West Point transmission line by considering energy dissipation at successive spans and supports.

Approach

Analysts performed a cascading failure risk assessment on TVA's 161-kV Lowndes-West Point transmission line using EPRI's CASE methodology. Specifically, TVA wanted to evaluate the cascading potential of the Type HS-1G and BHS-1G tangent structures that comprise the majority of the line. A review of the line profile revealed that there were a number of critical line segments that are inherently more likely to experience a cascading failure than the remaining segments. The cascading failure risk assessment focused on support structures and dynamic line parameters in those segments.

Results
Assessment results showed that lack of longitudinal strength in the Type HS-1G and BHS-1G steel pole H-frame coupled with the dynamic characteristics of the Lowndes-West Point line was likely to cause a cascading failure for a number of initiating event and load case combinations.

EPRI Perspective
To implement a mitigation approach that maximizes reliability while minimizing cost, it is important for utilities to assess a line's cascading risk. Identifying a line's current level of risk allows utilities to target the system components of the line that are most critical to maintaining the system's primary function — delivery of electric power. As a result, utilities will be able to implement cost-effective solutions to minimize outages while improving power transfer and quality on their transmission line systems. One primary advantage of the CASE method is that containment boundaries are based on the line's importance to the utility.

TR-108479

Interest Categories
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Keywords
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Transmission line failures
Overhead transmission
Transmission lines

ABSTRACT

The Electric Power Research Institute's (EPRI) Cascading Failure Risk Assessment (CASE) methodology was used to determine extreme event, unbalanced loads on Tennessee Valley Authority's (TVA) 161-kV, single circuit, Lowndes-West Point transmission line and to identify the cascading potential of the line under five different loading conditions. More specifically, TVA wanted to evaluate the cascading potential of the Type HS-1G and BHS-1G tangent structures which comprise the majority of the line. While other cascading assessment methods primarily focus on the magnitude of the unbalanced loads acting on the first structure from the initiating event, EPRI's CASE 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 application constituted an investigation into the nature of the extreme loads that are expected to occur on the 161-kV Lowndes-West Point transmission line during a cascading failure and the corresponding dynamic response. The goals of the investigation were:

- To quantify unbalanced longitudinal loads acting on structures adjacent to the broken insulator, shield wire, or conductor failure as well as down-line structures.
- To assess the cascading potential of the Lowndes-West Point transmission line by considering the energy dissipation at successive spans and supports.

One of the primary advantages of the CASE method is that containment boundaries can be defined based on the importance of the line to the operation of TVA's electric grid. This flexibility allows the CASE method to predict the unbalanced longitudinal loads at any structure within the containment boundary and at the critical containment structure.

The results of the CASE method indicate that the lack of longitudinal strength of the Type HS-1G and BHS-1G steel pole H-frame coupled with the dynamic characteristics of the Lowndes-West Point line was likely to result in a cascading failure for the more severe initiating event and load case combinations.

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INTRODUCTION

Deregulation and competition have changed the electric power industry's business environment. The emphasis has shifted to minimizing costs and maximizing the 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.

A number of catastrophic transmission line failures have occurred in the recent past when a multitude of support structures failed longitudinally or transversely along the line. These cascading failures caused the affected utilities extremely high economic losses because these failures 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 high dynamic loads at each structure. A successful and economic line design or upgrade requires the acceptance of a limited number of structure failures 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. Identifying a line's current level of risk allows a utility to target the system components of the line that are most critical to maintaining the system's 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, the Electric Power Research Institute's (EPRI's) **C**ascading F**a**ilure Ri**s**k Ass**e**ssment (CASE) methodology was used to determine extreme event, unbalanced loads on Tennessee Valley Authority's (TVA's) 161-kV, single circuit, Lowndes-West Point transmission line and to identify the cascading potential of the line under different loading conditions. While other cascading assessment methods primarily focus on the magnitude of the unbalanced loads acting on the first structure from the initiating event, EPRI's 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.

One of the primary advantages of the CASE method is that containment boundaries are defined based on the importance of the line to the operation of TVA's electric grid. This flexibility allows the CASE method to predict the unbalanced longitudinal loads at any structure within the containment boundary and at the critical containment structure. The critical containment structure is defined as the first structure away from the initiating failure event that is not lost to a cascading failure (i.e., the structure at which a cascading failure is arrested).

1.1 Background

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 was 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, in 1958 P.P. Bonar (1) stated 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 "...that the failure of these elements should not be considered in tower design...", while a 1960 AIEE survey (3) 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 vertical forces caused by wind and ice loading on the conductors and shield wires. The consensus of the industry was that it was not economical to design transmission structures to withstand extreme event loads. Consequently, an increasing number of new transmission lines were designed and constructed with reduced longitudinal resistance to extreme event loads.

Since the early 1960's, numerous cases of multiple transmission structure failures have been documented that can be directly related to the lack of nationally recognized or mandated design provisions for longitudinal strength. Records indicate that over a period of 35 years, at least 28 different cascading failures have occurred nationwide, resulting 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 resulting from significant wind or ice loads, it is apparent that a sizable number of these cascades occurred under normal loading conditions. Some of the cascades which occur under otherwise normal loading conditions may be caused by elevated temperature operation resulting in failures of conductors and splices. 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

The CASE assessment constituted of an investigation into the nature of the extreme loads that are expected to occur on the 161-kV Lowndes-West Point transmission line during a cascading failure and the corresponding dynamic response. The goals of the investigation were:

- To quantify unbalanced longitudinal loads acting on structures adjacent to the broken insulator, shield wire, or conductor failure as well as down-line structures.
- To assess the cascading potential of the Lowndes-West Point transmission line by considering the energy dissipation at successive spans and supports.

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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 seem 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 up 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 people 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 (Part 2, Section 252-C1) requires that when sections of Grade B construction are required in lines of lower than Grade B construction that the unbalanced longitudinal loads in the direction of the higher construction grade be considered 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 (e.g., dead ends), specific line characteristics (e.g., unequal spans), or particular construction situations (e.g., 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.' (Part 2, Section 252-C3)
>
> '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.' (Part 2, Section 252-C4)
>
> 'Consideration should be given to longitudinal loads that may occur on the structure during wire stringing operations.' (Part 2, Section 252-C5)
>
> 'It is recommended that structures having a longitudinal strength capability be provided at reasonable intervals along the line.' (Part 2, Section 252-C6)
>
> '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.' (Part 2, Section 252-D)

Unfortunately, the NESC code neither provides any 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 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 (Section I, Rule 13). 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, 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.' (Section IV, Rule 47.3)

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 pounds. 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.' (Section IV, Rule 47.4)

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.' (Section IV, Rule 47.5)

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 (Section VI, Rule 61.3-B). 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 (Section VI, Rule 61.3-B).

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 transmission line structure cascading can be reduced by one of three methods. These methods are:

- Design All Structures for Broken Wire Loads: 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. (Section 3.1.2.1)

- Install Stop Structures at Specified Intervals: 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. (Section 3.1.2.2)

- Install Release Mechanisms: 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. (Section 3.1.2.3)

Additionally, the ASCE Manual provides supplemental information on longitudinal loads resulting from stringing and broken wires with comments 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

LOWNDES-WEST POINT TRANSMISSION LINE

The transmission line evaluated in this Cascading Failure Risk Assessment project is TVA's 161-kV, single circuit, steel H-frame transmission line from Lowndes to West Point which ties into the existing connection from West Point to the Alabama State line. The transmission line was designed to meet the minimum requirements of the National Electric Safety Code. An extreme event, longitudinal load was not considered in the design. The overall length of the transmission line from Lowndes to West Point is approximately 22 miles.

A review of the line profile reveals that there are a number of critical line segments that are inherently more likely to experience a cascading failure than the remaining segments. These critical segments, in no particular order, stretch from structure No. 10 to No. 17, No. 21 to No. 54, No. 56 to No. 63, No. 65 to No. 81, No. 83 to No. 91, and No. 97 to No. 135. Upon a closer review of the segments, one will notice that there are two segments that are more likely to experience a cascading failure with more than 10 to 15 structures involved (i.e., Segments from No. 21 to No. 54 and No. 97 to No. 135). Consequently, the cascading failure risk assessment will focus on the support structures and dynamic line parameters found in those two segments.

Further review of the line and profile reveals that the majority of the support structures in the two focus transmission line segments consist of either the Type HS-1G or the BHS-1G steel pole H-frames which both have similar characteristics. These structures are described in more detail in Section 3.2.

3.1 Conductors, Ground Wires, Fiber Optic Wires, and Insulators

The phase conductors of the Lowndes-West Point 161-kV transmission line consist of a single 1590 kcmil 45/7 ACSR 'Lapwing' conductors arranged in a horizontal single circuit configuration. The average weight span and ruling span of the line (segment from No. 21 to No. 54) are 750 and 800 feet, respectively. The average weight span and ruling span of the second line segment (segment from No. 97 to No. 135) are approximately 1050 and 1000 feet, respectively. There is one 3 No. 6 Alumoweld ground wire attached to the top of one of the two H-frame steel poles while an 80 mm^2 Optical Ground Wire (OPGW) attaches to the top of the other steel pole. The conductors, ground wire, and the optical ground wire of the first segment are strung at approximately 14%, 6.5%, and 7.5% of the Rated Tensile Strength (RTS) at a temperature of 60°F, respectively. Stringing tensions in the second segment are approximately 19%, 9.5% and 10% of the RTS for the conductor, ground wire, and optical ground wire, respectively. The phase conductors are supported by ceramic suspension insulators while the 3 No. 6 and optical ground wires are attached directly to the shield wire cross-arm of the H-frame structure. The length of each suspension insulator is approximately six feet.

