GROUND LINE MOMENT ANALYSIS OF SINGLE CIRCUIT BODY EXTENDED 161KV TRANSMISSION TOWERS

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A Thesis Submitted to the Faculty of the University of
Tennessee at Chattanooga in Partial
Fulfillment of the Requirements of the Degree
of Master of Science: Engineering

The University of Tennessee at Chattanooga
Chattanooga, Tennessee

December 2018

ABSTRACT

This study simplified the analysis required for the extension of a single circuit tangent 161kV transmission tower. The parameters were modified and modern criteria used to evaluate the tangent tower with various body extensions. The basis of analysis for the extended lattice towers compared the ground-line moment of the tallest tower in each class to the ground-line moment of various tower heights. This study analyzed 62,640 design input combinations for the tower using modern NESC loadings and determined which combinations fall below the maximum design ground-line forces. The ground-line force analysis was modernized by lowering the overload factors from their original design values of to modern NESC Medium Loading Zone values. This decrease in overload factors resulted in a decrease of compression and tension ground-line forces. These decreases in ground-line forces result in an increase of 25% for compression capacity and 33% for tension capacity.

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ρ_{ice}, Density of ice

Att, Attachment Height

d_{ice}, Diameter of Ring of Ice

d_{wire}, Diameter of Wire

H, Horizontal Load

H_{ult}, Ultimate Horizontal Load

HU, Horizontal Unit Load

K, Adjustment Factor

L_{ice}, Load due to Ice

L_{wind}, Load due to Wind

L_{ult}, Ultimate Longitudinal Load

M_H, Horizontal Moment

M_L, Longitudinal Moment

M_V, Vertical Moment

OLF_w, Wind Overload Factor

OLF_t, Tension Overload Factor

T, Tension Load

t_{ice}, Thickness of Ring of Ice

TL, Total Load

V, Vertical Load

V_{ult}, Ultimate Vertical Load

VU, Vertical Unit Load

W, Wind Load

W_C, Weight of Conductor

CHAPTER 1

INTRODUCTION

Background

On August 14, 2003, the Stuart-Atlanta 345kV Transmission Line, owned by Dayton Power and Light, came into direct contact with a tree that had encroached into the cleared right-of-way. This contact caused a short circuit to ground and tripped the circuit breakers on each end of the line. Although this short circuit was not the immediate cause the United States Northeast Blackout of 2003, it, paired with an inadequate understanding of the greater bulk power system in the general area, was a major contributing factor. In the four days that followed, more than 45 million individuals were affected in the United States and Canada with the estimated total cost of the outages exceeding $10 billion. As a direct result of this blackout, many recommendations were made by a joint US-Canadian Task Force to support and strengthen the North American Reliability Corporation. The North American Electric Reliability Corporation (NERC) is an international regulatory authority whose task is to reduce risks to and increase reliability of the bulk electric grid. One of these recommendations was to 'establish enforceable standards for maintenance of electrical clearances in right-of-way areas.' (U.S.-Canada Power System Outage Task Force, 2004)

In the Energy Policy Act of 2005, the United States Congress addressed this recommendation by empowering the Federal Energy Regulatory Commission (FERC) to establish an electric reliability organization (ERO). (Energy Policy Act of 2005, 16 USC § 824o, 2005) On July 20, 2006, FERC selected NERC as the national ERO, effective January 1, 2007. (North American Electric Reliability Corporation, 2017) On October 7, 2010, NERC issued a *Recommendation to Industry* with the following statement:

> NERC has become aware of discrepancies between the design and actual field conditions of transmission facilities, including transmission conductors. These discrepancies may be both significant and widespread, with the potential to result in discrepancies in line ratings. (Adamski, 2010)

After this recommendation, guidance on a method to maintain transmission line ratings was also issued by NERC. The suggested method is outlined below.

- Acquire aerial survey data based on 3D laser scanning (LiDAR)
- Use LiDAR survey data to build right-of-way computer models in PLS-CADD
- Use PLS-CADD to perform sag-tension analysis to identify ratings discrepancies
  - Discrepancies are defined as areas where conductors do not meet NESC clearance requirements
- Document and track ratings discrepancies using various software tools
- Implement permanent remediation measures including some of the following;
  - Raising, modifying, or replacing transmission structures
  - Installing new mid-span transmission structures
  - Installing floating dead-ends
  - Installing dead-ends on towers or cross-arms
  - Re-sagging line sections
  - Installing new conductors

Based on this recommendation and guidance, a review of every high-voltage transmission line in the United States for NESC clearance criteria was initiated to ensure safety and reliability. (North American Electric Reliability Corporation, 2015)

The first enforceable code for transmission line design in the United States, named the National Bureau of Standards (NBS) Circular 49, was published by the NBS in 1916. The circular was updated multiple times between 1916 and 1948, when the final NBS code was issued. This final 1948 code was revised many times over the next twenty five years. In 1973, the Institute of Electrical and Electronic Engineers (IEEE) assumed the functions performed by the NBS and issued the first edition of the modern National Electrical Safety Code (NESC) in 1981. The most recent edition of the NESC was published in 2017. (Institute of Electrical and Electronics Engineers, 2016)

Per the NERC guidance previously described, NESC vertical clearance requirements are to be used to evaluate transmission line clearances to ensure the electrical ratings of each line. A list of the most common clearance requirements are listed below.

Table 1 2017 NESC Clearance Requirements

	Neutral	12.5kV	25kV	35kV
Fields and Forests	15.5'		18.5'	
Railroads	23.5'		26.5'	
Trucks	15.5'		18.5'	
Water - No Sailboats	14.0'		17.0'	
Swimming Pools	22.0'		25.0'	
Signs/Billboards	10.5'		13.5'	
Buildings	10.5'		13.5'	

The 2017 NESC also gives guidance on calculating the maximum sag curves that should be used for the overhead conductor to determine the minimum line clearance. The maximum sag of an electrical conductor can be affected by many different factors including ambient temperature, ice and wind loads, and operating temperatures. (Institute of Electrical and Electronics Engineers, 2016) Figure 1 illustrates a conductor between two lattice steel towers with minimum cold and maximum full load conditions shown.

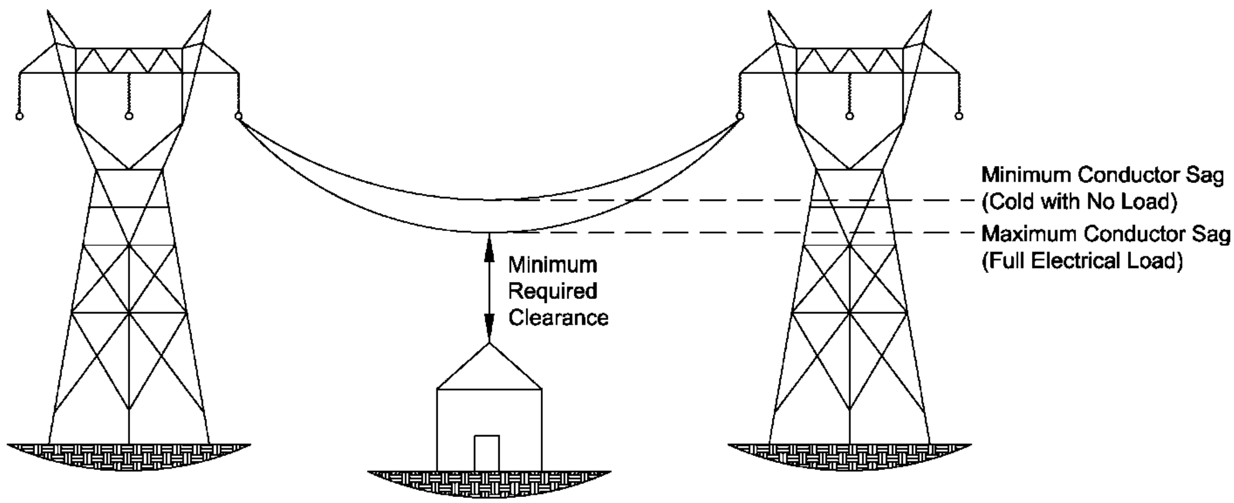

Figure 1 Sags of electrical conductors

Statement of the Problem

Due to evolving electrical codes and environmental conditions, transmission line operators continually evaluate their systems for changing services needs and reliability concerns. These evaluations often require structural modifications to existing transmission line structures. These modifications involve costly structural analysis and design calculations, especially modifications that involve the extension of older steel lattice transmission towers based on outdated and rarely used structural codes.

Objective of the Study

This study simplified the analysis required for the extension of a single circuit tangent 161kV transmission tower using original design criteria, environmental conditions, and overload factors to calculate a maximum allowable ground-line moment. The design parameters were modified and modern environmental conditions and overload factors applied to evaluate the tangent tower with various body extensions. The new ground-line moment was compared to the original design value to determine if the tower will withstand the modified design parameters. Pass and fail rates were calculated and any noticeable trends were recognized and documented. Conclusions were made on the effect the differing design parameters have on the overall effectiveness of the structure.

Scope and Limitations of the Study

For this study, only a single circuit tangent lattice tower was analyzed. Angle, dead end, and double circuit towers were not considered. The design inputs that were selected represent commonly used values as site-specific inputs for real-life application were not available for this study. The ground-line moments found during the course of this study were assumed to be the controlling factor in the original tower design. It is assumed that member failure will not occur if the ground-line moment remains less than the maximum allowed ground-line moment from the original tower design.

Significance of the Study

The resulting calculation from this study was used to evaluate any single circuit tangent tower to model anticipated vertical, horizontal, and longitudinal forces and predict the resulting ground-line moments. The trends that recognized during this study helped simplify the process for tangent tower analysis and enabled the design engineer to make better engineering assumptions when extending lattice transmission towers.

CHAPTER 2

LITERATURE REVIEW

Introduction

Many high voltage transmission lines built in the early-to-mid 20th century use hot-formed steel lattice towers to elevate the conductor and achieve required clearances. Similar modern day lines are often built with steel monopoles, H-frames, or various other structure types due to the increased price of steel and the high labor cost of assembling lattice towers. (Wilhoite, 1985) When a previously discussed NESC rating discrepancy is found on a steel lattice tower transmission line, a simple and cost effective form of mitigation consists of extending the body of the tower to elevate the conductor further than the original tower design. These extended lattice towers require various and unique analysis to ensure they can sustain increased conductor loading and modern environmental conditions after the required height increase for NESC compliance. This chapter will use existing studies to present background information on the analysis and design of transmission towers, their common environmental loadings, and existing studies on lattice tower extensions.

Analysis and Design of Transmission Tower

The goal of this study was to present a method of analysis for a double circuit transmission line tower. Environmental details for this study included wind speeds, maximum and minimum temperatures, and varying factors from the applicable codes used. The tower was a 54 meter (177’) with twelve conductor and one shield wire attachment. The tower face was divided into various panels and the calculated wind load applied to each panel to id in the design the individual tower members. STAAD.Pro is used to verify the results that were found. The study concluded by analyzing a standard tower foundation design that is checked for uplift forces and bearing pressure. (Punsi, 2014)

Structural Behavior of Lattice Transmission Towers Subjected to Wind Load

This paper compared the wind loading of two 400kV transmission line towers analyzed with four different international codes. The codes that were used are the North American ASCE SEI 7, the Australian/New Zealand 1170.2, the Wind Design Chapter of the Civil Engineering Manual of the Mexican Federal Electricity Commission, and the Guidelines of Mexico's Federal District Code. The towers were 53 meter double circuit structures, made with A-572 steel and ASTM A394 bolts, and had maximum line angles of 10 and 60 degrees. A 400 meter span was considered in the analysis with Bluejay ASCR 1113 Conductor tensioned to 9.32 kN. The calculations considered surrounding terrain, structure height and shape, and wind and gust factors under three load cases: wind acting parallel to the conductor, wind acting perpendicular to the conductors, and a broken conductor case.

