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Comparison of Advanced Analysis Techniques to Traditional Methods

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Abstract

We report on two transmission lines that demonstrate the need for more sophisticated analysis of transmission systems. Topics covered include the stability of wood H-Frames, ruling span vs. finite element based sag-tension, and complete finite element line modeling as opposed to the modeling of structures, insulators and conductors in isolation. We demonstrate that traditional ruling span based sag-tension can be incorrect resulting in unexpected longitudinal loads and erroneous sags. We discuss a complete system approach that treats an entire line as a large structure, allowing the analysis to consider the effects of unbalanced line loading, structure flexibility and the resulting interactions between structures. We will conclude with a line that experienced flashover failure as a result of the interaction between flexible steel poles, unbalanced line loading and unstable hinged braced post insulators.

Introduction

The advent of fast, inexpensive computers enables engineers to perform vastly more sophisticated analysis of transmission systems than possible in either the era of hand calculations or the era of slow computers and limited memory circa 1990. Computer assisted analysis can be used at the structure, wire system or the line (combined structure and wire system) level to provide enhanced understanding of system behavior. The use of finite element based software for structural analysis has been a well-accepted practice for many years. The use of finite element software for modeling the wire system is less common, but still practiced by many conscientious engineers in cases where traditional approximations are not acceptable [BCH '90, EDF '85]. Total system analysis has been predominantly limited to failure investigations, but the exponential growth of computer power and the advent of easy to use software will make this practice just as common as finite element based structural analysis is today.

The sag-tension and loading results we present here are generated by an enhanced version of the PLS-CADD program [PLS '92], the analysis engine of which (SAPS [Peyrot '78]) has been available for more than 20 years. The structural analysis results are from the PLS-POLE program [PLS '00], which is also based on SAPS.

Structures

We first consider a section of a wood H-Frame line designed by a large utility in the Midwest United States. In our experience this type of construction is quite common and the design methodology is representative of utility practice in the United States. This section consists of five suspension H-Frames and two deadends with a single three phase circuit of 138 KV conductor and two ground wires all in horizontal configurations (see Fig. 1).

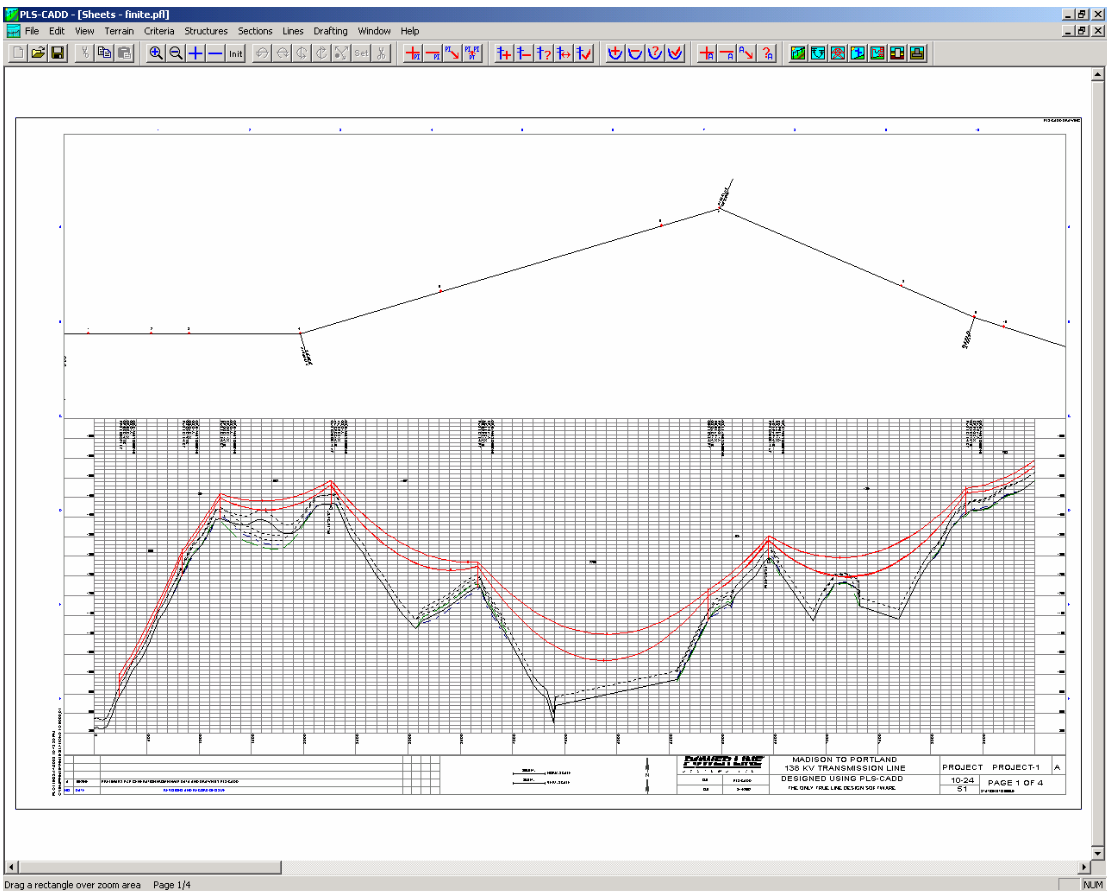

Figure 1 (vertical scale at 5:1)