3.2 Single Circuit Steel H-Frames

The structures most prevalent on the Lowndes-West Point transmission line are the Type HS-1G and BHS-1G steel pole H-frames, with pole heights varying from 75 to 120 ft and an average pole height of 85 feet. In addition to angle and dead end configurations, other structures include the S-1G single circuit steel pole, the DS-1G double circuit two pole frame, the B-37 and C-37 500-kV single circuit towers with underbuild, and the A-24 single circuit lattice tower.

Experience shows that light angle structures are very similar to tangent structures with respect to their dynamic response (i.e., light angle structure bi-sector guys contribute negligible stiffness in the longitudinal direction of the line resulting in a similar load-displacement-frequency response). Consequently, the light angle structures in the line were not considered separately from the Type HS-1G and BHS-1G H-frames in the cascading failure risk assessment. Medium and heavy angle H-frames and dead end structures have been omitted from the assessment since they do not significantly change the results of the risk assessment for the straight line segments.

Figure 3-1 is a sketch of the Type HS-1G H-frame that shows the overall layout of the structure including dimensions of the transverse face. Similarly, Figure 3-2 shows a sketch of the Type BHS-1G configuration. Essentially, the BHS-1G structure is equivalent to the HS-1G structure except for the addition of a set of outside cross-arm braces and a doubled-up ground wire cross-arm. More detailed drawings of the HS-1G and BHS-1G structures are included in Appendix A.

3.3 Span Lengths, Sags, and Tensions

The weight span of the line for the HS-1G structures varies from 650 to 810 ft (i.e., 800-ft ruling span used in CASE assessment of first segment). Similarly, the average weight span of the line for the BHS-1G structures varies from 900 to 1150 ft (i.e., 1000-ft ruling span used in assessment of second segment). Conductor, ground wire, and fiber optic wire sags and tensions were calculated for each load case and verified using TVA's sag-tension tables wherever appropriate. Tables 3-1 and 3-3 show the sag values for each load case (i.e., Service Load (SL), Cold Temperature (CT), NESC, Extreme Wind (EW), and Extreme Ice (EI)) considered in the cascading failure risk assessment for the HS-1G and BHS-1G structures. Tables 3-2 and 3-4 show the tension values for these load cases. The load cases are described further in Section 4.0.

Table 3-1
Ground Wire, Optical Wire and Conductor Sags - 800' Span

Structure from Failure	Line Component	Span Length (ft.)	**Tangent Structure - HS1G Sags (ft.)**				
			SL Sag	CT Sag	NESC Sag	EW Sag	EI Sag
1 to 10	SW	800	22.27	20.65	25.66	24.69	33.01
	OW	800	22.39	20.57	23.32	23.85	28.30
	C	800	26.61	24.34	25.29	27.19	27.50

Table 3-2
Ground Wire, Optical Wire and Conductor Tensions - 800' Span

Structure from Failure	Line Component	Span Length (ft.)	**Tangent Structure - HS1G Tensions (lb.)**				
			SL Tension	CT Tension	NESC Tension	EW Tension	EI Tension
1 to 10	SW	800	642	693	2074	1318	4640
	OW	800	1637	1782	3457	2571	7024
	C	800	5419	5920	8368	7045	14464

Table 3-3
Ground Wire, Optical Wire and Conductor Sags - 1000' Span

Structure from Failure	Line Component	Span Length (ft.)	**Tangent Structure -BHS1G Sags (ft.)**				
			SL Sag	CT Sag	NESC Sag	EW Sag	EI Sag
1 to 10	SW	1000	24.94	22.85	31.08	29.08	41.98
	OW	1000	25.68	23.36	27.89	28.14	35.45
	C	1000	31.66	28.77	30.33	32.62	33.82

Table 3-4
Ground Wire, Optical Wire and Conductor Tensions - 1000' Span

Structure from Failure	Line Component	Span Length (ft.)	**Tangent Structure - BHS1G Tensions (lb.)**				
			SL Tension	CT Tension	NESC Tension	EW Tension	EI Tension
1 to 10	SW	1000	896	978	2673	1748	5702
	OW	1000	2229	2450	4514	3404	8763
	C	1000	7114	7823	10898	9173	18374