In the subject study, SAP2000 was used to model the two towers with a linear static analysis that considered the self-weight and tension of the conductors and the wind acting on the tower body. The loading patterns of all four international codes used Bernoulli's Equation of non-aerodynamic bodies to calculate the wind load.

$$\mathbf{F} = \frac{1}{2}\boldsymbol{\rho V}(\boldsymbol{z})^2\boldsymbol{G C_d A_f} \quad (1)$$

These forces were used to find a solidarity ratio, which was defined as the effective solid area on which the winds act divided by the total area of the exposed surface. It was found during this study that the solidarity ratio did not vary along the height of each tower. The final objective of this paper was a nonlinear, pushover analysis based on the horizontal forces from the four structural codes. This analysis also provided a seismic evaluation for the two lattice towers. (Rajalakshmi, 2018)

Analysis and Design of Double Circuit Tower with Extension

This study used an 110kV transmission line with a 9 meter tower extension to achieve the required vertical clearance over the centerline of a railway. The specific tower analyzed is a large angle, 32 meter double circuit structure with a vertical conductor configuration. The environmental conditions used for this study assume a maximum temperature of 36 and a minimum temperature of 30 degrees Celsius. ASCR Panther conductor was used with a 200 meter span. STAAD.Pro V8i is used for modeling the tower and analysis of the load conditions, resulting in calculating the axial forces of each member. The member was then economically sized for the loads that were calculated. This study concluded the bottom tier members of the tower have a large role in withstanding axial forces while the upper tier members are more responsible for lateral and transverse tower deformation. The twisting moment on the tower was found to be insignificant. (Edgar, 2017)

Summary

From the research performed, studies to further the analysis and economical design of lattice towers were commonplace. No studies were found analyzing and comparing the ground-line moment of an existing lattice tower design to an extended tower with similar design parameters.

CHAPTER 3

METHODOLOGY

Introduction

There are four common single circuit lattice towers currently in use by transmission line operators. These tower types include:

- A Tower – Single Circuit Tangent Suspension Tower
- B Tower – Single Circuit Small Angle Suspension Tower
- C Tower – Single Circuit Large Angle Suspension Tower
- D Tower – Single Circuit Dead End Tower

A tangent structure has no line angle as the wires pass the structure. A small angle tower is used for a line angle of up to 4°, while a large angle tower can accommodate a maximum line angle of 17°. These four tower types all support a horizontal configuration of wire, which provides the lowest geometric profile while accommodating necessary phase-to-phase spacing. (Task Committee on Updating Manual 52 of the Structural Division of ASCE, 1988) Of these four tower types, only the dead end tower cannot be extended to meet NESC vertical clearance criteria.

The following table gives the minimum and maximum ground-to-conductor heights for the three extendable towers, with intermediate height intervals of 4 ft, and the available tower extension that can be used with each type.

Table 2 Ground to Conductor Design Heights

Type	Minimum	Maximum	Ext.
A	56	108	12 & 16
B	56	124	14
C	56	124	8

The basis of analysis for the extended lattice towers compared the ground-line moment of the tallest tower in each class under maximum design conditions to the ground-line moment of various tower heights with a variety of design inputs for each design condition. The design inputs used for this analysis are listed below:

- Conductor Selection
    - Weight per Linear Foot (W_C)
    - Diameter of Conductor (d_{wire})
    - Conductor Tension (T)
- Ground Wire Selection
    - Weight per Linear Foot (W_C)
    - Diameter of Wire (d_{wire})
    - Ground Wire Tension (T)
- Design Span
    - Horizontal (Weight) Span
    - Vertical (Wind) Span
- Line Angle

Information for conductor and ground wire selection was found in the Southwire Overhead Conductor Manual, 2nd Edition. (Thrash, 2007)

Ground Line Analysis

To begin the tower analysis, determine the type of conductor and shield wire, the installed tensions of the conductor and shield wire, the horizontal and vertical spans, the wire attachment heights, and the line angle at the subject tower. Conductor and shield wire type and tensions are section dependent and should not change along a line segment. The horizontal and vertical spans, wire attachment heights, and the line angle at the subject tower are structure dependent.

Environmental conditions for transmission line analysis are determined based on geographical location. There are three loading zones in the United States with regard to environmental conditions of overhead electrical lines.

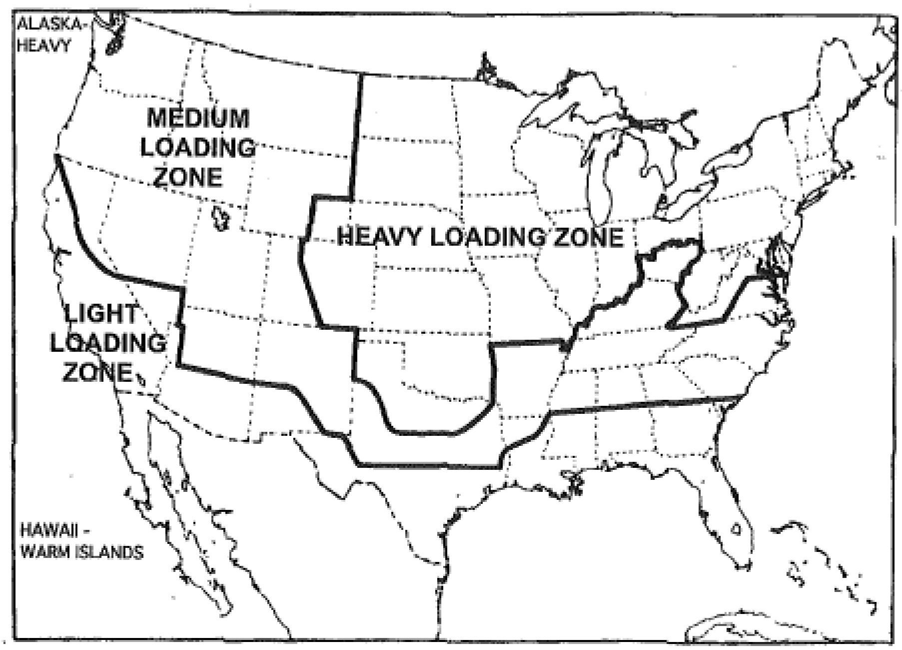

Figure 2 A map of NESC loading zones (Institute of Electrical and Electronics Engineers, 2016)

For this research an NESC Medium Loading Zone will be considered, consisting of a 0.25 inch ring of ice surrounding the conductor (t_{ice}), a 4 psi wind load (*W*), an ambient temperature of 15° Fahrenheit, and an adjustment constant of 0.2 lb./ft (*K*). Load factors in the Medium Zone are 1.5 for vertical loads, 2.5 for transverse wind loads, 1.65 for transverse wire tension loads, and 1.1 for general longitudinal loads. (Institute of Electrical and Electronics Engineers, 2016)

Calculation Procedure

The calculation procedure for the lattice tower analysis described above uses simple statics to determine the ground-line moment. Calculating the total load due to cable properties, weight, and environmental conditions is the first step of the calculation procedure. The load due to the wire weight and the ring of ice that is assumed to form in the NESC Medium Load case is calculated by the equation:

$$\mathbf{L_{ice}} = \mathbf{W_C} + \boldsymbol{\rho}_{\mathbf{ice}} \frac{\pi}{4}\left[(\mathbf{d_{wire}} + \mathbf{2t_{ice}})^2 - \mathbf{d^2_{wire}}\right] \text{ (2)}$$

The load due to the wind on the wire is calculated by the equation:

$$\mathbf{L_{wind}} = \boldsymbol{W_C} \times (\mathbf{d_{wire}} + \mathbf{2t_{ice}}) \text{ (3)}$$

The total load is then calculated by the equation:

$$\mathbf{TL} = \sqrt{\mathbf{L^2_{ice}} + \mathbf{L^2_{wind}}} \text{ (4)}$$

The second step is to determine what percentage of the span will be maintained in a broken wire case. This percentage can be any value between 10% and 90%.

The horizontal and vertical unit loads, the load per linear foot of wire are then calculated by the equations:

$$\mathrm{HU} = \frac{\mathrm{TL}\times[\mathrm{W}(\mathrm{d_{wire}}+2\mathrm{t_{ice}})]}{\mathrm{TL}-\mathrm{K}} \text{ (5)}$$

$$\mathrm{VU} = \frac{\mathrm{TL}\times(\mathrm{W}+\rho_{\mathrm{ice}}\frac{\pi}{4}[(\mathrm{d_{wire}}+2\mathrm{t_{ice}})^2-\mathrm{d^2_{wire}}])}{\mathrm{TL}-\mathrm{K}} \text{ (6)}$$

Overload factors are then used to calculate the Ultimate Loads:

$$\mathrm{H_{ult}} = \mathrm{OLF_{wind}}\mathrm{H}(\mathrm{HU}) + 2(\mathrm{OLF_t})\mathrm{T}\sin\theta \text{ (7)}$$

$$\mathrm{L_{ult}} = \mathrm{OLF_t}(\mathrm{T}) \text{ (8)}$$

$$\mathrm{V_{ult}} = \mathrm{OLF_t}(\mathrm{V})\mathrm{VU} \text{ (9)}$$

The moment created by each cable set is the calculated by multiplying the ultimate loads by their respective attachment heights:

$$M_H = H_{ult} \times \text{Att} \ (10)$$

$$M_L = L_{ult} \times \text{Att} \ (11)$$

$$M_V = V_{ult} \times \text{Att} \ (12)$$

The moments are summed for each load case in all three directions; longitudinal (along the line), transverse (orthogonal to the line), and vertical. The compression and tension ground forces are then derived by decoupling the summed moments based on the width of the tower base.

Original Tower Design

Transmission tower loads are often presented based on combinations of vertical, longitudinal, and transverse loads at defined load points with specific overload factors. The geometric properties and design loadings of the single circuit tangent tower that will be used in this study is shown in Figure 3 below. Any single circuit tangent tower could be analyzed using this method and the result would remain valid.

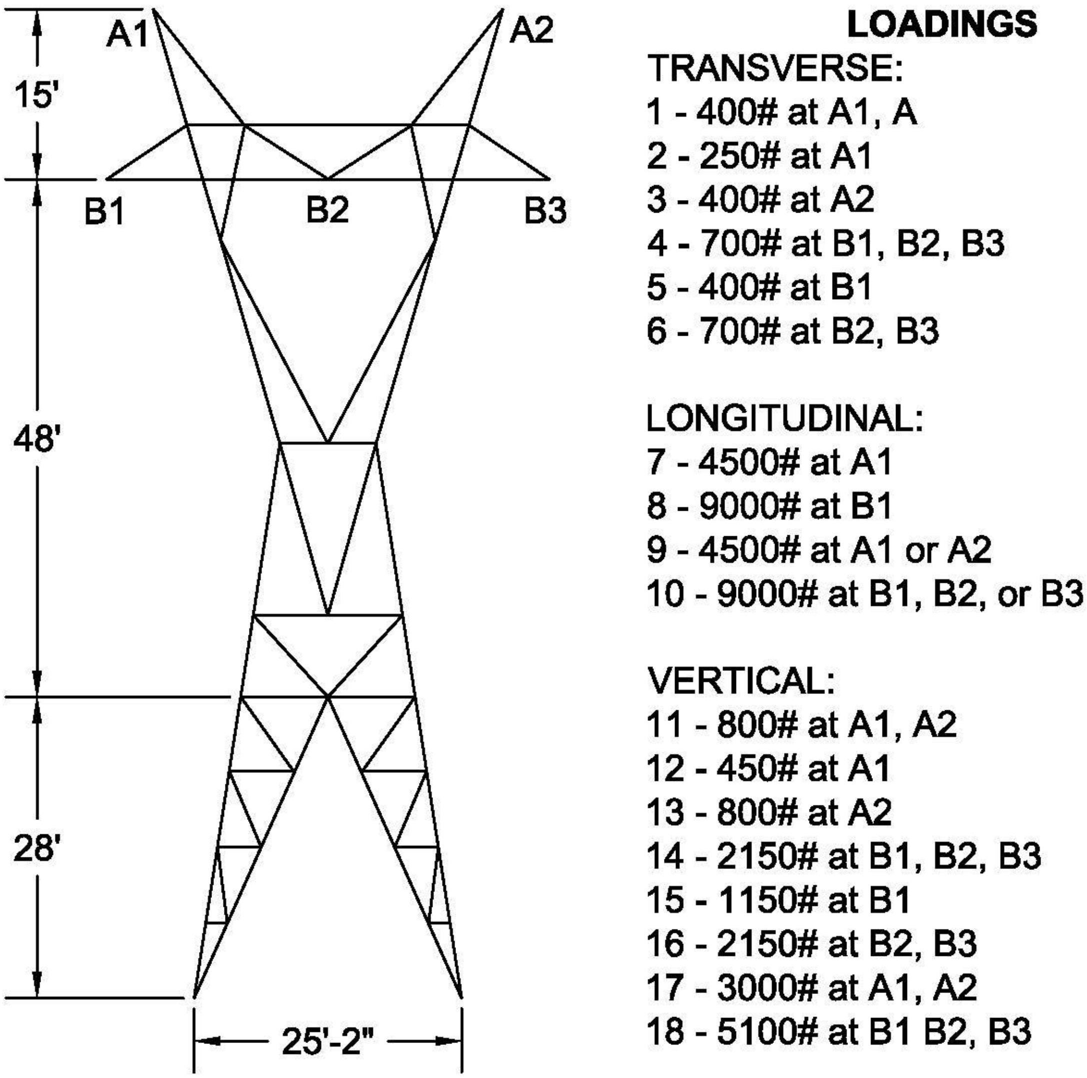

Figure 3 A-Tower load tree

The first step to modernizing the load analysis for the lattice tower is to apply the design information given in the figure above to the previously described calculation procedure. The subject tower utilized 795kcmil ACSR conductor, 7/16" high-strength steel groundwire, a maximum horizontal span of 1300 feet, and a maximum vertical span of 1800 feet. An overload factor of 1.75 was used for all loadings in the previous figure, with the exception of Loads 1 and 4, where a 4.0 overload factor was used. Conductor and shield wire properties, maximum horizontal and vertical spans, and overload factors are combined with the NESC Loading Zone to calculate ultimate loads. This study also assumes multiple load cases or combinations to simulate various real-life situations. These cases include:

- Case I - All wires intact (conductor and shield wire)
  - Loads 1, 4, 11, 14
- Case II - One broken conductor (All other wires intact)
  - Loads 2, 3, 4, 7, 12, 13, 14
- Case III - One broken shield wire (All other wires intact)
  - Loads 1, 5, 6, 8, 11, 15, 16
- Case IV - Heavy Vertical (Icy conditions)
  - Loads 17, 18

Once the ultimate loads are obtained, the remainder of the steps can be applied to the lattice tower geometry, including multiple leg heights, to calculate the maximum moment, compression, and tensile forces at the ground-line for that specific tower type. The complete As-Designed Calculation for the A-Tower can be seen in Supplement 1.

Once the as-designed calculation is complete, modern NESC overload factors can then be applied to calculate the ground-line compression and tension force for any desired combination of design inputs. These forces can then be compared to the as-designed ground-line forces to determine if the tower is structurally adequate for a specific load combination.

Design Inputs

For the A-Tower the following design inputs were used to create loading combinations for the modified tower analysis.

Table 3 A Tower Design Input

Conductor	Shield Wire	Conductor Tension (lb)	Shield Wire Tension (lb)	Horizontal Span (ft)	Vertical Span (ft)
636 kcmil 26/7	7/16 Steel	7000	4000	1200	1700
795 kcmil 26/7	7 No. 9 Alumoweld	8000	4500	1300	1800
954 kcmil 45/7	48 Fiber Alumocore	9000	5000	1400	1900
1351 kcmil 45/7		10000			2000
1590 kcmil 45/7					

With the various leg styles and body extensions available for the original design there are 29 possible conductor heights for the A-Tower. These heights occur at 2' intervals between 68' and 124', with the width of the tower base increasing from 25'-2" to 34'-10". A number of sample calculations with various design inputs can be found in Supplement 1.

CHAPTER 4

RESULTS AND ANALYSIS

Results

In total there are 51 design inputs and 62,640 possible design input combinations for the A Tower. All possible combinations, passing or failing determination, ground-line forces, and controlling load case can be found in Supplement 2.

General Analysis

The following table shows the number of passing and failing load combinations and the pass rate when each design input is held constant. The passing rates for each tower height ranged from 90.3% to 96%, increasing from the 68' tower to the 120' tower. The highest pass rates, 100%, occurred when the 636 kCmil conductor input and the 7000 lb. conductor tension input remained constant. The lowest pass rate, 78.6%, occurred with the heaviest 1590 kCmil conductor. Other low pass rates included the 10000 lb. conductor tension at 79.9%, the 48 Fiber Alumocore at 88.9%, and the 1400 ft horizontal span at 89.2%. All other design inputs resulted in passing rates in the 90th percentile when compared to design ground-line forces.

Cond Height	# Pass	# Fail	% Pass
68	1950	210	90.28%
70	1965	195	90.97%
72	1974	186	91.39%
74	1983	177	91.81%
76	1983	177	91.81%
78	1995	165	92.36%
80	2001	159	92.64%
82	2007	153	92.92%
84	2010	150	93.06%
86	2016	144	93.33%
88	2022	138	93.61%
90	2034	126	94.17%
92	2043	117	94.58%
94	2049	111	94.86%
96	2049	111	94.86%
98	2049	111	94.86%
100	2052	108	95.00%
102	2052	108	95.00%
104	2055	105	95.14%
106	2064	96	95.56%
108	2064	96	95.56%
110	2067	93	95.69%
112	2070	90	95.83%
114	2073	87	95.97%
116	2073	87	95.97%
118	2073	87	95.97%
120	2073	87	95.97%
122	1977	183	91.53%
124	1983	177	91.81%

Conductor Type	# Pass	# Fail	% Pass
636 kcmil 26/7	12528	0	100.00%
795 kcmil 26/7	12522	6	99.95%
954 kcmil 45/7	12492	36	99.71%
1351 kcmil 45/7	11415	1113	91.12%
1590 kcmil 45/7	9849	2679	78.62%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	20355	525	97.49%
7/16 Steel	19881	999	95.22%
48 Fiber Alumocore	18570	2310	88.94%

Conductor Tension	# Pass	# Fail	% Pass
7000	15660	0	100.00%
8000	15642	18	99.89%
9000	15000	660	95.79%
10000	12504	3156	79.85%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	19602	1278	93.88%
4500	19602	1278	93.88%
5000	19602	1278	93.88%

Horizontal Span	# Pass	# Fail	% Pass
1200	20481	399	98.09%
1300	19701	1179	94.35%
1400	18624	2256	89.20%

Vertical Span	# Pass	# Fail	% Pass
1700	14997	663	95.77%
1800	14808	852	94.56%
1900	14598	1062	93.22%
2000	14403	1257	91.97%

Figure 4 Application output showing the passing rates per design input

Constant Single Design Input

The next several pages contain pass/fail tables where one of the fifty one design inputs remains constant while evaluating the design calculation for all combinations of the remaining inputs. Maximum and minimum design values are presented in this section. Other design values can be found in Supplement 3.

Conductor Height

For Tables 5 and 6 the conductor height remains constant and pass rates are evaluated and displayed for all possible design combinations for the 68' and 124' Tower. Passing rates for conductor heights had a tendency to increase as the tower increased in height. This was counter to the result that was expected and is further discussed later in this study. All conductor heights had multiple 100% passing combinations with the 636 kCmil conductor input and the 7000 lb. conductor tension input always passing as described in the previous section. The 795 kCmil conductor and the 954 kCmil conductor result in a 100% passing rate beginning at the 72' and the 82' tower, respectively. The 8000 lb. design tension results in a 100% passing rate starting at the 78' tower. The shield wire tension passing rates remain constant for each conductor height, while the passing rates for the horizontal and vertical spans gradually increase with conductor height.

H	68

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	432	0	100%
795 kCmil 26/7	429	3	99%
954 kCmil 45/7	426	6	99%
1351 kCmil 45/7	360	72	83%
1590 kCmil 45/7	303	129	70%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	684	36	95%
7/16 Steel	663	57	92%
48 Fiber Alumocore	603	117	84%

Conductor Tension	# Pass	# Fail	% Pass
7000	540	0	100%
8000	537	3	99%
9000	492	48	91%
10000	381	159	71%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	650	70	90%
4500	650	70	90%
5000	650	70	90%

Horizontal Span	# Pass	# Fail	% Pass
1200	693	27	96%
1300	654	66	91%
1400	603	117	84%

Vertical Span	# Pass	# Fail	% Pass
1700	501	39	93%
1800	492	48	91%
1900	483	57	89%
2000	474	66	88%

Figure 5 Application output showing the passing rates for a 68' tower

H	124

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	432	0	100%
795 kCmil 26/7	432	0	100%
954 kCmil 45/7	429	3	99%
1351 kCmil 45/7	372	60	86%
1590 kCmil 45/7	318	114	74%

Shield Wire	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	693	27	96%
7/16 Steel	669	51	93%
48 Fiber Alumocore	621	99	86%

Conductor Tension	# Pass	# Fail	% Pass
7000	540	0	100%
8000	540	0	100%
9000	504	36	93%
10000	399	141	74%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	661	59	92%
4500	661	59	92%
5000	661	59	92%

Horizontal Span	# Pass	# Fail	% Pass
1200	696	24	97%
1300	663	57	92%
1400	624	96	87%

Vertical Span	# Pass	# Fail	% Pass
1700	510	30	94%
1800	501	39	93%
1900	489	51	91%
2000	483	57	89%

Figure 6 Application output showing the passing rates for a 124' tower

Conductor Type

For Figures 7 and 8 the conductor type remains constant and pass rates are evaluated and displayed for all possible design combinations. As expected, passing rates start at 100% for the lightest conductor and drop steadily. Except for the combinations where a 7000 lb. conductor tension input is used, there are no input combinations that give a 100% passing rate with the heaviest conductor.

Conductor Type	636 kCmil 26/7

Cond Height	# Pass	# Fail	% Pass
68	432	0	100.0%
70	432	0	100.0%
72	432	0	100.0%
74	432	0	100.0%
76	432	0	100.0%
78	432	0	100.0%
80	432	0	100.0%
82	432	0	100.0%
84	432	0	100.0%
86	432	0	100.0%
88	432	0	100.0%
90	432	0	100.0%
92	432	0	100.0%
94	432	0	100.0%
96	432	0	100.0%
98	432	0	100.0%
100	432	0	100.0%
102	432	0	100.0%
104	432	0	100.0%
106	432	0	100.0%
108	432	0	100.0%
110	432	0	100.0%
112	432	0	100.0%
114	432	0	100.0%
116	432	0	100.0%
118	432	0	100.0%
120	432	0	100.0%
122	432	0	100.0%
124	432	0	100.0%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	4176	0	100.0%
7/16 Steel	4176	0	100.0%
48 Fiber Alumocore	4176	0	100.0%

Conductor Tension	# Pass	# Fail	% Pass
7000	3132	0	100.0%
8000	3132	0	100.0%
9000	3132	0	100.0%
10000	3132	0	100.0%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	4176	0	100.0%
4500	4176	0	100.0%
5000	4176	0	100.0%

Horizontal Span	# Pass	# Fail	% Pass
1200	4176	0	100.0%
1300	4176	0	100.0%
1400	4176	0	100.0%

Vertical Span	# Pass	# Fail	% Pass
1700	3132	0	100.0%
1800	3132	0	100.0%
1900	3132	0	100.0%
2000	3132	0	100.0%

Figure 7 Application output showing the passing rates for a 636 kCmil conductor

Conductor Type	1590 kCmil 45/7

Cond Height	# Pass	# Fail	% Pass
68	303	129	70.1%
70	309	123	71.5%
72	312	120	72.2%
74	318	114	73.6%
76	318	114	73.6%
78	321	111	74.3%
80	324	108	75.0%
82	327	105	75.7%
84	330	102	76.4%
86	333	99	77.1%
88	333	99	77.1%
90	342	90	79.2%
92	345	87	79.9%
94	348	84	80.6%
96	348	84	80.6%
98	348	84	80.6%
100	351	81	81.3%
102	351	81	81.3%
104	354	78	81.9%
106	357	75	82.6%
108	357	75	82.6%
110	360	72	83.3%
112	363	69	84.0%
114	366	66	84.7%
116	366	66	84.7%
118	366	66	84.7%
120	366	66	84.7%
122	315	117	72.9%
124	318	114	73.6%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	3723	453	89.2%
7/16 Steel	3426	750	82.0%
48 Fiber Alumocore	2700	1476	64.7%

Conductor Tension	# Pass	# Fail	% Pass
7000	3132	0	100.0%
8000	3114	18	99.4%
9000	2577	555	82.3%
10000	1026	2106	32.8%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	3283	893	78.6%
4500	3283	893	78.6%
5000	3283	893	78.6%

Horizontal Span	# Pass	# Fail	% Pass
1200	3837	339	91.9%
1300	3300	876	79.0%
1400	2712	1464	64.9%

Vertical Span	# Pass	# Fail	% Pass
1700	2634	498	84.1%
1800	2505	627	80.0%
1900	2400	732	76.6%
2000	2310	822	73.8%

Figure 8 Application output showing the passing rates for a 1590 kCmil conductor

Shield Wire Type

For Figures 9 through 11 the shield wire type remains constant and pass rates are evaluated and displayed for all possible design combinations. As with the conductor types, the shield wire type passing rates decrease as the shield wire increases in weight. The fiber optic shield wire results in the lowest passing rates for this analysis.