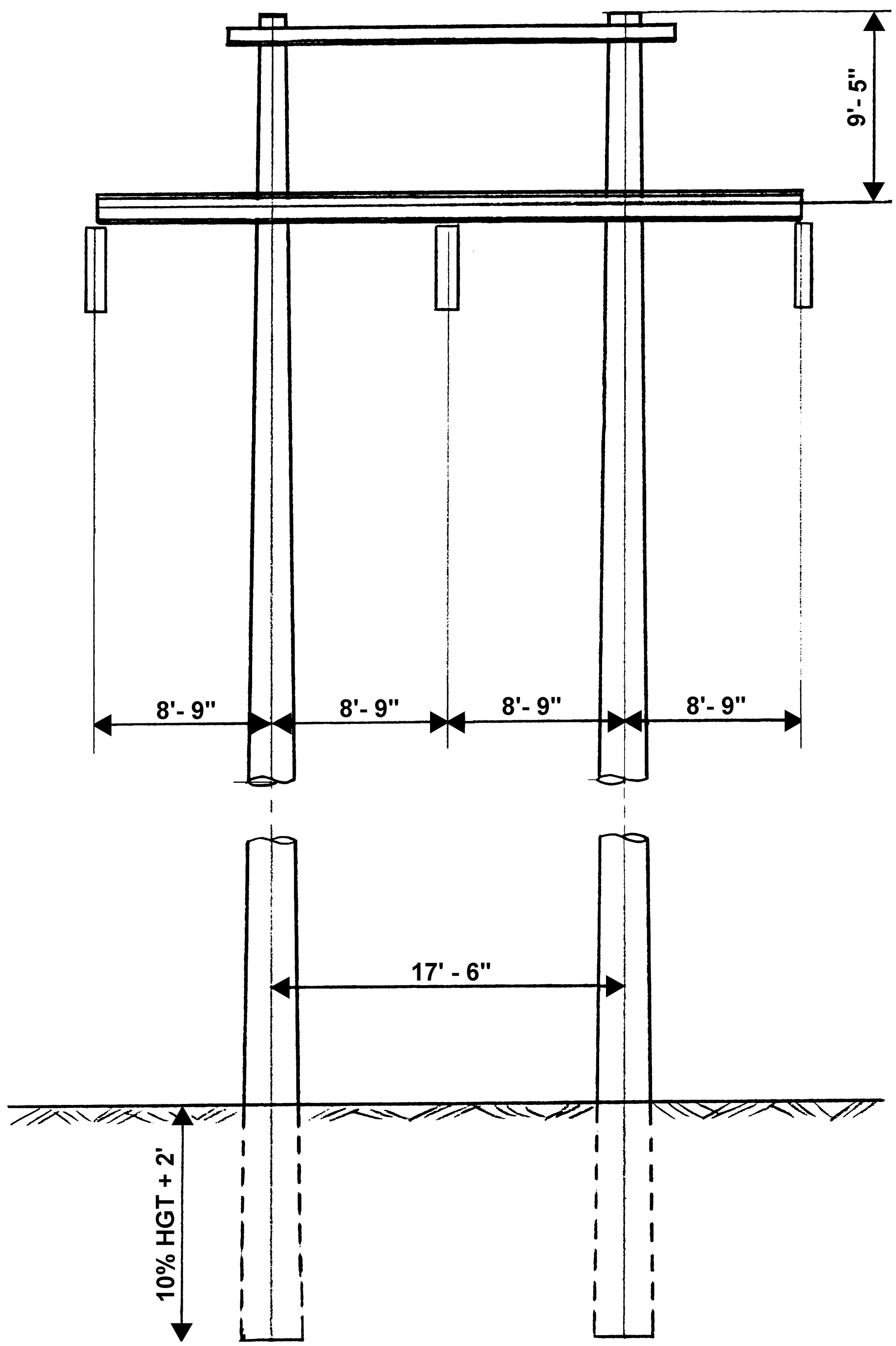


Figure 3-1
Type HS-1G Steel Pole H-Frame

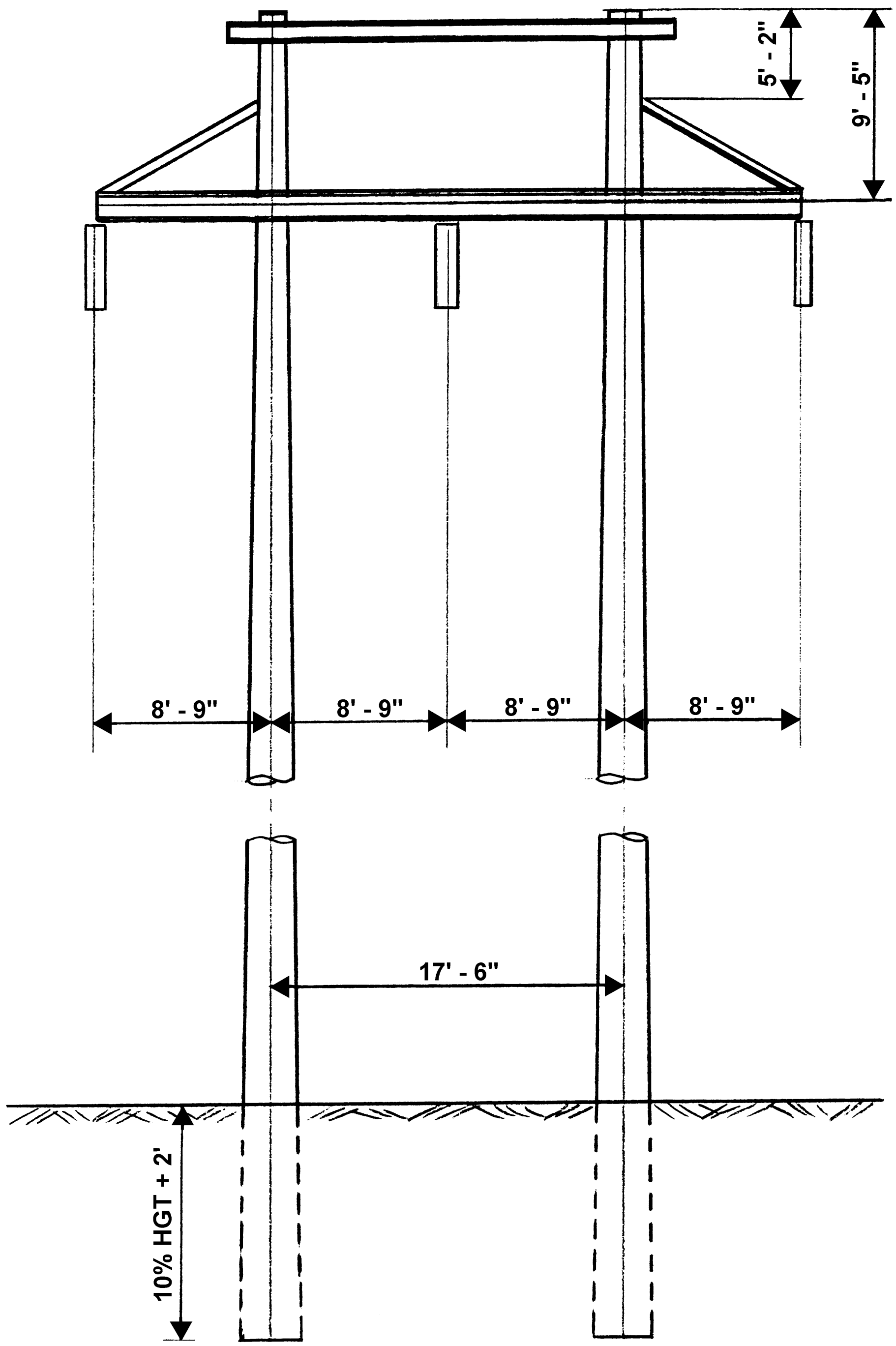


Figure 3-2
Type BHS-1G Steel Pole H-Frame

4

CASCADING FAILURE RISK ASSESSMENT (CASE)

The simplified Cascading Failure Risk Assessment (CASE) method was developed based on analytical and experimental studies (2, and 7 through 17) 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. However, the magnitudes of the longitudinal loads calculated at the sixth, seventh, or eighth structure are typically not critical since it is commonly assumed that containment of a cascading failure can not be achieved if the third or fourth structure fails.

While all parameters calculated using the cascading failure risk assessment method are presented as exact values, it should be remembered that there are a variety of assumptions made in the prediction of the cascading potential. Conditions such as greatly varying spans, elevation differences, and other related line parameters influence the results and their effects should be considered in the evaluation and interpretation of the results.

Additionally, the cascading failure risk assessment method relies on the prediction of the ultimate load carrying capacity of a structure for a load applied to any of the wire attachment points which is usually based on a collapse load analysis. Such an analysis is based on a variety of assumptions with respect to the engineering parameters and analysis models used that may or may not be appropriate for each structure.

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 I, II, III, and IV, of EPRI's report TR-107087 (7 through 10).

4.1 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.

4.1.1 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.

4.1.2 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.

4.1.3 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 (i.e., NESC Medium used in the TVA study).

4.1.4 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 (i.e., 70 mph NESC Extreme Wind used in the TVA study).

4.1.5 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.

4.2 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 actually 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 clevises or pins, and/or structural failures of support arms.

4.2.1 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.

4.2.2 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.

4.2.3 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.

4.2.4 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.

4.3 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.

4.4 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.

4.4.1 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.

4.4.2 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.

4.4.3 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 4-1 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:

$$d_{\mathrm{N}} = \mathrm{e}^{-(\mathrm{N}/3)} \qquad \text{(eq. 4-1)}$$

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 $N+1_{th}$ structure along the transmission line, counting from the initial failure (i.e., the location at which the initiating event occurred). The amount of energy transferred decreases exponentially as the distance from the initial failure increases.

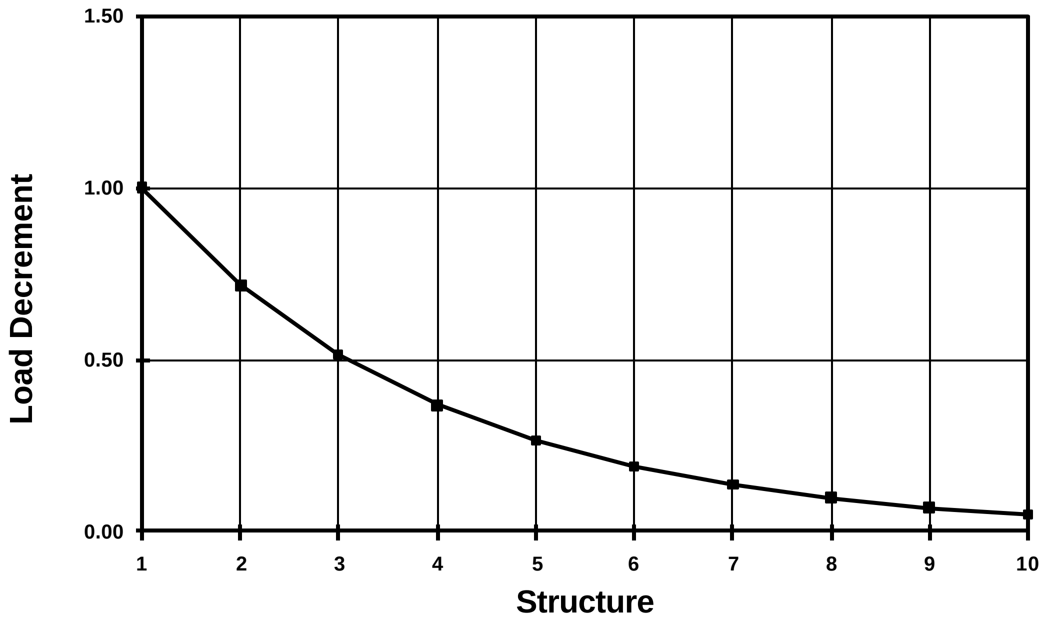


Figure 4-1
Load Decrement Coefficient

4.4.4 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 (Y_0) is constant. Response coefficients are required to determine the longitudinal load factor on each support structure. The response coefficients for each structure equal:

$$Y_1 = Y_0 \qquad \text{(eq. 4-2a)}$$

$$Y_N = \frac{Y_0}{\left(e^{d_{N-1}}\right)!} \qquad \text{(eq. 4-2b)}$$

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 4-2 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.

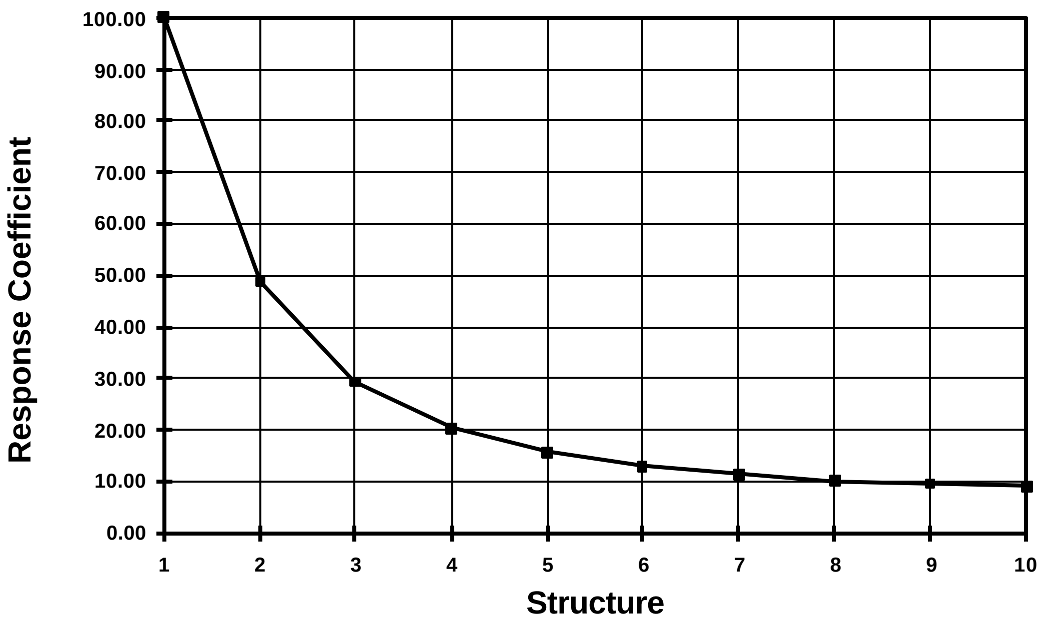


Figure 4-2
Load Response Coefficient

4.4.5 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 and 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:

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

$(LLF)_N$ - 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 4-3 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.