Shield Wire Type	7/16 Steel

Cond Height	# Pass	# Fail	% Pass
68	663	57	92.1%
70	666	54	92.5%
72	666	54	92.5%
74	672	48	93.3%
76	672	48	93.3%
78	675	45	93.8%
80	675	45	93.8%
82	675	45	93.8%
84	678	42	94.2%
86	684	36	95.0%
88	684	36	95.0%
90	687	33	95.4%
92	693	27	96.3%
94	693	27	96.3%
96	693	27	96.3%
98	693	27	96.3%
100	693	27	96.3%
102	693	27	96.3%
104	696	24	96.7%
106	699	21	97.1%
108	699	21	97.1%
110	699	21	97.1%
112	699	21	97.1%
114	699	21	97.1%
116	699	21	97.1%
118	699	21	97.1%
120	699	21	97.1%
122	669	51	92.9%
124	669	51	92.9%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100.0%
795 kCmil 26/7	4176	0	100.0%
954 kCmil 45/7	4176	0	100.0%
1351 kCmil 45/7	3927	249	94.0%
1590 kCmil 45/7	3426	750	82.0%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100.0%
8000	5220	0	100.0%
9000	5139	81	98.4%
10000	4302	918	82.4%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	6627	333	95.2%
4500	6627	333	95.2%
5000	6627	333	95.2%

Horizontal Span	# Pass	# Fail	% Pass
1200	6912	48	99.3%
1300	6663	297	95.7%
1400	6306	654	90.6%

Vertical Span	# Pass	# Fail	% Pass
1700	5061	159	97.0%
1800	5022	198	96.2%
1900	4935	285	94.5%
2000	4863	357	93.2%

Figure 9 Application output showing the passing rates for a 7/16 steel shield wire

Shield Wire Type	7 No. 9 Alumoweld

Cond Height	# Pass	# Fail	% Pass
68	684	36	95.0%
70	690	30	95.8%
72	693	27	96.3%
74	693	27	96.3%
76	693	27	96.3%
78	693	27	96.3%
80	699	21	97.1%
82	699	21	97.1%
84	699	21	97.1%
86	699	21	97.1%
88	699	21	97.1%
90	705	15	97.9%
92	705	15	97.9%
94	705	15	97.9%
96	705	15	97.9%
98	705	15	97.9%
100	708	12	98.3%
102	708	12	98.3%
104	708	12	98.3%
106	708	12	98.3%
108	708	12	98.3%
110	711	9	98.8%
112	711	9	98.8%
114	711	9	98.8%
116	711	9	98.8%
118	711	9	98.8%
120	711	9	98.8%
122	690	30	95.8%
124	693	27	96.3%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100.0%
795 kCmil 26/7	4176	0	100.0%
954 kCmil 45/7	4176	0	100.0%
1351 kCmil 45/7	4104	72	98.3%
1590 kCmil 45/7	3723	453	89.2%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100.0%
8000	5220	0	100.0%
9000	5217	3	99.9%
10000	4698	522	90.0%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	6785	175	97.5%
4500	6785	175	97.5%
5000	6785	175	97.5%

Horizontal Span	# Pass	# Fail	% Pass
1200	6960	0	100.0%
1300	6840	120	98.3%
1400	6555	405	94.2%

Vertical Span	# Pass	# Fail	% Pass
1700	5148	72	98.6%
1800	5100	120	97.7%
1900	5070	150	97.1%
2000	5037	183	96.5%

Figure 10 Application output showing the passing rates for a 7 No. 9 Alumoweld shield wire

Shield Wire Type	48 Fiber Alumocore

Cond Height	# Pass	# Fail	% Pass
68	603	117	83.8%
70	609	111	84.6%
72	615	105	85.4%
74	618	102	85.8%
76	618	102	85.8%
78	627	93	87.1%
80	627	93	87.1%
82	633	87	87.9%
84	633	87	87.9%
86	633	87	87.9%
88	639	81	88.8%
90	642	78	89.2%
92	645	75	89.6%
94	651	69	90.4%
96	651	69	90.4%
98	651	69	90.4%
100	651	69	90.4%
102	651	69	90.4%
104	651	69	90.4%
106	657	63	91.3%
108	657	63	91.3%
110	657	63	91.3%
112	660	60	91.7%
114	663	57	92.1%
116	663	57	92.1%
118	663	57	92.1%
120	663	57	92.1%
122	618	102	85.8%
124	621	99	86.3%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100.0%
795 kCmil 26/7	4170	6	99.9%
954 kCmil 45/7	4140	36	99.1%
1351 kCmil 45/7	3384	792	81.0%
1590 kCmil 45/7	2700	1476	64.7%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100.0%
8000	5202	18	99.7%
9000	4644	576	89.0%
10000	3504	1716	67.1%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	6190	770	88.9%
4500	6190	770	88.9%
5000	6190	770	88.9%

Horizontal Span	# Pass	# Fail	% Pass
1200	6609	351	95.0%
1300	6198	762	89.1%
1400	5763	1197	82.8%

Vertical Span	# Pass	# Fail	% Pass
1700	4788	432	91.7%
1800	4686	534	89.8%
1900	4593	627	88.0%
2000	4503	717	86.3%

Figure 11 Application output showing the passing rates for a 48 fiber Alumocore shield wire

Conductor Tension

For Figures 12 and 13 the conductor tension remains constant and pass rates are evaluated and displayed for all possible design combinations. As with the previous inputs, the passing rates decrease as the conductor tension increases. Other than the 636 kCmil conductor, there are no 100% passing rates with the highest conductor tension.

Conductor Tension	7000

Cond Height	# Pass	# Fail	% Pass
68	540	0	100.0%
70	540	0	100.0%
72	540	0	100.0%
74	540	0	100.0%
76	540	0	100.0%
78	540	0	100.0%
80	540	0	100.0%
82	540	0	100.0%
84	540	0	100.0%
86	540	0	100.0%
88	540	0	100.0%
90	540	0	100.0%
92	540	0	100.0%
94	540	0	100.0%
96	540	0	100.0%
98	540	0	100.0%
100	540	0	100.0%
102	540	0	100.0%
104	540	0	100.0%
106	540	0	100.0%
108	540	0	100.0%
110	540	0	100.0%
112	540	0	100.0%
114	540	0	100.0%
116	540	0	100.0%
118	540	0	100.0%
120	540	0	100.0%
122	540	0	100.0%
124	540	0	100.0%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	3132	0	100.0%
795 kCmil 26/7	3132	0	100.0%
954 kCmil 45/7	3132	0	100.0%
1351 kCmil 45/7	3132	0	100.0%
1590 kCmil 45/7	3132	0	100.0%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	5220	0	100.0%
7/16 Steel	5220	0	100.0%
48 Fiber Alumocore	5220	0	100.0%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	5220	0	100.0%
4500	5220	0	100.0%
5000	5220	0	100.0%

Horizontal Span	# Pass	# Fail	% Pass
1200	5220	0	100.0%
1300	5220	0	100.0%
1400	5220	0	100.0%

Vertical Span	# Pass	# Fail	% Pass
1700	3915	0	100.0%
1800	3915	0	100.0%
1900	3915	0	100.0%
2000	3915	0	100.0%

Figure 12 Application output showing the passing rates for a 7000 lb. conductor tension

Conductor Tension	10000

Cond Height	# Pass	# Fail	% Pass
68	381	159	70.6%
70	390	150	72.2%
72	396	144	73.3%
74	402	138	74.4%
76	402	138	74.4%
78	408	132	75.6%
80	414	126	76.7%
82	417	123	77.2%
84	417	123	77.2%
86	423	117	78.3%
88	426	114	78.9%
90	435	105	80.6%
92	441	99	81.7%
94	444	96	82.2%
96	444	96	82.2%
98	444	96	82.2%
100	447	93	82.8%
102	447	93	82.8%
104	450	90	83.3%
106	456	84	84.4%
108	456	84	84.4%
110	459	81	85.0%
112	462	78	85.6%
114	462	78	85.6%
116	462	78	85.6%
118	462	78	85.6%
120	462	78	85.6%
122	396	144	73.3%
124	399	141	73.9%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	3132	0	100.0%
795 kCmil 26/7	3126	6	99.8%
954 kCmil 45/7	3096	36	98.9%
1351 kCmil 45/7	2124	1008	67.8%
1590 kCmil 45/7	1026	2106	32.8%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	4698	522	90.0%
7/16 Steel	4302	918	82.4%
48 Fiber Alumocore	3504	1716	67.1%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	4168	1052	79.8%
4500	4168	1052	79.8%
5000	4168	1052	79.8%

Horizontal Span	# Pass	# Fail	% Pass
1200	4821	399	92.4%
1300	4176	1044	80.0%
1400	3507	1713	67.2%

Vertical Span	# Pass	# Fail	% Pass
1700	3336	579	85.2%
1800	3207	708	81.9%
1900	3045	870	77.8%
2000	2916	999	74.5%

Figure 13 Application output showing the passing rates for a 10000 lb. conductor tension

Shield Wire Tension

For Figures 14 through 16 the shield wire tension remains constant and pass rates are evaluated and displayed for all possible design combinations. As with the conductor tension, the passing rates decrease as the shield wire tension increases. At the highest tension, only the 636 and 795 kCmil conductor have a 100% pass rate.

Shield Wire Tension	4000

Cond Height	# Pass	# Fail	% Pass
68	650	70	90%
70	655	65	91%
72	658	62	91%
74	661	59	92%
76	661	59	92%
78	665	55	92%
80	667	53	93%
82	669	51	93%
84	670	50	93%
86	672	48	93%
88	674	46	94%
90	678	42	94%
92	681	39	95%
94	683	37	95%
96	683	37	95%
98	683	37	95%
100	684	36	95%
102	684	36	95%
104	685	35	95%
106	688	32	96%
108	688	32	96%
110	689	31	96%
112	690	30	96%
114	691	29	96%
116	691	29	96%
118	691	29	96%
120	691	29	96%
122	659	61	92%
124	661	59	92%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100%
795 kCmil 26/7	4174	2	100%
954 kCmil 45/7	4164	12	100%
1351 kCmil 45/7	3805	371	91%
1590 kCmil 45/7	3283	893	79%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	6785	175	97%
7/16 Steel	6627	333	95%
48 Fiber Alumocore	6190	770	89%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100%
8000	5214	6	100%
9000	5000	220	96%
10000	4168	1052	80%

Horizontal Span	# Pass	# Fail	% Pass
1200	6827	133	98%
1300	6567	393	94%
1400	6208	752	89%

Vertical Span	# Pass	# Fail	% Pass
1700	4999	221	96%
1800	4936	284	95%
1900	4866	354	93%
2000	4801	419	92%

Figure 14 Application output showing the passing rates for a 4000 lb. shield wire tension

Shield Wire Tension	4500

Cond Height	# Pass	# Fail	% Pass
68	650	70	90%
70	655	65	91%
72	658	62	91%
74	661	59	92%
76	661	59	92%
78	665	55	92%
80	667	53	93%
82	669	51	93%
84	670	50	93%
86	672	48	93%
88	674	46	94%
90	678	42	94%
92	681	39	95%
94	683	37	95%
96	683	37	95%
98	683	37	95%
100	684	36	95%
102	684	36	95%
104	685	35	95%
106	688	32	96%
108	688	32	96%
110	689	31	96%
112	690	30	96%
114	691	29	96%
116	691	29	96%
118	691	29	96%
120	691	29	96%
122	659	61	92%
124	661	59	92%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100%
795 kCmil 26/7	4174	2	100%
954 kCmil 45/7	4164	12	100%
1351 kCmil 45/7	3805	371	91%
1590 kCmil 45/7	3283	893	79%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	6785	175	97%
7/16 Steel	6627	333	95%
48 Fiber Alumocore	6190	770	89%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100%
8000	5214	6	100%
9000	5000	220	96%
10000	4168	1052	80%

Horizontal Span	# Pass	# Fail	% Pass
1200	6827	133	98%
1300	6567	393	94%
1400	6208	752	89%

Vertical Span	# Pass	# Fail	% Pass
1700	4999	221	96%
1800	4936	284	95%
1900	4866	354	93%
2000	4801	419	92%

Figure 15 Application output showing the passing rates for a 4500 lb. shield wire tension

Shield Wire Tension	5000

Cond Height	# Pass	# Fail	% Pass
68	650	70	90%
70	655	65	91%
72	658	62	91%
74	661	59	92%
76	661	59	92%
78	665	55	92%
80	667	53	93%
82	669	51	93%
84	670	50	93%
86	672	48	93%
88	674	46	94%
90	678	42	94%
92	681	39	95%
94	683	37	95%
96	683	37	95%
98	683	37	95%
100	684	36	95%
102	684	36	95%
104	685	35	95%
106	688	32	96%
108	688	32	96%
110	689	31	96%
112	690	30	96%
114	691	29	96%
116	691	29	96%
118	691	29	96%
120	691	29	96%
122	659	61	92%
124	661	59	92%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100%
795 kCmil 26/7	4174	2	100%
954 kCmil 45/7	4164	12	100%
1351 kCmil 45/7	3805	371	91%
1590 kCmil 45/7	3283	893	79%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	6785	175	97%
7/16 Steel	6627	333	95%
48 Fiber Alumocore	6190	770	89%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100%
8000	5214	6	100%
9000	5000	220	96%
10000	4168	1052	80%

Horizontal Span	# Pass	# Fail	% Pass
1200	6827	133	98%
1300	6567	393	94%
1400	6208	752	89%

Vertical Span	# Pass	# Fail	% Pass
1700	4999	221	96%
1800	4936	284	95%
1900	4866	354	93%
2000	4801	419	92%

Figure 16 Application output showing the passing rates for a 5000 lb. shield wire tension

Horizontal Span

For Figures 17 through 19 the horizontal span remains constant and pass rates are evaluated and displayed for all possible design combinations. The horizontal span has a large effect on the passing rates of each design input, decreasing the rate by a considerable percentage when increased. At the longest horizontal span, only the 636 kCmil conductor has a 100% pass rate.

Horizontal Span	1200

Cond Height	# Pass	# Fail	% Pass
68	693	27	96.3%
70	696	24	96.7%
72	696	24	96.7%
74	699	21	97.1%
76	699	21	97.1%
78	702	18	97.5%
80	702	18	97.5%
82	702	18	97.5%
84	702	18	97.5%
86	705	15	97.9%
88	708	12	98.3%
90	708	12	98.3%
92	708	12	98.3%
94	711	9	98.8%
96	711	9	98.8%
98	711	9	98.8%
100	711	9	98.8%
102	711	9	98.8%
104	711	9	98.8%
106	711	9	98.8%
108	711	9	98.8%
110	711	9	98.8%
112	714	6	99.2%
114	714	6	99.2%
116	714	6	99.2%
118	714	6	99.2%
120	714	6	99.2%
122	696	24	96.7%
124	696	24	96.7%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100.0%
795 kCmil 26/7	4176	0	100.0%
954 kCmil 45/7	4176	0	100.0%
1351 kCmil 45/7	4116	60	98.6%
1590 kCmil 45/7	3837	339	91.9%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	6960	0	100.0%
7/16 Steel	6912	48	99.3%
48 Fiber Alumocore	6609	351	95.0%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100.0%
8000	5220	0	100.0%
9000	5220	0	100.0%
10000	4821	399	92.4%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	6827	133	98.1%
4500	6827	133	98.1%
5000	6827	133	98.1%

Vertical Span	# Pass	# Fail	% Pass
1700	5175	45	99.1%
1800	5145	75	98.6%
1900	5097	123	97.6%
2000	5064	156	97.0%

Figure 17 Application output showing the passing rates for a 1200' horizontal span

Horizontal Span	1300

Cond Height	# Pass	# Fail	% Pass
68	654	66	90.8%
70	660	60	91.7%
72	663	57	92.1%
74	663	57	92.1%
76	663	57	92.1%
78	666	54	92.5%
80	669	51	92.9%
82	672	48	93.3%
84	672	48	93.3%
86	672	48	93.3%
88	672	48	93.3%
90	681	39	94.6%
92	684	36	95.0%
94	684	36	95.0%
96	684	36	95.0%
98	684	36	95.0%
100	687	33	95.4%
102	687	33	95.4%
104	690	30	95.8%
106	696	24	96.7%
108	696	24	96.7%
110	696	24	96.7%
112	696	24	96.7%
114	696	24	96.7%
116	696	24	96.7%
118	696	24	96.7%
120	696	24	96.7%
122	663	57	92.1%
124	663	57	92.1%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100.0%
795 kCmil 26/7	4176	0	100.0%
954 kCmil 45/7	4176	0	100.0%
1351 kCmil 45/7	3873	303	92.7%
1590 kCmil 45/7	3300	876	79.0%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	6840	120	98.3%
7/16 Steel	6663	297	95.7%
48 Fiber Alumocore	6198	762	89.1%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100.0%
8000	5220	0	100.0%
9000	5085	135	97.4%
10000	4176	1044	80.0%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	6567	393	94.4%
4500	6567	393	94.4%
5000	6567	393	94.4%

Vertical Span	# Pass	# Fail	% Pass
1700	5043	177	96.6%
1800	4959	261	95.0%
1900	4878	342	93.4%
2000	4821	399	92.4%

Figure 18 Application output showing the passing rates for a 1300' horizontal span

Horizontal Span	1400

Cond Height	# Pass	# Fail	% Pass
68	603	117	83.8%
70	609	111	84.6%
72	615	105	85.4%
74	621	99	86.3%
76	621	99	86.3%
78	627	93	87.1%
80	630	90	87.5%
82	633	87	87.9%
84	636	84	88.3%
86	639	81	88.8%
88	642	78	89.2%
90	645	75	89.6%
92	651	69	90.4%
94	654	66	90.8%
96	654	66	90.8%
98	654	66	90.8%
100	654	66	90.8%
102	654	66	90.8%
104	654	66	90.8%
106	657	63	91.3%
108	657	63	91.3%
110	660	60	91.7%
112	660	60	91.7%
114	663	57	92.1%
116	663	57	92.1%
118	663	57	92.1%
120	663	57	92.1%
122	618	102	85.8%
124	624	96	86.7%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	4176	0	100.0%
795 kCmil 26/7	4170	6	99.9%
954 kCmil 45/7	4140	36	99.1%
1351 kCmil 45/7	3426	750	82.0%
1590 kCmil 45/7	2712	1464	64.9%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	6555	405	94.2%
7/16 Steel	6306	654	90.6%
48 Fiber Alumocore	5763	1197	82.8%

Conductor Tension	# Pass	# Fail	% Pass
7000	5220	0	100.0%
8000	5202	18	99.7%
9000	4695	525	89.9%
10000	3507	1713	67.2%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	6208	752	89.2%
4500	6208	752	89.2%
5000	6208	752	89.2%

Vertical Span	# Pass	# Fail	% Pass
1700	4779	441	91.6%
1800	4704	516	90.1%
1900	4623	597	88.6%
2000	4518	702	86.6%

Figure 19 Application output showing the passing rates for a 1400' horizontal span

Vertical Span

For Figures 20 through 23 the horizontal span remains constant and pass rates are evaluated and displayed for all possible design combinations. Vertical span has less of an effect on the passing rates when compared to horizontal span. At the longest span, only the 636 kCmil conductor has a 100% pass rate.

Vertical Span	1700

Cond Height	# Pass	# Fail	% Pass
68	501	39	92.8%
70	507	33	93.9%
72	510	30	94.4%
74	510	30	94.4%
76	510	30	94.4%
78	510	30	94.4%
80	510	30	94.4%
82	510	30	94.4%
84	510	30	94.4%
86	513	27	95.0%
88	513	27	95.0%
90	516	24	95.6%
92	519	21	96.1%
94	522	18	96.7%
96	522	18	96.7%
98	522	18	96.7%
100	522	18	96.7%
102	522	18	96.7%
104	522	18	96.7%
106	522	18	96.7%
108	522	18	96.7%
110	525	15	97.2%
112	525	15	97.2%
114	528	12	97.8%
116	528	12	97.8%
118	528	12	97.8%
120	528	12	97.8%
122	510	30	94.4%
124	510	30	94.4%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	3132	0	100.0%
795 kCmil 26/7	3132	0	100.0%
954 kCmil 45/7	3132	0	100.0%
1351 kCmil 45/7	2967	165	94.7%
1590 kCmil 45/7	2634	498	84.1%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	5148	72	98.6%
7/16 Steel	5061	159	97.0%
48 Fiber Alumocore	4788	432	91.7%

Conductor Tension	# Pass	# Fail	% Pass
7000	3915	0	100.0%
8000	3915	0	100.0%
9000	3831	84	97.9%
10000	3336	579	85.2%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	4999	221	95.8%
4500	4999	221	95.8%
5000	4999	221	95.8%

Horizontal Span	# Pass	# Fail	% Pass
1200	5175	45	99.1%
1300	5043	177	96.6%
1400	4779	441	91.6%

Figure 20 Application output showing the passing rates for a 1700’ vertical span

Vertical Span	1800

Cond Height	# Pass	# Fail	% Pass
68	492	48	91.1%
70	495	45	91.7%
72	498	42	92.2%
74	501	39	92.8%
76	501	39	92.8%
78	504	36	93.3%
80	507	33	93.9%
82	510	30	94.4%
84	510	30	94.4%
86	510	30	94.4%
88	510	30	94.4%
90	510	30	94.4%
92	513	27	95.0%
94	513	27	95.0%
96	513	27	95.0%
98	513	27	95.0%
100	513	27	95.0%
102	513	27	95.0%
104	516	24	95.6%
106	519	21	96.1%
108	519	21	96.1%
110	519	21	96.1%
112	522	18	96.7%
114	522	18	96.7%
116	522	18	96.7%
118	522	18	96.7%
120	522	18	96.7%
122	498	42	92.2%
124	501	39	92.8%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	3132	0	100.0%
795 kCmil 26/7	3132	0	100.0%
954 kCmil 45/7	3132	0	100.0%
1351 kCmil 45/7	2907	225	92.8%
1590 kCmil 45/7	2505	627	80.0%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	5100	120	97.7%
7/16 Steel	5022	198	96.2%
48 Fiber Alumocore	4686	534	89.8%

Conductor Tension	# Pass	# Fail	% Pass
7000	3915	0	100.0%
8000	3915	0	100.0%
9000	3771	144	96.3%
10000	3207	708	81.9%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	4936	284	94.6%
4500	4936	284	94.6%
5000	4936	284	94.6%

Horizontal Span	# Pass	# Fail	% Pass
1200	5145	75	98.6%
1300	4959	261	95.0%
1400	4704	516	90.1%

Figure 21 Application output showing the passing rates for a 1800’ vertical span

Vertical Span	1900

Cond Height	# Pass	# Fail	% Pass
68	483	57	89.4%
70	486	54	90.0%
72	486	54	90.0%
74	492	48	91.1%
76	492	48	91.1%
78	495	45	91.7%
80	498	42	92.2%
82	498	42	92.2%
84	501	39	92.8%
86	501	39	92.8%
88	504	36	93.3%
90	510	30	94.4%
92	510	30	94.4%
94	510	30	94.4%
96	510	30	94.4%
98	510	30	94.4%
100	510	30	94.4%
102	510	30	94.4%
104	510	30	94.4%
106	513	27	95.0%
108	513	27	95.0%
110	513	27	95.0%
112	513	27	95.0%
114	513	27	95.0%
116	513	27	95.0%
118	513	27	95.0%
120	513	27	95.0%
122	489	51	90.6%
124	489	51	90.6%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	3132	0	100.0%
795 kCmil 26/7	3132	0	100.0%
954 kCmil 45/7	3123	9	99.7%
1351 kCmil 45/7	2811	321	89.8%
1590 kCmil 45/7	2400	732	76.6%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	5070	150	97.1%
7/16 Steel	4935	285	94.5%
48 Fiber Alumocore	4593	627	88.0%

Conductor Tension	# Pass	# Fail	% Pass
7000	3915	0	100.0%
8000	3915	0	100.0%
9000	3723	192	95.1%
10000	3045	870	77.8%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	4866	354	93.2%
4500	4866	354	93.2%
5000	4866	354	93.2%