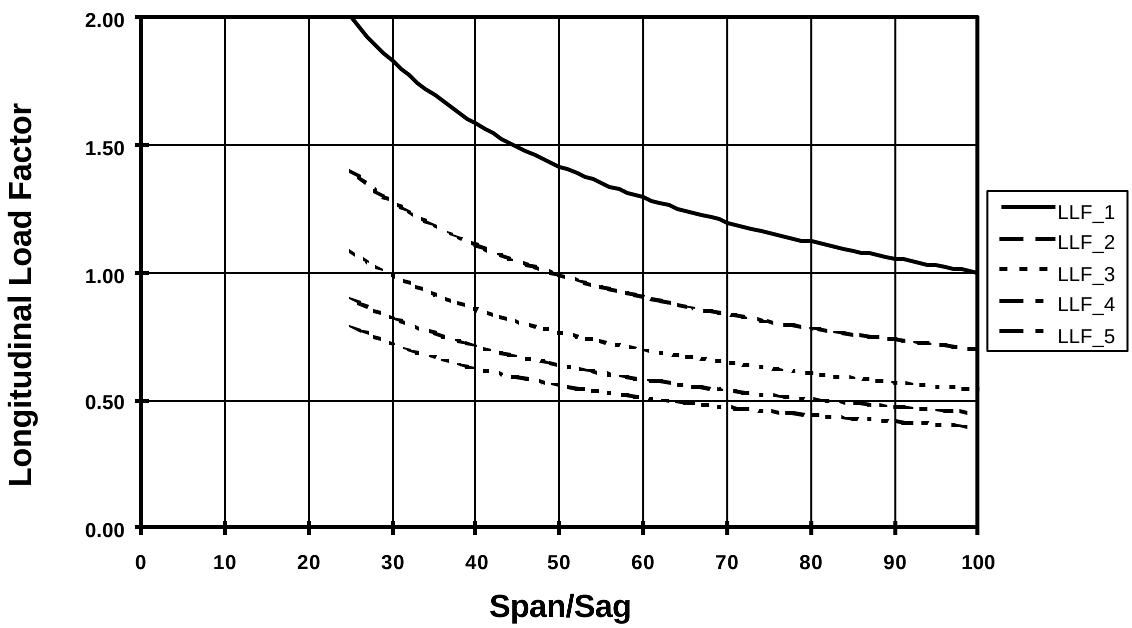


Figure 4-3
Longitudinal Load Factor

4.4.6 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:

$$(CF_{S/I})_{\mathrm{N}} = 1 \qquad \text{(Optical/Shield Wire)} \qquad \text{(eq. 4-4a)}$$

$$(CF_{S/I})_{\mathrm{N}} = \left(1 - \frac{\left(S/I\right)_N}{2000}\right) \qquad \text{(Conductor)} \qquad \text{(eq. 4-4b)}$$

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

$(S/I)_N$ - Span/Insulator Ratio for N_{th} Structure (50<(S/I)<200)

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

Figure 4-4 shows the variation of the $(CF_{S/I})_N$ as a function of the span/insulator ratio. The $(CF_{S/I})_N$ equals 0.975 for a span/insulator ratio of 50 and the value of the $(CF_{S/I})_N$ decreases linearly to 0.90 for a span/insulator ratio of 200.

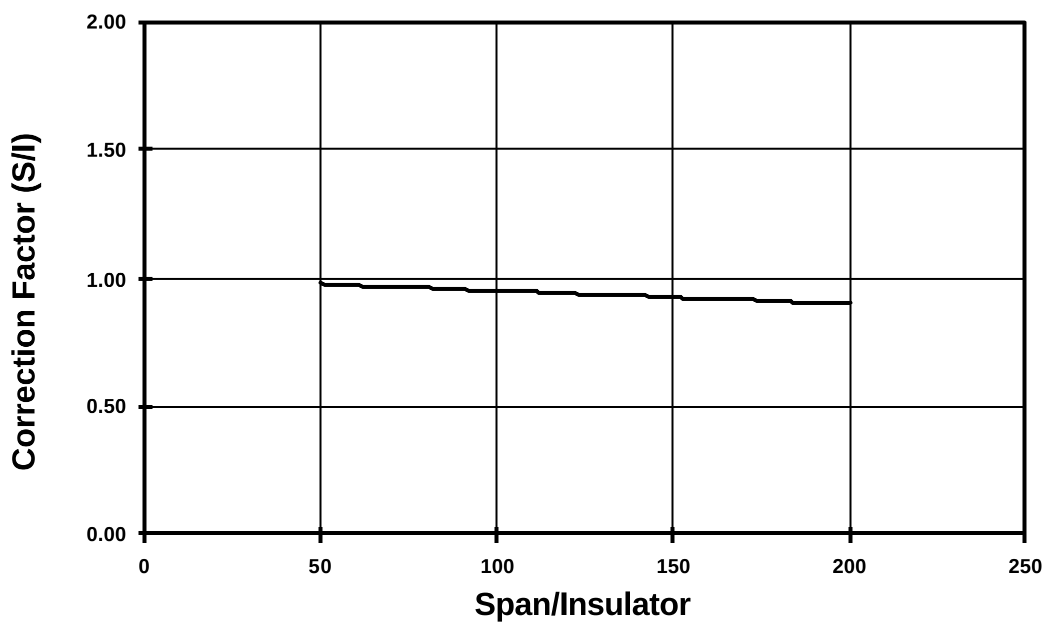


Figure 4-4
Correction Factor for Span/Insulator Ratio

4.4.7 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 flexibility 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:

$$(CF_{1/K})_{\mathrm{N}} = e^{-\left((1/K)_N / 200 \right)} \qquad \text{(eq. 4-5)}$$

$(CF_{1/K})_N$ - 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 4-5 shows the variation of the $(CF_{1/K})_N$ as a function of the structural flexibility of

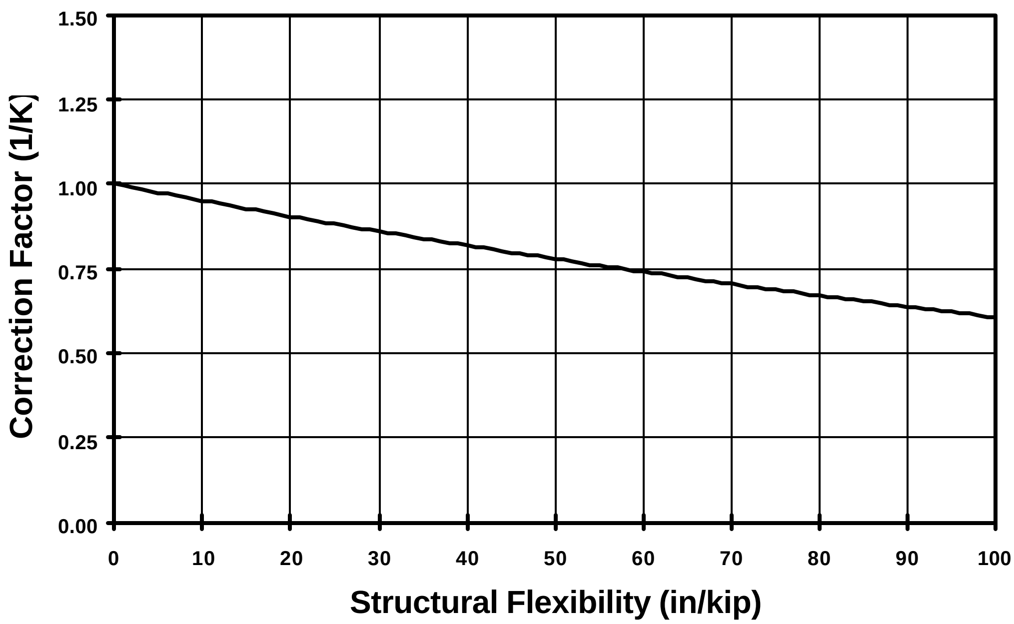


Figure 4-5
Correction Factor for Support Structure Flexibility

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 0.6 for a structural flexibility of 100 in/kip. $(CF_{1/K})_N$ factors of less than 0.7 are rarely justified and should be verified.

4.5 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 N_{th} structure away from the initial failure equals:

$$\left[(H_{UL})_{LS}^{LC}\right]_N = \left[(H)_{LS}^{LC}\right]_N \cdot \left[(LLF)_{LS}^{LC}\right]_N \cdot \left(CF_{S/I}\right)_N \cdot \left(CF_{1/K}\right)_N \qquad \text{(eq. 4-6a)}$$

$(H_{UL})_N$	-	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:

$$\left[H_{UL}\right]_N = \begin{bmatrix} (H_{UL})_{BI}^{SL} & (H_{UL})_{BI}^{CT} & (H_{UL})_{BI}^{NESC} & (H_{UL})_{BI}^{EW} & (H_{UL})_{BI}^{EI} \\ (H_{UL})_{BC}^{SL} & (H_{UL})_{BC}^{CT} & (H_{UL})_{BC}^{NESC} & (H_{UL})_{BC}^{EW} & (H_{UL})_{BC}^{EI} \\ (H_{UL})_{BSW}^{SL} & (H_{UL})_{BSW}^{CT} & (H_{UL})_{BSW}^{NESC} & (H_{UL})_{BSW}^{EW} & (H_{UL})_{BSW}^{EI} \\ (H_{UL})_{BS}^{SL} & (H_{UL})_{BS}^{CT} & (H_{UL})_{BS}^{NESC} & (H_{UL})_{BS}^{EW} & (H_{UL})_{BS}^{EI} \end{bmatrix}_N \qquad \text{(eq. 4-6b)}$$

4.6 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.

4.6.1 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. That is, it is necessary to identify the structure at which:

$$\left[R_U\right]_N - \left[\left(F_{UL}\right)_{LS}^{LC}\right]_N \geq \{0\} \qquad \text{(eq. 4-7)}$$

$[R_U]_N$ - 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:

$$\left[\left(R_U\right)_{LS}^{LC}\right]_N = \begin{bmatrix} P_U \\ V_U \\ M_U \\ T_U \end{bmatrix}_N \qquad \text{(eq. 4-8a)}$$

$$\left[\left(F_{UL}\right)_{LS}^{LC}\right]_N = \begin{bmatrix} \left(P_{UL}\right)_{LS}^{LC} \\ \left(V_{UL}\right)_{LS}^{LC} \\ \left(M_{UL}\right)_{LS}^{LC} \\ \left(T_{UL}\right)_{LS}^{LC} \end{bmatrix}_N \qquad \text{(eq. 4-8b)}$$

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 down time 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.