Horizontal Span	# Pass	# Fail	% Pass
1200	5097	123	97.6%
1300	4878	342	93.4%
1400	4623	597	88.6%

Figure 22 Application output showing the passing rates for a 1900’ vertical span

Vertical Span	2000

Cond Height	# Pass	# Fail	% Pass
68	474	66	87.8%
70	477	63	88.3%
72	480	60	88.9%
74	480	60	88.9%
76	480	60	88.9%
78	486	54	90.0%
80	486	54	90.0%
82	489	51	90.6%
84	489	51	90.6%
86	492	48	91.1%
88	495	45	91.7%
90	498	42	92.2%
92	501	39	92.8%
94	504	36	93.3%
96	504	36	93.3%
98	504	36	93.3%
100	507	33	93.9%
102	507	33	93.9%
104	507	33	93.9%
106	510	30	94.4%
108	510	30	94.4%
110	510	30	94.4%
112	510	30	94.4%
114	510	30	94.4%
116	510	30	94.4%
118	510	30	94.4%
120	510	30	94.4%
122	480	60	88.9%
124	483	57	89.4%

Conductor Type	# Pass	# Fail	% Pass
636 kCmil 26/7	3132	0	100.0%
795 kCmil 26/7	3126	6	99.8%
954 kCmil 45/7	3105	27	99.1%
1351 kCmil 45/7	2730	402	87.2%
1590 kCmil 45/7	2310	822	73.8%

Shield Wire Type	# Pass	# Fail	% Pass
7 No. 9 Alumoweld	5037	183	96.5%
7/16 Steel	4863	357	93.2%
48 Fiber Alumocore	4503	717	86.3%

Conductor Tension	# Pass	# Fail	% Pass
7000	3915	0	100.0%
8000	3897	18	99.5%
9000	3675	240	93.9%
10000	2916	999	74.5%

Shield Wire Tension	# Pass	# Fail	% Pass
4000	4801	419	92.0%
4500	4801	419	92.0%
5000	4801	419	92.0%

Horizontal Span	# Pass	# Fail	% Pass
1200	5064	156	97.0%
1300	4821	399	92.4%
1400	4518	702	86.6%

Figure 23 Application output showing the passing rates for a 2000’ vertical span

Usage Percentage Per Design Input

The following data illustrate the percent of allowable ground-line usage for all conductor heights with a single variable design input while all other design inputs remain constant. Unless otherwise noted, the following standard design inputs values were used for this analysis.

- 1351 kCmil 45/7 ACSR Conductor
- 10,000 lb. Conductor Tension
- 7/16” Steel Shield Wire
- 4,500 lb. Shield Wire Tension
- 1300 ft Horizontal Span
- 1800 ft Vertical Span

Table 4 Usage Percentage per Conductor Type

H	636 kCmil 26/7	795 kCmil 26/7	954 kCmil 45/7	1351 kCmil 45/7	1590 kCmil 45/7
68	89.87%	92.82%	93.64%	99.41%	102.65%
70	89.68%	92.62%	93.45%	99.22%	102.45%
72	89.50%	92.44%	93.27%	99.03%	102.26%
74	89.33%	92.27%	93.10%	98.85%	102.08%
76	89.17%	92.11%	92.93%	98.69%	101.91%
78	89.02%	91.96%	92.78%	98.53%	101.75%
80	88.88%	91.82%	92.64%	98.38%	101.60%
82	88.75%	91.68%	92.50%	98.24%	101.45%
84	88.62%	91.55%	92.37%	98.10%	101.32%
86	88.50%	91.43%	92.24%	97.97%	101.19%
88	88.38%	91.31%	92.12%	97.85%	101.06%
90	87.98%	90.90%	91.71%	97.43%	100.63%
92	87.88%	90.80%	91.61%	97.32%	100.52%
94	87.79%	90.71%	91.52%	97.22%	100.42%
96	87.70%	90.61%	91.42%	97.13%	100.33%
98	87.61%	90.53%	91.34%	97.04%	100.23%
100	87.53%	90.44%	91.25%	96.95%	100.15%
102	87.45%	90.36%	91.17%	96.87%	100.06%
104	87.37%	90.29%	91.09%	96.79%	99.98%
106	87.20%	90.11%	90.91%	96.60%	99.79%
108	87.13%	90.04%	90.84%	96.53%	99.72%
110	87.07%	89.97%	90.77%	96.46%	99.65%
112	87.00%	89.91%	90.71%	96.39%	99.58%
114	86.94%	89.84%	90.65%	96.33%	99.51%
116	86.88%	89.78%	90.59%	96.27%	99.45%
118	86.83%	89.73%	90.53%	96.21%	99.39%
120	86.77%	89.67%	90.47%	96.15%	99.33%
122	89.44%	92.40%	93.23%	99.01%	102.25%
124	89.34%	92.30%	93.13%	98.90%	102.14%

Table 5 Usage Percentage per Shield Wire Type

H	7/16 Steel	7 No. 9 Alumoweld	48 Fiber Alumocore
68	99.41%	97.69%	103.00%
70	99.22%	97.50%	102.78%
72	99.03%	97.32%	102.57%
74	98.85%	97.15%	102.38%
76	98.69%	96.99%	102.20%
78	98.53%	96.83%	102.02%
80	98.38%	96.69%	101.86%
82	98.24%	96.55%	101.71%
84	98.10%	96.42%	101.56%
86	97.97%	96.30%	101.42%
88	97.85%	96.18%	101.28%
90	97.43%	95.76%	100.84%
92	97.32%	95.66%	100.72%
94	97.22%	95.56%	100.62%
96	97.13%	95.47%	100.51%
98	97.04%	95.38%	100.41%
100	96.95%	95.30%	100.32%
102	96.87%	95.22%	100.22%
104	96.79%	95.14%	100.14%
106	96.60%	94.96%	99.94%
108	96.53%	94.89%	99.86%
110	96.46%	94.82%	99.78%
112	96.39%	94.76%	99.71%
114	96.33%	94.69%	99.64%
116	96.27%	94.63%	99.57%
118	96.21%	94.58%	99.51%
120	96.15%	94.52%	99.44%
122	99.01%	97.36%	102.38%
124	98.90%	97.25%	102.27%

Table 6 Usage Percentage per Conductor Tension

H	7000	8000	9000	10000
68	87.37%	92.46%	97.56%	102.65%
70	87.19%	92.28%	97.36%	102.45%
72	87.03%	92.10%	97.18%	102.26%
74	86.87%	91.94%	97.01%	102.08%
76	86.73%	91.79%	96.85%	101.91%
78	86.59%	91.64%	96.69%	101.75%
80	86.46%	91.50%	96.55%	101.60%
82	86.33%	91.37%	96.41%	101.45%
84	86.21%	91.25%	96.28%	101.32%
86	86.10%	91.13%	96.16%	101.19%
88	85.99%	91.02%	96.04%	101.06%
90	85.63%	90.63%	95.63%	100.63%
92	85.54%	90.53%	95.53%	100.52%
94	85.45%	90.44%	95.43%	100.42%
96	85.37%	90.35%	95.34%	100.33%
98	85.29%	90.27%	95.25%	100.23%
100	85.21%	90.19%	95.17%	100.15%
102	85.14%	90.11%	95.09%	100.06%
104	85.07%	90.04%	95.01%	99.98%
106	84.91%	89.87%	94.83%	99.79%
108	84.84%	89.80%	94.76%	99.72%
110	84.78%	89.74%	94.69%	99.65%
112	84.72%	89.68%	94.63%	99.58%
114	84.67%	89.62%	94.57%	99.51%
116	84.61%	89.56%	94.51%	99.45%
118	84.56%	89.50%	94.45%	99.39%
120	84.51%	89.45%	94.39%	99.33%
122	86.92%	92.03%	97.14%	102.25%
124	86.83%	91.93%	97.04%	102.14%

For this analysis, a 1590 kCmil 45/7 ACSR Conductor was used.

Table 7 Usage Percentage per Shield Wire Tension

H	4000	4500	5000
68	87.72%	87.72%	87.72%
70	87.54%	87.54%	87.54%
72	87.37%	87.37%	87.37%
74	87.21%	87.21%	87.21%
76	87.05%	87.05%	87.05%
78	86.91%	86.91%	86.91%
80	86.77%	86.77%	86.77%
82	86.64%	86.64%	86.64%
84	86.52%	86.52%	86.52%
86	86.40%	86.40%	86.40%
88	86.29%	86.29%	86.29%
90	85.90%	85.90%	85.90%
92	85.81%	85.81%	85.81%
94	85.72%	85.72%	85.72%
96	85.63%	85.63%	85.63%
98	85.54%	85.54%	85.54%
100	85.46%	85.46%	85.46%
102	85.39%	85.39%	85.39%
104	85.31%	85.31%	85.31%
106	85.15%	85.15%	85.15%
108	85.08%	85.08%	85.08%
110	85.02%	85.02%	85.02%
112	84.95%	84.95%	84.95%
114	84.89%	84.89%	84.89%
116	84.84%	84.84%	84.84%
118	84.78%	84.78%	84.78%
120	84.73%	84.73%	84.73%
122	87.29%	87.29%	87.29%
124	87.19%	87.19%	87.19%

For this analysis, a 795 kCmil 45/7 ACSR Conductor with a 9000 lb. design tension was used.

Table 8 Usage Percentage per Horizontal Span

H	1200	1300	1400
68	96.66%	99.41%	102.17%
70	96.46%	99.22%	101.97%
72	96.29%	99.03%	101.77%
74	96.12%	98.85%	101.59%
76	95.96%	98.69%	101.41%
78	95.81%	98.53%	101.25%
80	95.66%	98.38%	101.09%
82	95.53%	98.24%	100.95%
84	95.40%	98.10%	100.81%
86	95.27%	97.97%	100.67%
88	95.16%	97.85%	100.55%
90	94.75%	97.43%	100.10%
92	94.65%	97.32%	100.00%
94	94.55%	97.22%	99.89%
96	94.46%	97.13%	99.79%
98	94.37%	97.04%	99.70%
100	94.29%	96.95%	99.61%
102	94.21%	96.87%	99.52%
104	94.13%	96.79%	99.44%
106	93.96%	96.60%	99.24%
108	93.89%	96.53%	99.17%
110	93.82%	96.46%	99.10%
112	93.76%	96.39%	99.03%
114	93.69%	96.33%	98.96%
116	93.64%	96.27%	98.90%
118	93.58%	96.21%	98.83%
120	93.52%	96.15%	98.77%
122	96.30%	99.01%	101.72%
124	96.19%	98.90%	101.62%

Table 9 Usage Percentage per Vertical Span

H	1700	1800	1900	2000
68	98.71%	99.41%	100.11%	100.82%
70	98.52%	99.22%	99.92%	100.62%
72	98.33%	99.03%	99.73%	100.43%
74	98.15%	98.85%	99.55%	100.25%
76	97.98%	98.69%	99.39%	100.09%
78	97.83%	98.53%	99.23%	99.93%
80	97.68%	98.38%	99.08%	99.78%
82	97.54%	98.24%	98.94%	99.64%
84	97.40%	98.10%	98.80%	99.50%
86	97.27%	97.97%	98.67%	99.37%
88	97.15%	97.85%	98.55%	99.25%
90	96.73%	97.43%	98.13%	98.83%
92	96.62%	97.32%	98.02%	98.72%
94	96.52%	97.22%	97.92%	98.62%
96	96.43%	97.13%	97.83%	98.53%
98	96.34%	97.04%	97.74%	98.44%
100	96.25%	96.95%	97.65%	98.35%
102	96.17%	96.87%	97.57%	98.27%
104	96.09%	96.79%	97.49%	98.19%
106	95.90%	96.60%	97.30%	98.00%
108	95.83%	96.53%	97.23%	97.93%
110	95.76%	96.46%	97.16%	97.86%
112	95.69%	96.39%	97.09%	97.79%
114	95.63%	96.33%	97.03%	97.73%
116	95.57%	96.27%	96.97%	97.67%
118	95.51%	96.21%	96.91%	97.61%
120	95.45%	96.15%	96.85%	97.55%
122	98.31%	99.01%	99.71%	100.41%
124	98.20%	98.90%	99.60%	100.31%

Failure Analysis

The following data show the number of failed combinations per each design input.