4.6.2 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 (e.g., 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:

$$\left[(SL)_{LS}^{LC}\right]_I = \frac{1}{I-1} \cdot \sum_{N=1}^{I-1} \ln\left(\frac{\left((CF)_{LS}^{LC}\right)_N}{\left((CF)_{LS}^{LC}\right)_{N+1}}\right) \qquad \text{(eq. 4-9a)}$$

$(CF)_N$ - 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:

$$[SL]_I = \begin{bmatrix} (SL)_{BI}^{SL} & (SL)_{BI}^{CT} & (SL)_{BI}^{NESC} & (SL)_{BI}^{EW} & (SL)_{BI}^{EI} \\ (SL)_{BC}^{SL} & (SL)_{BC}^{CT} & (SL)_{BC}^{NESC} & (SL)_{BC}^{EW} & (SL)_{BC}^{EI} \\ (SL)_{BSW}^{SL} & (SL)_{BSW}^{CT} & (SL)_{BSW}^{NESC} & (SL)_{BSW}^{EW} & (SL)_{BSW}^{EI} \\ (SL)_{BS}^{SL} & (SL)_{BS}^{CT} & (SL)_{BS}^{NESC} & (SL)_{BS}^{EW} & (SL)_{BS}^{EI} \end{bmatrix}_I \qquad \text{(eq. 4-9b)}$$

4.6.3 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 (see EPRI Center Test Reports Volume 1 through 138), 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.

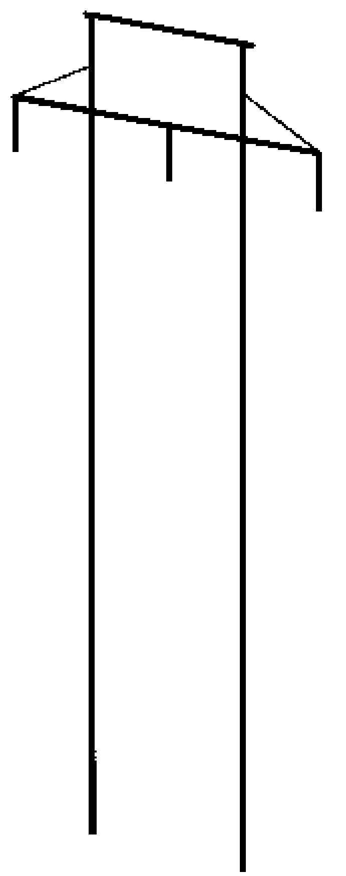
As a result of the uncertainties involved in the prediction of the ultimate strength of a transmission structure and the magnitude of the unbalanced longitudinal load, it may be advantageous to define broader ranges of cascading risk to group transmission lines with similar cascading potential. For example, 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 cascading failure at the third structure from the initiating event is shown in Table 4-1.

Table 4-1
Cascading Potential Classification

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

5

CASE ASSESSMENT OF LOWNDES-WEST POINT TRANSMISSION LINE



General information used in the CASE assessment of the Lowndes-West Point transmission line is shown below. Additional information required to perform the assessment 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 were determined by hand calculations and a detailed structural analysis using Powerline's™ steel frame analysis program SFRAME™. Calculated values were compared to results from full-scale tests of the DS-1G steel frame that was tested at EPRI's Power Delivery Center in Haslet, Texas. In the hand calculation, the transverse, longitudinal, and torsional flexibility were calculated at the centroidal position of the shield wire, fiber optical wire, and phase conductors and the restraining effect of the wires on the structure was neglected.

Table 5-1
Input Parameters Required for CASE Assessment

Load Parameters		
Basic Wind Speed		70 mph
NESC Ice Thickness		0.25 inch
Extreme Ice Thickness		1.00 inch
Average Daily Temperature		60°F
NESC Combined Temperature		15°F
Extreme Wind Temperature		60°F
Extreme Ice Temperature		15°F
Wire Parameters		
Conductor:	1590 kcmil 45/7 ACSR	'Lapwing'
	Diameter	1.504 inch
	Weight	1.79 lb./ft
	Rated Strength	42,200 lb.
Shield Wire:	3 No. 6 Alumoweld	
	Diameter	0.349 inch
	Weight	0.178 lb./ft
	Rated Strength	10,200 lb.
Fiber Optic Wire	80 MM SQ Cable	
	Diameter	0.587 inch
	Weight	0.456 lb./ft
	Rated Strength	23,060 lb.
Sag/Tension:	Shield Wire	Table (5-2)
	Fiber Optic Cable	Table (5-3)
	Conductor	Table (5-4)
Insulators:	I-String	6 ft
Line Parameters		
Tangent Structure - HS-1G:	Front Span	800 ft
	Back Span	800 ft
Tangent Structure - BHS-1G:	Front Span	1000 ft
	Back Span	1000 ft

5.1 Sag and Tension

Sag and tension values for the conductor and shield wire were determined by means of a sag-tension analysis program for a variety of temperature and loading conditions. Sag and tension values for the shield wires, fiber optic wires, and phase conductors are shown in Table 5-2, 5-3, and 5-4 for ruling spans of 800 ft and 1000 ft, respectively. Sag-tension values were determined with SAG/T™, the sag-tension analysis program at temperatures ranging from 15 to 60 °F.

Table 5-2

Sag-Tensions of 3 No. 6 Alumoweld Ground Wire

3 No. 6 Alumoweld, 2150 lb. (1/4” Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
15	1	2	0	0	None	33.01	4640	33.01	4640
15	0.25	4	0.2	0	Design	24.73	2150	25.66	2074
15	0	0.25	0	0	None	18.91	756	20.65	693
60	0	12.5	0	0	None	23.48	1386	24.69	1318
60	0	0	0	6.5	None	20.59	694	22.27	642

3 No. 6 Alumoweld, 2850 lb (1/4” Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
15	1	2	0	0	None	41.98	5702	41.98	5702
15	0.25	4	0.2	0	Design	29.14	2850	31.08	2673
15	0	0.25	0	0	None	19.21	1162	22.85	978
60	0	12.5	0	0	None	26.54	1914	29.08	1748
60	0	0	0	6.5	None	21.38	1044	24.94	896

Table 5-3

Sag-Tensions of 80 MM Fiber Optic Wire

80 mm^2 OPGW, 3600 lb (1/4” Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
15	1	2	0	0	None	28.30	7024	28.30	7024
15	0.25	4	0.2	0	Design	22.38	3600	23.32	3457
15	0	0.25	0	0	None	19.25	1903	20.57	1782
60	0	12.5	0	0	None	22.77	2692	23.85	2571
60	0	0	0	7.3	None	21.14	1733	22.39	1637

80 mm^2 OPGW, 4825 lb (1/4” Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
15	1	2	0	0	None	35.45	8763	35.45	8763
15	0.25	4	0.2	0	Design	26.08	4825	27.89	4514
15	0	0.25	0	0	None	20.53	2786	23.36	2450
60	0	12.5	0	0	None	25.92	3693	28.14	3404
60	0	0	0	7.3	None	22.92	2495	25.68	2229

Table 5-4
Sag-Tensions of 1590 kcmil 45/7 ACSR 'Lapwing'

1590 kcmil ACSR 'Lapwing', 9000 lb (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
15	1	2	0	0	None	26.90	14782	27.50	14464
15	0.25	4	0.2	0	Design	23.49	9000	25.29	8368
15	0	0.25	0	0	None	21.96	6556	24.34	5920
60	0	12.5	0	0	None	25.13	7618	27.19	7045
60	0	0	0	13.8	None	24.17	5960	26.61	5419

1590 kcmil ACSR 'Lapwing', 12000 lb (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Temperature (°F)	Ice (in)	Wind (psf)	NESC Constant	UTS %	Constraint	Initial Sag (ft)	Initial Tension (lb.)	Final Sag (ft)	Final Tension (lb.)
15	1	2	0	0	None	33.06	18795	33.82	18374
15	0.25	4	0.2	0	Design	27.52	12000	30.33	10898
15	0	0.25	0	0	None	24.93	9017	28.77	7823
60	0	12.5	0	0	None	29.32	10193	32.62	9173
60	0	0	0	13.8	None	27.69	8121	31.66	7114

5.2 Sag, Tension, and Span-Sag Ratio

Sag values used in the CASE assessment for the conductor, shield wire, and fiber optic wire are shown in Table 5-5. Table 5-6 shows a summary of the conductor, shield wire, and fiber optic wire tensions used in the CASE assessment, while Table 5-7 summarizes calculated span/sag ratios. 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., ruling span concept). Different assumptions would have required the calculation of sags and span/sag ratios at each structure from the initiating failure event. However, based on a review of the line characteristics, it was determined that the use of the ruling span length would produce slightly conservative but sufficiently accurate results.

Table 5-5
Sag Values for CASE Assessment

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Structure from Failure	Line Component	Span Length (ft)	Tangent Structure - HS1G Sags				
			SL Sag (ft)	CT Sag (ft)	NESC Sag (ft)	EW Sag (ft)	EI Sag (ft)
1 to 10	SW	800	22.27	20.65	25.66	24.69	33.01
	OW	800	22.39	20.57	23.32	23.85	28.30
	C	800	26.61	24.34	25.29	27.19	27.50

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Structure from Failure	Line Component	Span Length (ft)	Tangent Structure - BHS1G Sags				
			SL Sag (ft)	CT Sag (ft)	NESC Sag (ft)	EW Sag (ft)	EI Sag (ft)
1 to 10	SW	1000	24.94	22.85	31.08	29.08	41.98
	OW	1000	25.68	23.36	27.89	28.14	35.45
	C	1000	31.66	28.77	30.33	32.62	33.82

Table 5-6
Tension Values for CASE Assessment

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Structure from Failure	Line Component	Span Length (ft)	Tangent Structure - HS1G Tensions				
			SL Tension (lb.)	CT Tension (lb.)	NESC Tension (lb.)	EW Tension (lb.)	EI Tension (lb.)
1 to 10	SW	800	642	693	2074	1318	4640
	OW	800	1637	1782	3457	2571	7024
	C	800	5419	5920	8368	7045	14464

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Structure from Failure	Line Component	Span Length (ft)	Tangent Structure - BHS1G Tensions				
			SL Tension (lb.)	CT Tension (lb.)	NESC Tension (lb.)	EW Tension (lb.)	EI Tension (lb.)
1 to 10	SW	1000	896	978	2673	1748	5702
	OW	1000	2229	2450	4514	3404	8763
	C	1000	7114	7823	10898	9173	18374

Table 5-7
Span/Sag Ratios for CASE Assessment

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Structure from Failure	Line Component	Span Length (ft)	Tangent Structure - HS1G Span/Sag Ratios (S/S) SL	(S/S) CT	(S/S) NESC	(S/S) EW	(S/S) EI
1 to 10	SW	800	35.92	38.74	31.18	32.40	24.24
	OW	800	35.73	38.89	34.31	33.54	28.27
	C	800	30.06	32.87	31.63	29.42	29.09

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Structure from Failure	Line Component	Span Length (ft)	Tangent Structure - BHS1G Span/Sag Ratios (S/S) SL	(S/S) CT	(S/S) NESC	(S/S) EW	(S/S) EI
1 to 10	SW	1000	40.10	43.76	32.18	34.39	23.82
	OW	1000	38.94	42.81	35.86	35.54	28.21
	C	1000	31.59	34.76	32.97	30.66	29.57

5.3 Longitudinal Load Factor

Longitudinal load factors were calculated at each structure from the initiating event. Table 5-8 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, 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., 0.25 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 5-8 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.

Table 5-8
Longitudinal Load Factors

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Structure from Failure	Line Component	Span Length (ft)	Tangent Structure - Type HS1G Longitudinal Load Factors				
			LLF SL	LLF CT	LLF NESC	LLF EW	LLF EI
1	SW	800	1.67	1.61	1.79	1.76	2.03
	OW	800	1.67	1.60	1.71	1.73	1.88
	C	800	1.82	1.74	1.78	1.84	1.85
2	SW	800	1.17	1.12	1.25	1.23	1.42
	OW	800	1.17	1.12	1.19	1.21	1.31
	C	800	1.27	1.22	1.24	1.29	1.30
3	SW	800	0.90	0.87	0.97	0.95	1.10
	OW	800	0.90	0.87	0.92	0.93	1.02
	C	800	0.99	0.94	0.96	1.00	1.00
4	SW	800	0.75	0.72	0.81	0.79	0.91
	OW	800	0.75	0.72	0.77	0.78	0.85
	C	800	0.82	0.78	0.80	0.83	0.83
5	SW	800	0.66	0.63	0.71	0.69	0.80
	OW	800	0.66	0.63	0.67	0.68	0.74
	C	800	0.72	0.69	0.70	0.73	0.73

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Structure from Failure	Line Component	Span Length (ft)	Tangent Structure - Type BHS1G Longitudinal Load Factors				
			LLF SL	LLF CT	LLF NESC	LLF EW	LLF EI
1	SW	1000	1.58	1.51	1.76	1.71	2.05
	OW	1000	1.60	1.53	1.67	1.68	1.88
	C	1000	1.78	1.70	1.74	1.81	1.84
2	SW	1000	1.10	1.06	1.23	1.19	1.43
	OW	1000	1.12	1.07	1.17	1.17	1.32
	C	1000	1.24	1.19	1.22	1.26	1.29
3	SW	1000	0.85	0.82	0.95	0.92	1.11
	OW	1000	0.87	0.83	0.90	0.91	1.02
	C	1000	0.96	0.92	0.94	0.98	0.99
4	SW	1000	0.71	0.68	0.79	0.77	0.92
	OW	1000	0.72	0.69	0.75	0.75	0.85
	C	1000	0.80	0.76	0.78	0.81	0.83
5	SW	1000	0.62	0.60	0.70	0.67	0.81
	OW	1000	0.63	0.60	0.66	0.66	0.74
	C	1000	0.70	0.67	0.69	0.71	0.73

5.4 Unbalanced Longitudinal Load

Unbalanced longitudinal loads derived for the Type HS-1G structures are shown in Table 5-9(a) for all five limit states and five load cases. Shaded areas separate the more severe failure mode - load combinations from the less severe incidents. For example, the unbalanced longitudinal loads acting on the third structure away from the initiating failure event at service loads are 503 lb., 1287 lb., 3754 lb., 4513 lb., and 14545 lb. for the broken shield wire, broken fiber optic wire, broken insulator, broken conductor, and broken structure limit state, respectively. Similarly, the unbalanced longitudinal loads acting on the second structure away from the initiating failure event at NESC loading are 2257 lb., 3586 lb., 6793 lb., 8781 lb., and 30858 lb. for the broken shield wire, broken fiber optic wire, broken insulator, broken conductor, and broken structure limit state.

Table 5-9 (a)
Unbalanced Longitudinal Loads - Type HS-1G

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Structure Number	Limit State	Tangent Structure - HS1G Unbalanced Longitudinal Loads UL SL (lb.)	UL CT (lb.)	UL NESC (lb.)	UL EW (lb.)	UL EI (lb.)
1	BSW	931	968	3229	2013	8194
	BOW	2381	2484	5131	3859	11485
	BI	5833	6095	8781	7666	15828
	BC	8346	8721	12565	10969	22647
	BS	26902	28098	44153	36931	84330
2	BSW	651	676	2257	1407	5727
	BOW	1664	1736	3586	2697	8027
	BI	4513	4715	6793	5930	12244
	BC	5833	6095	8781	7666	15828
	BS	18801	19637	30858	25811	58937
3	BSW	503	523	1746	1088	4430
	BOW	1287	1343	2774	2087	6209
	BI	3754	3923	5652	4934	10187
	BC	4513	4715	6793	5930	12244
	BS	14545	15191	23872	19967	45593
4	BSW	419	435	1453	905	3686
	BOW	1071	1117	2308	1736	5166
	BI	3291	3438	4954	4325	8929
	BC	3754	3923	5652	4934	10187
	BS	12101	12639	19861	16612	37933
5	BSW	367	382	1273	794	3231
	BOW	939	979	2023	1522	4528
	BI	2994	3128	4508	3935	8125
	BC	3291	3438	4954	4325	8929
	BS	10607	11078	17408	14561	33249

While the unbalanced longitudinal loads of the wires are not significantly affected by changes in the temperature of the conductors there is a noticeable reduction in the magnitude that can approach differences of up to 15 percent of the cold temperature value. Of course, the largest differences in the magnitude of the unbalanced longitudinal load is typically observed wherever ice loading of the conductors and ground wires is considered. For example, the unbalanced longitudinal load acting on the second structure caused by a broken shield wire when subjected to extreme ice loads (i.e., 1 inch radial ice) is 5727 lb. which is approximately nine times larger than the equivalent unbalanced longitudinal load predicted at service load condition (i.e., 651 lb.).

Unbalanced longitudinal loads are also shown for the first and second structure and the fourth and fifth 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. If a cascading failure is to be arrested within three structures, each tangent structure should be designed to resist the forces acting on the third structure. Consequently, a conservative approach would be to design a dead end structure to resist the forces acting on the first structure from the initiating event.

Unbalanced longitudinal loads derived for the Type BHS-1G structures are shown in Table 5-9(b). Again, shaded areas separate the more severe failure mode - load combinations from the less severe incidents. For the BHS-1G structure the unbalanced longitudinal loads acting on the third structure away from the initiating failure event at service loads are 696 lb., 1756 lb., 4818 lb., 5791 lb., and 18765 lb. for the broken shield wire, broken fiber optic wire, broken insulator, broken conductor, and broken structure limit state, respectively. At the same time, the unbalanced longitudinal loads acting on the second structure away from the initiating failure event at NESC loading are 2995 lb., 4791 lb., 8683 lb., 11224 lb., and 39663 lb. for the broken shield wire, broken fiber optic wire, broken insulator, broken conductor, and broken structure limit state.

Unbalanced longitudinal loads for the BHS-1G steel frame are approximately 30 to 35 percent higher than comparable values for the HS-1G structure. This difference can be attributed mostly to the 30 to 40% higher stringing tensions and the increased span-sag ratios prevalent in the BHS-1G line segment compared to the ratios in the HS-1G line segment. Span-sag ratios in the BHS-1G line segment vary from 24 to 44 while the ratios of the HS-1G segment range from 24 to 39.

Unbalanced longitudinal loads shown in Table 5-9(a) or 5-9(b) 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 (using Table 5-9(b)) is 696 lb. and 5791 lb. for the shield wire and phase conductor, respectively. Similarly, the minimum longitudinal strength to be provided in the event of a single shield wire or phase conductor breakage at extreme ice loads is 5744 lb. and 15459 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 5744 lb. and 8112 lb. (i.e., 1 shield wire and 1 fiber optical wire) and three times 15459 lb. (i.e., single circuit configuration) to avoid a cascading failure.