H	# Fail
68	210
70	195
72	186
74	177
76	177
78	165
80	159
82	153
84	150
86	144
88	138
90	126
92	117
94	111
96	111
98	111
100	108
102	108
104	105
106	96
108	96
110	93
112	90
114	87
116	87
118	87
120	87
122	183
124	177

Conductor Type	# Fail
636 kCmil 26/7	0
795 kCmil 26/7	6
954 kCmil 45/7	36
1351 kCmil 45/7	1113
1590 kCmil 45/7	2679

Shield Wire Type	# Fail
7 No. 9 Alumoweld	525
7/16 Steel	999
48 Fiber Alumocore	2310

Conductor Tension	# Fail
7000	0
8000	18
9000	660
10000	3156

Shield Wire Tension	# Fail
4000	1278
4500	1278
5000	1278

Horizontal Span	# Fail
1200	399
1300	1179
1400	2256

Vertical Span	# Fail
1700	663
1800	852
1900	1062
2000	1257

Figure 24 Application output showing the number of failures per design input

The charts below illustrate the distribution of failed combinations for each design input. Due to the large number of conductor heights and the relatively even distribution of failures, it is not included in these results.

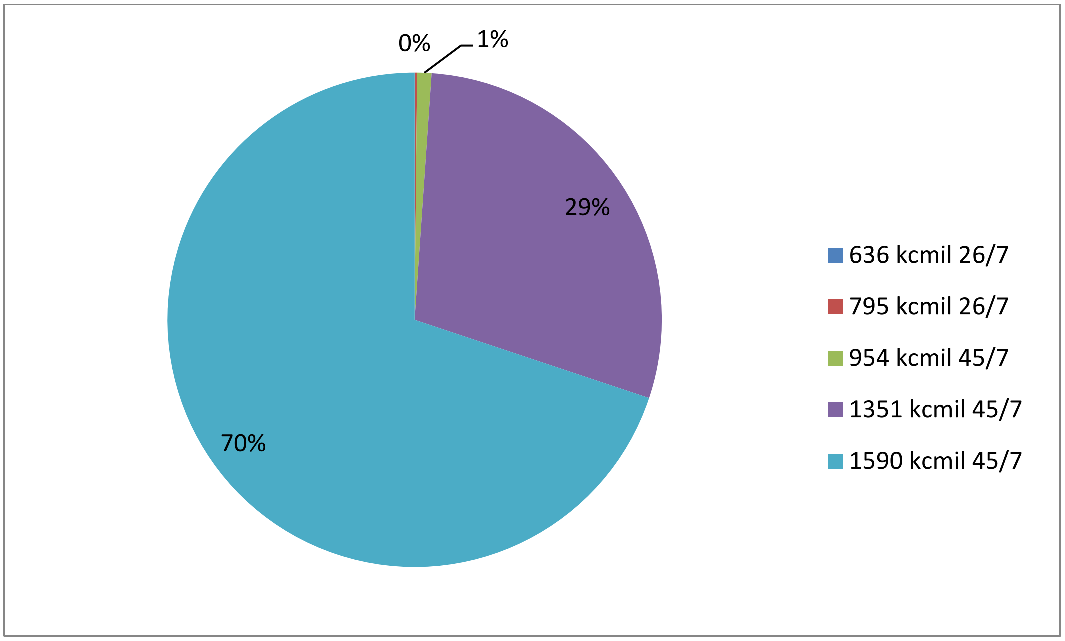

Figure 25 A pie chart showing conductor type failure percentages

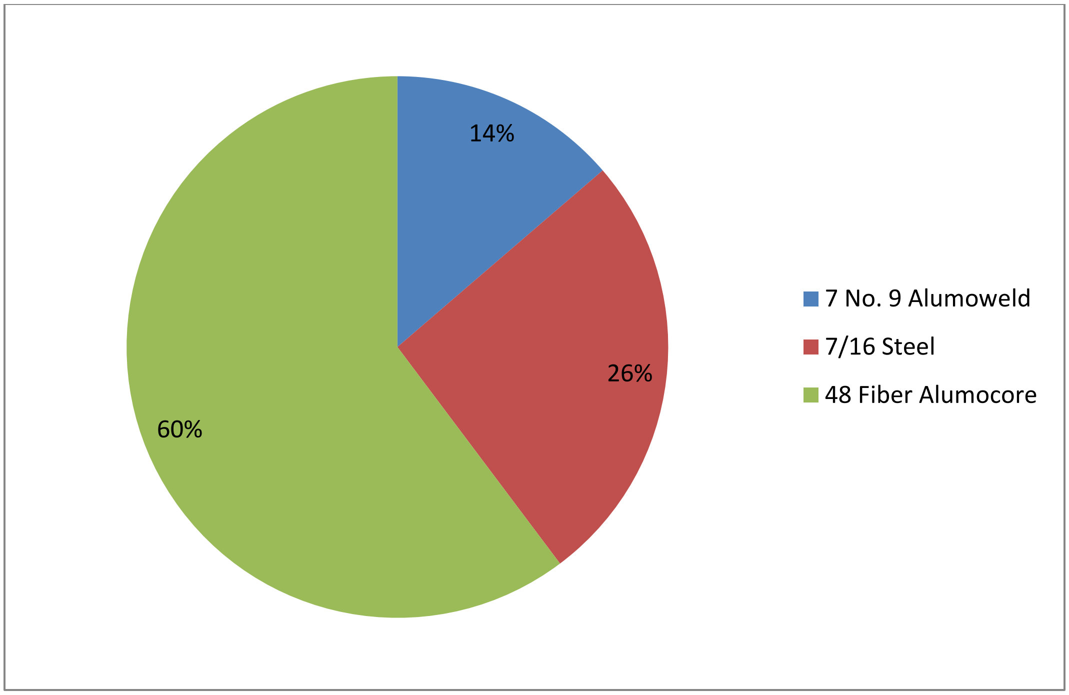

Figure 26 A pie chart showing shield wire type failure percentages

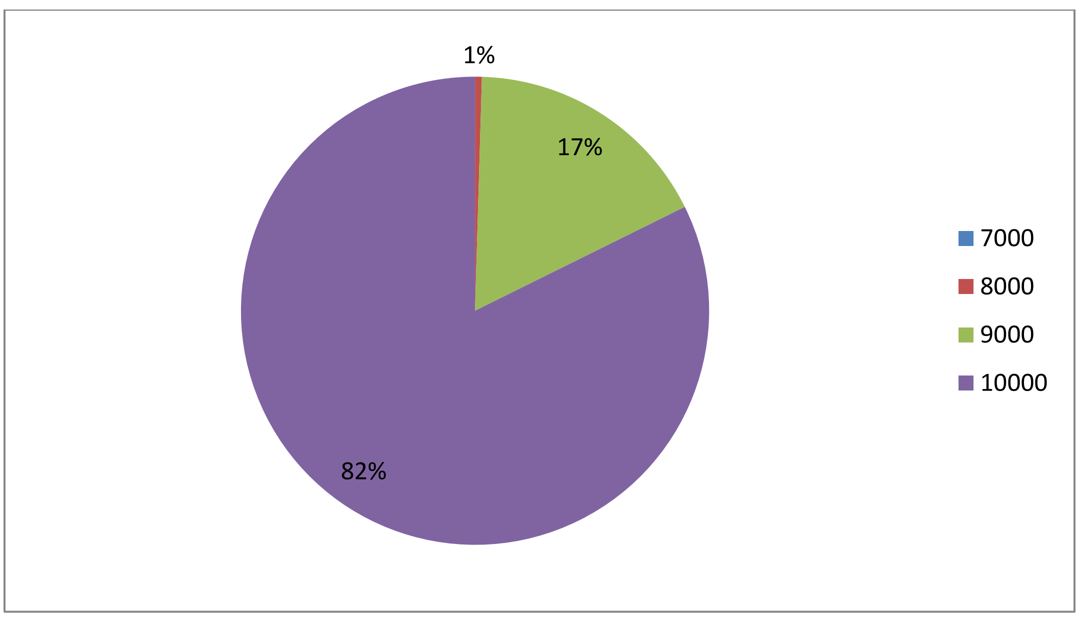

Figure 27 A pie chart showing conductor tension failure percentages

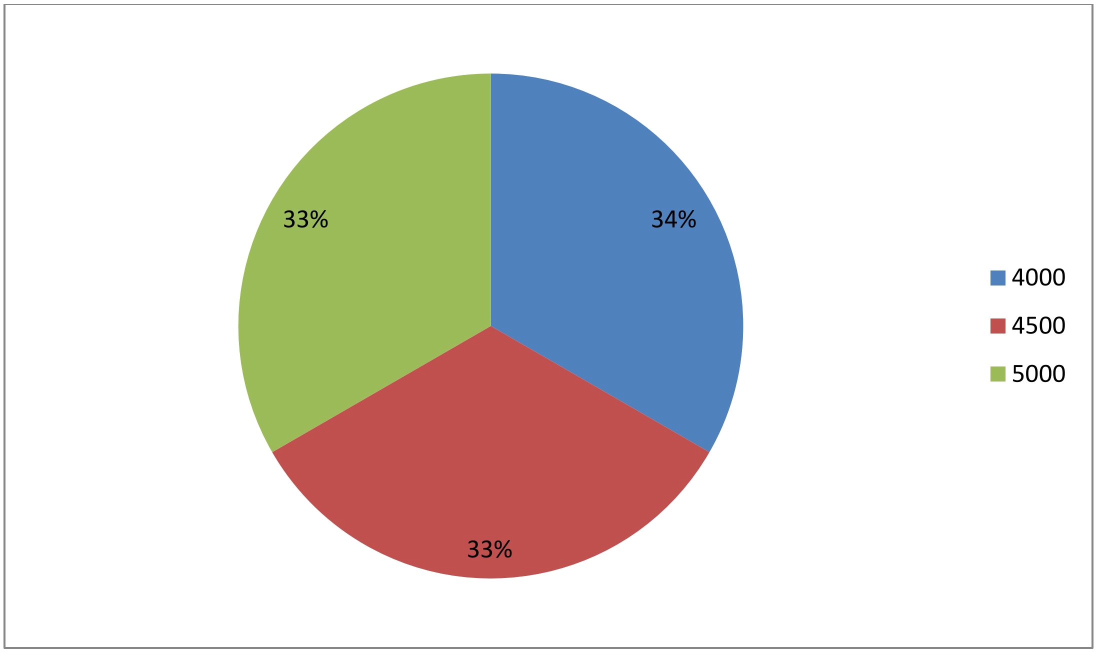

Figure 28 A pie chart showing shield wire tension failure percentages

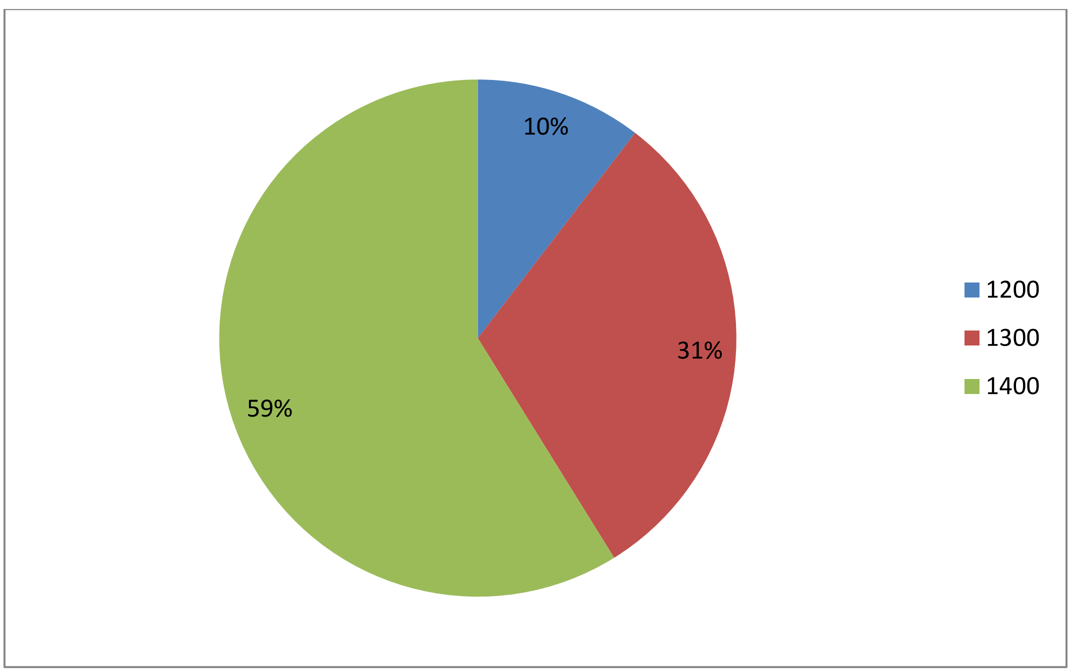

Figure 29 A pie chart showing horizontal span failure percentages

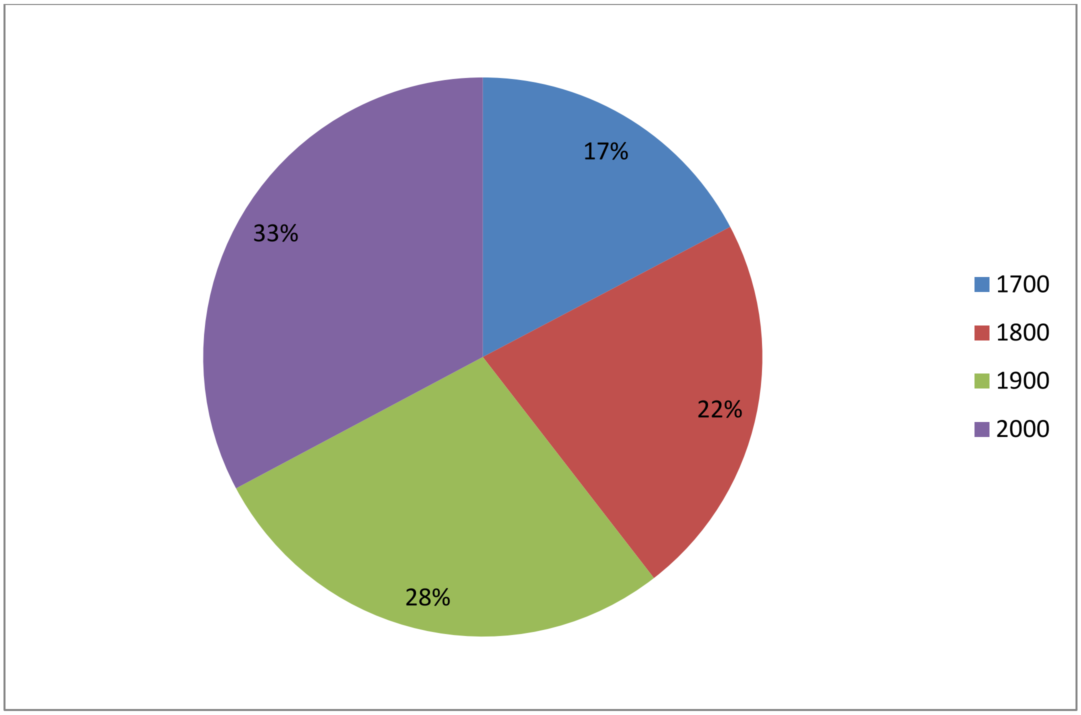

Figure 30 A pie chart showing vertical span failure percentages

CHAPTER 5

DISCUSSION AND CONCLUSION

Introduction

In this study the ground-line force analysis was modernized by lowering the overload factors from their original design values of 4.0 and 1.75 to the modern NESC Medium Loading Zone values of 1.5 for vertical loads, 2.5 for transverse wind loads, 1.65 for transverse wire tension loads, and 1.1 for general longitudinal loads. This decrease in overload factors resulted in a decrease of compression ground-line force from 34.8 kips to 26.2 kips and a decrease of tension ground-line force from 28.6 kips to 19.2kips. These decreases in ground-line forces result in an increase of 25% for compression capacity and 33% for tension capacity.

Objectives of the Study

The objectives of this study were met as described in Chapter 1. The design calculation spreadsheet found in Supplement 1 can be used to evaluate any single circuit tangent lattice tower for vertical, horizontal, and longitudinal loadings and ground-line moments. Multiple trends and significant findings were found and evaluated for simplifying future engineering assumptions and analysis of tangent towers.

Summary of the Findings

This study analyzed 62,640 design input combinations for the A Tower using the modern NESC loading calculation. Of these combinations 58,806 (94%) fell below the maximum ground-line forces that were found using the original design calculation. These combinations were assigned passing criteria with adequate structural capacity. Of the passing combinations, 96% are controlled by the Broken Conductor load case while the remaining 4% are controlled by the Broken Shield Wire load case. Cases I and IV never controlled the failure state for the A Tower.

The minimum ground-line compression was found to be 23.58 kips (32% understress) and occurred with the following design input combination:

- 120' Conductor Height
- 636 kCmil 26/7 ACSR Conductor @ 7,000lb tension
- 7 No. 9 Alumoweld Shield Wire @ all tensions
- 1200 ft Horizontal Span
- 1700 ft Vertical Span

The minimum ground-line tension was found to be 17.87 kips (29% understress) and occurred with the following design input combination:

- 120' Conductor Height
- 636 kCmil 26/7 ACSR Conductor @ 7,000lb tension
- 7/16" Steel Shield Wire @ all tensions
- 1200 ft Horizontal Span
- 2000 ft Vertical Span

Only 3,834 (6%) of the researched combinations were found to fail the comparison to the original structural capacity. All failures in this study occur in the Broken Conductor load case with the compression leg always controlling the failure.

The maximum ground-line compression was found to be 38.64 kips (11% overstress) and occurred with the following design input combination:

- 68’ Conductor Height
- 1590 kCmil 45/7 ACSR Conductor @ 10,000lb tension
- 48 Fiber Alumocore Shield Wire @ all tensions
- 1400 ft Horizontal Span
- 2000 ft Vertical Span

The maximum ground-line tension was found to be 27.90 kips (8% overstress) and occurred with the following design input combination:

- 68’ Conductor Height
- 1590 kCmil 45/7 ACSR Conductor @ 10,000lb tension
- 48 Fiber Alumocore Shield Wire @ all tensions
- 1400 ft Horizontal Span
- 1700 ft Vertical Span

Conclusions

The pass/fail rate of any particular combination was found to most heavily depend on, in order, Conductor Type and Tension, Shield Wire Type, Vertical Span, and Horizontal Span. As expected, larger wires, higher tensions, and longer spans result in an increase of failures against the original calculated capacity. In all researched combinations, the Shield Wire Tension had no effect on the pass/fail rate of the A Tower due to the fact that all Broken Shield Wire Case controlled combinations pass the original structural capacity check.

Conductor Height did not play a major role in determining the pass/fail rate of any specific design criteria combination. Due to the increased distance between tower legs in the taller configurations, the failure rate actually decreased as the conductor height increased. The only exception to this rule occurs in the tallest conductor heights of 122’ and 124’. The failure rate for these combinations increase due to the original, non-extended tower design reaching a maximum leg spacing at a 108’conductor height.

Of the failed combinations 82% contained a 10,000 lb. conductor tension, 70% contained the heaviest conductor (1590 kCmil 48/7 ASCR), 60% contained the heaviest ground wire (48 Fiber Alumocore), 59% has a horizontal span on 1400 ft, and 33% had a vertical span on 2000 ft. There were no failures for combinations containing the lightest conductor (636 kCmil 26/7 ASCR) or a 7,000 lb. conductor tension. As stated previously shield wire tension had no effect the pass/fail rate, so each shield wire tension design value is equally represented in the pool of failed combinations.

Recommendations for Further Study

Further study on this topic is recommended with emphasis placed on small and large angle transmission line towers. The added design criteria of the line angle would greatly increase the scope of the calculation and the usefulness of the findings in a wider variety of real world applications. Computer modeling of the subject towers in PLS Pole and STAAD.Pro can be used to verify the ground-line moments that were found during the course of this study. Further study could be performed on the member and joint capacity of the subject tower to validate the assumption that the maximum ground-line moment controls the strength of the tower.

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APPENDIX A

SUPPLEMENTAL DATA ACCESS INFORMATION

SUPPLEMENT 1 – A TOWER DESIGN: CALCULATIONS

Supplement 1 contains the example design calculations that provide the as-designed groundline forces, as well as the maximum and minimum groundline forces. This data can be downloaded from http://scholar.utc.edu.

SUPPLEMENT 2 – A TOWER FULL RESULTS

Supplement 2 contains the entire results set of all possible design input combinations, groundline forces, pass/fail criteria, and controlling load case. This data can be downloaded from http://scholar.utc.edu.

SUPPLEMENT 3 – CONSTANT DESIGN INPUT PASS RATES

Supplement 3 contain pass/fail tables where one of the 51 design inputs remains constant while evaluating the design calculation for all combinations of the remaining inputs. This data can be downloaded from http://scholar.utc.edu.

APPENDIX B

TRANSMISSION LINE DESIGN GLOSSARY

ACSR – Aluminium conductor steel-reinforced cable is a type of high-capacity, high-strength conductor typically used in overhead power lines.

Alumoweld – A high-strength steel rod with a high-purity aluminum powder compacted around it.

Angle Structure – Angle structures are used where transmission line conductors change direction. These types of structures are designed to withstand the forces placed on them by the change in direction.

Conductor – A material, usually in the form of a wire or cable, suitable for carrying electric current.

Dead End Structure – A dead-end structure is typically used where transmission line conductors turn at a wide angle or end. Compared to tangent structures, a dead-end structure is designed to be stronger and often is a larger structure.

Double Circuit – A double-circuit transmission line carries conductors for two electrical circuits. For a three-phase system, this implies that each tower supports six conductors.

Ground Line Moment – The moment experienced at the ground line as loads are applied to the structure. Common loads include wind pressure on conductors and the structure, ice load on conductors, conductor weight, and tension imbalance at the structure due to uneven spans, and line angles.

Ground Wire – Bare conductors supported at the top of transmission towers. They serve to shield the line and intercept lighting stroke before it hits the current carrying conductors below. Ground wires normally do not carry current.

Ground Wire Peak – The top portion of the lattice transmission line tower. The ground wires will attach at the peak of this area.

Horizontal Span – The sum of half the span lengths on either side of the supporting structure. Also known as wind span. Used to calculated conductor wind area supported by structure.

Kcmil - A circular mil is a unit of area, equal to the area of a circle with a diameter of one mil (one thousandth of an inch). It corresponds to 5.067×10^{-4} mm².

Line angle – The projected angle at which the transmission line changes direction at a struture.

OPGW – An optical ground wire that combines the functions of grounding and communications. An OPGW cable contains a tubular structure with one or more optical fibers in it, surrounded by layers of steel and aluminum wire.

Overtension – The practice of installing an overhead conductor at a tension higher than its intended design tension. This results in less sag in a span.

Sag – The difference in level between points of supports and the lowest point on the conductor in a span.

Single Circuit – A single-circuit transmission line carries conductors for only one electrical circuit. For a three-phase system, this implies that each tower supports three conductors.

Span – The distance between two subsequent transmission structures.

Special Extension – A steel lattice extension that can be added to a lattice transmission tower after the transmission line is constructed and in operation.

Standard Extension – A steel lattice extension that is installed in a lattice transmission tower when the transmission line is initially constructed.

Stranding - A stranded conductor consists of several wires of small cross-sectional area called strands combined to create a conductor with a larger cross section. ACSR stranding is given in (Aluminium/Steel) strands.

Suspension Structure – A structure where the conductors are simply suspended from the tower with the mechanical tension being the same on each side. In this case, the tower is supposed to carry a downward force, and a lateral force, but not a longitudinal force.

Tangent Structure – Tangent structures are the type most commonly used on a transmission line and are used on relatively straight portions of the transmission line. Because the conductors are in a relatively straight line passing through them, tangent structures are designed only to handle small line angles (changes in direction) of 0 to 2 degrees.

Tension – The axial force in the conductor cause by pulling the conductor up from the ground elevation.

Tower Body – The main trunk of a lattice transmission line tower. The conductors will attach in this area.

Tower Leg – The bottom portion of a lattice transmission line tower. Different leg heights can be used to elevate the conductor above ground or other aerial obstacles.

Undertension – The practice of installing an overhead conductor at a tension lower than its intended design tension. This results in more sag in a span.

Vertical Span – The sum of the horizontal distances from the structure to the low point of the conductor in each supported span. Also known as weight span. Used to calculate the conductor weight supported by the structure.

VITA

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