Table 5-9(b)
Unbalanced Longitudinal Loads - Type BHS-1G

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Structure Number	Limit State	Tangent Structure - BHS1G Unbalanced Longitudinal Loads				
		UL SL (lb.)	UL CT (lb.)	UL NESC (lb.)	UL EW (lb.)	UL EI (lb.)
1	BSW	1287	1344	4285	2711	10624
	BOW	3248	3405	6855	5193	15004
	BI	7486	7847	11224	9798	19983
	BC	10711	11228	16060	14019	28593
	BS	34707	36373	56751	47479	107027
2	BSW	899	940	2995	1894	7425
	BOW	2270	2380	4791	3629	10486
	BI	5791	6071	8683	7580	15459
	BC	7486	7847	11224	9798	19983
	BS	24256	25421	39663	33182	74800
3	BSW	696	727	2317	1466	5744
	BOW	1756	1841	3706	2807	8112
	BI	4818	5051	7224	6306	12862
	BC	5791	6071	8683	7580	15459
	BS	18765	19665	30683	25670	57865
4	BSW	579	605	1928	1219	4779
	BOW	1461	1532	3084	2336	6749
	BI	4223	4427	6332	5527	11273
	BC	4818	5051	7224	6306	12862
	BS	15612	16361	25528	21357	48143
5	BSW	507	530	1690	1069	4189
	BOW	1281	1343	2703	2047	5916
	BI	3843	4028	5761	5029	10257
	BC	4223	4427	6332	5527	11273
	BS	13684	14341	22375	18720	42198

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 service loads or cold temperature loading are likely 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 5-10(a)
Critical Force Ratios - Type HS-1G

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

		Tangent Structure - HS1G Critical Force Ratios				
Structure Number	Limit State	CF SL	CF CT	CF NESC	CF EW	CF EI
1	BSW	0.18	0.18	0.62	0.38	1.00
	BOW	0.45	0.47	0.98	0.74	1.00
	BI	0.97	1.00	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	BSW	0.12	0.13	0.43	0.27	1.00
	BOW	0.32	0.33	0.68	0.51	1.00
	BI	0.75	0.79	1.00	0.99	1.00
	BC	0.97	1.00	1.00	1.00	1.00
	BS	1.00	1.00	1.00	1.00	1.00
3	BSW	0.10	0.10	0.33	0.21	0.84
	BOW	0.25	0.26	0.53	0.40	1.00
	BI	0.63	0.65	0.94	0.82	1.00
	BC	0.75	0.79	1.00	0.99	1.00
	BS	1.00	1.00	1.00	1.00	1.00
4	BSW	0.08	0.08	0.28	0.17	0.70
	BOW	0.20	0.21	0.44	0.33	0.98
	BI	0.55	0.57	0.83	0.72	1.00
	BC	0.63	0.65	0.94	0.82	1.00
	BS	1.00	1.00	1.00	1.00	1.00
5	BSW	0.07	0.07	0.24	0.15	0.62
	BOW	0.18	0.19	0.39	0.29	0.86
	BI	0.50	0.52	0.75	0.66	1.00
	BC	0.55	0.57	0.83	0.72	1.00
	BS	1.00	1.00	1.00	1.00	1.00

5.5 Critical Force Ratio

Critical force ratios (i.e., Ratio of Unbalanced Loads to Ultimate Resistances as defined in Section 4.6.1) are shown in Table 5-10(a) and 5-10(b) for the Type HS-1G and Type BHS-1G tangent structure as a function of the load case and limit state. For example, as shown in Table 5-10(a) (i.e., Type HS-1G), the critical force ratio at the fourth structure away from the initiating event for a broken conductor at NESC 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. On the contrary, in Table 5-10(b) (i.e., Type BHS-1G), the critical load ratio at the fourth structure away from the initiating event for a broken conductor at NESC loading is 0.80 which is not very close to the ultimate resistance of the fourth structure. Consequently, it is more likely that the fourth structure would fail on the HS-1G line segment than on the BHS-1G line segment.

Table 5-10(b)
Critical Force Ratios - Type BHS-1G

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Structure Number	Limit State	Tangent Structure - BHS1G Critical Force Ratios CF SL	CF CT	CF NESC	CF EW	CF EI
1	BSW	0.16	0.17	0.53	0.33	1.00
	BOW	0.40	0.42	0.85	0.64	1.00
	BI	0.83	0.87	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	BSW	0.11	0.12	0.37	0.23	0.92
	BOW	0.28	0.29	0.59	0.45	1.00
	BI	0.64	0.67	0.96	0.84	1.00
	BC	0.83	0.87	1.00	1.00	1.00
	BS	1.00	1.00	1.00	1.00	1.00
3	BSW	0.09	0.09	0.29	0.18	0.71
	BOW	0.22	0.23	0.46	0.35	1.00
	BI	0.54	0.56	0.80	0.70	1.00
	BC	0.64	0.67	0.96	0.84	1.00
	BS	1.00	1.00	1.00	1.00	1.00
4	BSW	0.07	0.07	0.24	0.15	0.59
	BOW	0.18	0.19	0.38	0.29	0.83
	BI	0.47	0.49	0.70	0.61	1.00
	BC	0.54	0.56	0.80	0.70	1.00
	BS	1.00	1.00	1.00	1.00	1.00
5	BSW	0.06	0.07	0.21	0.13	0.52
	BOW	0.16	0.17	0.33	0.25	0.73
	BI	0.43	0.45	0.64	0.56	1.00
	BC	0.47	0.49	0.70	0.61	1.00
	BS	1.00	1.00	1.00	1.00	1.00

One should keep in mind 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 fourth structure (see Table 5-10(a)) from 0.94 to 1.00, indicating failure of the fourth HS-1G structure. Therefore, a more advantageous and conservative approach would be to assume that the fourth HS-1G structure will fail. Based on the critical force ratio of the fifth structure (i.e., 0.83) from the initial event (see Table 5-10(a)), 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.

Table 5-11(a)
Cascading Failure Security Levels - Type HS-1G

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 800 ft Ruling Span

Expected Number of Failed Structures	Limit State	Tangent Structure - HS1G Security Levels				
		Load Case (SL)	Load Case (CT)	Load Case (NESC)	Load Case (EW)	Load Case (EI)
0	BSW	N/A	N/A	N/A	N/A	N/A
	BOW	N/A	N/A	N/A	N/A	N/A
	BI	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	BSW	0.36	0.36	0.36	0.36	0.00
	BOW	0.36	0.36	0.36	0.36	0.00
	BI	0.26	0.24	0.00	0.01	0.00
	BC	0.03	0.00	0.00	0.00	0.00
	BS	0.00	0.00	0.00	0.00	0.00
2	BSW	0.31	0.31	0.31	0.31	0.08
	BOW	0.31	0.31	0.31	0.31	0.00
	BI	0.22	0.21	0.03	0.10	0.00
	BC	0.14	0.12	0.00	0.01	0.00
	BS	0.00	0.00	0.00	0.00	0.00
3	BSW	0.27	0.27	0.27	0.27	0.12
	BOW	0.27	0.27	0.27	0.27	0.01
	BI	0.19	0.19	0.06	0.11	0.00
	BC	0.16	0.14	0.02	0.07	0.00
	BS	0.00	0.00	0.00	0.00	0.00
4	BSW	0.23	0.23	0.23	0.23	0.12
	BOW	0.23	0.23	0.23	0.23	0.04
	BI	0.17	0.16	0.07	0.11	0.00
	BC	0.15	0.14	0.05	0.08	0.00
	BS	0.00	0.00	0.00	0.00	0.00

5.6 Security Level

Cascading Failure Security Levels for the HS-1G structure are shown in Table 5-11(a) 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 that one is willing to lose in an extreme event load case in each direction) in the containment of an initiating event. For example, if one is willing to lose two structures in a broken shield wire event at the service load condition, the security level of the HS-1G structure is 0.31 on a scale ranging from 0 to 1.0. 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 one is willing to lose two structures in a broken conductor event at the service load condition, the security level of the HS-1G structure is 0.14 which is significantly lower than 0.31 indicating a higher risk of cascading.

Table 5-11(b)
Cascading Failure Security Levels - Type BHS-1G

Design Condition (1/4" Ice+ 4# Wind @ 15°F+ 0.2) @ 1000 ft Ruling Span

Expected Number of Failed Structures	Limit State	Tangent Structure - BHS1G Security Levels				
		Load Case (SL)	Load Case (CT)	Load Case (NESC)	Load Case (EW)	Load Case (EI)
0	BSW	N/A	N/A	N/A	N/A	N/A
	BOW	N/A	N/A	N/A	N/A	N/A
	BI	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	BSW	0.36	0.36	0.36	0.36	0.09
	BOW	0.36	0.36	0.36	0.36	0.00
	BI	0.26	0.26	0.04	0.17	0.00
	BC	0.18	0.14	0.00	0.00	0.00
	BS	0.00	0.00	0.00	0.00	0.00
2	BSW	0.31	0.31	0.31	0.31	0.17
	BOW	0.31	0.31	0.31	0.31	0.00
	BI	0.22	0.22	0.11	0.18	0.00
	BC	0.22	0.20	0.02	0.09	0.00
	BS	0.00	0.00	0.00	0.00	0.00
3	BSW	0.27	0.27	0.27	0.27	0.18
	BOW	0.27	0.27	0.27	0.27	0.06
	BI	0.19	0.19	0.12	0.16	0.00
	BC	0.21	0.19	0.07	0.12	0.00
	BS	0.00	0.00	0.00	0.00	0.00
4	BSW	0.23	0.23	0.23	0.23	0.16
	BOW	0.23	0.23	0.23	0.23	0.08
	BI	0.17	0.17	0.11	0.15	0.00
	BC	0.19	0.18	0.09	0.12	0.00
	BS	0.00	0.00	0.00	0.00	0.00

Similarly, Cascading Failure Security Levels for the BHS-1G structure are shown in Table 5-11(b). Again, if it is acceptable to lose two structures in each direction from the initiating event, the security level of the BHS-1G structure in a broken shield wire event at the service load condition is 0.31. This equals the security level of the HS-1G structure under the same conditions. However, the security level of the BHS-1G structure for the broken conductor failure mode is 0.22, which is approximately 1.6 times as high as the security level calculated for the HS-1G structure for the same failure mode - load case combination.

As discussed previously in Section 4.6.3, 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). Table 5-12 shows a rough correlation between security levels and cascading potential.

Table 5-12
Cascading Potential Classification

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

Figure 5-1(a) and 5-1(b) show plots of the security levels for the HS-1G and BHS-1G structure (assuming two failed structures in each direction) to visualize the differences in the cascading potential. Cascading potentials of both line segments are similar in shape but differ in magnitude (i.e., security levels calculated for the BHS-1G segment are higher on average than comparable values for the HS-1G segment).

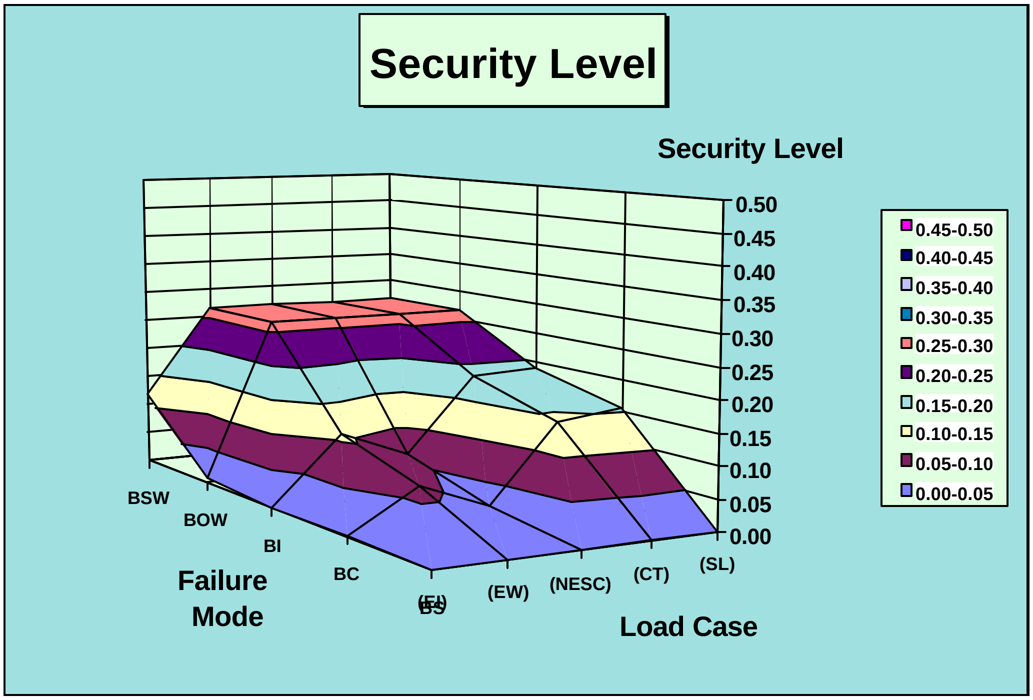


Figure 5-1(a)
Cascading Failure Performance - Type HS-1G

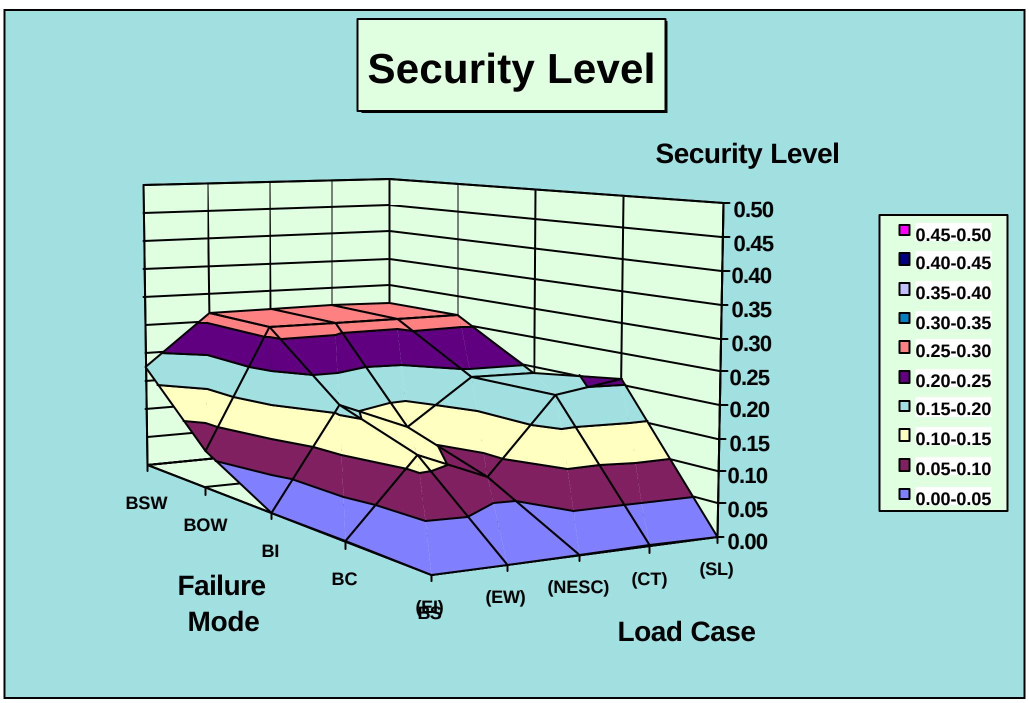


Figure 5-1(b)
Cascading Failure Performance - Type BHS-1G

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CONCLUSIONS

A cascading failure risk assessment was performed on TVA's Lowndes-West Point transmission line. The transmission line is a 161-kV, single circuit, steel H-frame line which ties into the existing connection from West Point to the Alabama State line. A review of the line profile revealed that there are a number of critical line segments that are inherently more likely to experience a cascading failure than the remaining segments. The critical segments stretch from structure No. 10 to No. 17, No. 21 to No. 54, No. 56 to No. 63, No. 65 to No. 81, No. 83 to No. 91, and No. 97 to No. 135. The cascading failure risk assessments were performed on two of these line segments that were identified to have the highest cascading potential. These critical line segments were the segment from structure No. 21 to No. 54 (i.e., mostly HS-1G structures) and the segment from structure No. 97 to No. 135 (i.e., mostly BHS-1G structures).

The results of the assessments show that the cascading potential of the HS-1G line segment is somewhat higher (i.e., lower security levels) than the cascading potential of the BHS-1G line segment for a number of load case and limit state combinations. The difference in the cascading potentials of the two line segments can be directly attributed to the differences in the stringing tensions and the span-sag ratios of the two segments and the differences in the stiffness of the HS-1G and BHS-1G steel H-frames.

The results also suggest that a significant number of the extremely severe load and limit state combinations are likely to cause a cascading failure for either of the two critical line segments. Table 6-1(a) and (b) show an estimate of the number of failed structures and the associated security level for each load case and limit state combination for the HS-1G line segment and the BHS-1G line segment, respectively. For example, the expected number of HS-1G structural failures for NESC loading combined with a broken conductor is 3 (Security Level - 0.02). Similarly, the expected number of BHS-1G structural failures for the same condition is 2 (Security Level - 0.02). Recall that the expected number of failed structures is defined as the number of structures expected to fail in each direction from the initiating event (i.e., the total number of failed structures is equal to twice the values listed in Table 6-1(a) and 6-1(b)). Consequently, the total number of failed structures expected on each of the line segments is 6 and 4, respectively.

Table 6-1(a)
Summary Evaluation of HS-1G Line Segment

Limit State		Lowndes - West Point Transmission Line 'Fiber Optic' Configuration				
		Load Case (SL)	Load Case (CT)	Load Case (NESC)	Load Case (EW)	Load Case (EI)
BSW	Expected Number of Failed Structures Security Level	0 (>0.36)	0 (>0.36)	0 (>0.36)	0 (>0.36)	2 (0.08)
BOW	Expected Number of Failed Structures Security Level	0 (>0.36)	0 (>0.36)	0 (>0.36)	0 (>0.36)	3 (0.01)
BI	Expected Number of Failed Structures Security Level	0 (0.26)	1 (0.24)	2 (0.03)	1 (0.01)	>10 (0.00)
BC	Expected Number of Failed Structures Security Level	1 (0.03)	2 (0.12)	3 (0.02)	2 (0.01)	>10 (0.00)
BS	Expected Number of Failed Structures Security Level	>10 (0.00)	>10 (0.00)	>10 (0.00)	>10 (0.00)	>10 (0.00)

Table 6-1(b)
Summary Evaluation of BHS-1G Line Segment

Limit State		Lowndes - West Point Transmission Line 'Fiber Optic' Configuration				
		Load Case (SL)	Load Case (CT)	Load Case (NESC)	Load Case (EW)	Load Case (EI)
BSW	Expected Number of Failed Structures Security Level	0 (>0.36)	0 (>0.36)	0 (>0.36)	0 (>0.36)	1 (0.09)
BOW	Expected Number of Failed Structures Security Level	0 (>0.36)	0 (>0.36)	0 (>0.36)	0 (>0.36)	3 (0.06)
BI	Expected Number of Failed Structures Security Level	0 (>0.26)	0 (>0.26)	1 (0.04)	1 (0.17)	7 (0.00)
BC	Expected Number of Failed Structures Security Level	1 (0.18)	1 (0.14)	2 (0.02)	2 (0.09)	8 (0.00)
BS	Expected Number of Failed Structures Security Level	>10 (0.00)	>10 (0.00)	>10 (0.00)	>10 (0.00)	>10 (0.00)

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