The structures should be analyzed by nonlinear finite element analysis to account for P-Delta effects [IEEE '91]. Standard practice would be to first determine the loads based on the wind and weight spans that the structure must support. Next these loads would be imported into structural analysis software and the analysis performed. When we went through this process using loads for the NESC heavy ice loading condition some of the structures are revealed to be longitudinally unstable. Structure number six [Figure 2] is one of these unstable structures. Unfortunately, it is difficult to know if the structure is inherently unstable or if the instability is an artifact of the modeling of the structure and its conductors in isolation. To answer this question, we analyze the structure with the conductors, ground wires and other structures out to the deadends included in the finite element model. We refer to this as the "Real Span" method. This provides a more accurate determination of the loads as it accounts for the feedback effect of structure deflection on wire tensions. With loads calculated through this process we discover that the structure does not buckle due to the restraining influence of these wires. As the structure starts to deflect longitudinally, the wires retard the movement and stabilize the structure so long as the other structures in the section are stiff enough. The further the structure deflects, the greater the tension in the wires and thus the system quickly finds equilibrium. However, whether or not the other structures acting through the wires provide sufficient restraint cannot practically be determined without doing the analysis and certainly cannot be determined with linear analysis or via hand methods such as the contraflexure method of IEEE-751 [IEEE '91].

Table 1 – Structure deflections and usages with different analysis techniques and loads

Analysis Method	Left Pole Tip Deflection cm (in)			Structure Usage %		
Loads calculated by	Ruling Span	Finite Element (Real Span)	Finite Element (Single Cable)	Ruling Span	Finite Element (Real Span)	Finite Element (Single Cable)
Contraflexure	Deflections not available with this method			91.7	90.5	114.6
Linear analysis – frame only	66.5 (26.2)	86.9 (34.2)	327.1 (128.8)	102	100	121
Nonlinear analysis – frame only	Unstable – cannot determine deflections			Unstable – cannot determine usage		
Nonlinear analysis with wire system and other structures in tension section included in model	Not applicable	95.7 (37. 7)	Not applicable	Not applicable	99	Not applicable

The instability of the frame under traditional nonlinear analysis has prevented many engineers from accounting for P-Delta effects that can make an important difference in structure usage. By including the wire system in the analysis, one can now use a nonlinear analysis and account for P-Delta effects while confirming the stability of the frame as shown above.

To make the results more directly comparable we used a slightly modified version of the contraflexure method that included longitudinal moments and the wind on the pole. Even with our more sophisticated implementation of this method it still produces dangerously liberal results for this structure (8-29% lower than the other methods). This can be seen with a simple example of a typical application of contraflexure-derived results being used to determine allowable windspan. In the case of a 300 m [1000 ft] span a 10% difference results in a 30 m [100 ft] difference in windspan or one less structure than necessary for every ten spotted.

Loads were calculated using three methods: traditional ruling span, real span (finite element accounting for interactions between wires and structure deflections), and single cable (finite

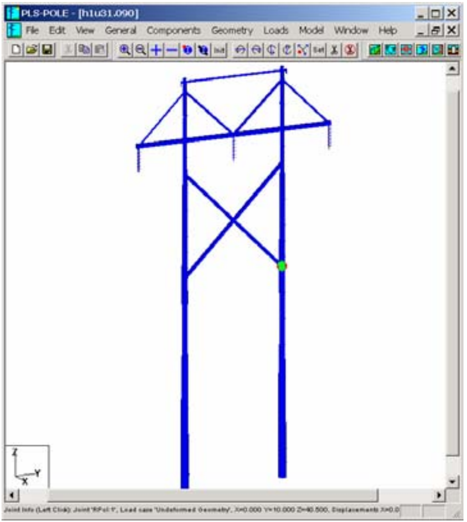

Figure 2

element with only a single wire considered at a time). While the single cable method accounts for the limited ability of insulators to swing and equalize tension, it does not account for the additional equalization caused by structure deflection. Therefore, it results in substantially higher longitudinal loading and hence much greater structure usage.

While traditional contraflexure methods can be dangerously liberal, using single wire methods can generate overly conservative results forcing unnecessary and costly modifications. For structure six, the single cable method resulted in 22% more usage and 3.4 times the deflection of the real span method. In this case, the cost savings from this structure justified the extra engineering time required to model the transmission line as a single coherent system and not as a sum of individual components.

Sag-tension

Traditional sag-tension methods use the “ruling span” approximation where one assumes that the horizontal component of tension is the same between deadends [Winkelman ’60]. This implies that insulators act as perfect roller supports to equalize tension between spans. While no transmission line can live up to this assumption, it is particularly dangerous for high temperature operation [Motlis ‘99] or in terrain with sharp relief such as the line shown in Figure 1. Finite element based sag-tension, which we have referred to as the “real span” method, models the insulators and wires with exact cable elements and uses a geometrically nonlinear finite element analysis. It takes into account the restriction of insulator geometry on swing, the geometry of the insulator attachment points (both uneven span lengths and elevation changes) and structure stiffness if known. The resulting tensions can differ from one suspension span to the next as shown in Table 2 in contradiction to the basic ruling span assumption. This is of interest to the structure designer since even suspension structures can experience tension imbalances and be subjected to loading for which they were not designed.

Table 2 – Span information for 149º C [300º F] emergency operating condition

Span #	Span Length m (ft)	Elevation Change m (ft)	Ruling Span Sag m (ft)	Real Span Sag m (ft)	Sag Diff (%)	Ruling Span Tension N (lbs)	Real Span Tension N (lbs)	Tension Diff (%)
1	183 (600)	98.7 (324)	5.1 (17)	7 (23)	26.56%	10409 (2340)	7651 (1720)	-36.05%
2	109.9 (361)	44.2 (145)	1.7 (6)	2.3 (7)	23.16%	10409 (2340)	7993 (1797)	-30.22%
3	323.4 (1061)	9.8 (32)	14.1 (46)	16.2 (53)	12.88%	10409 (2340)	9074 (2040)	-14.71%
4	428.6 (1406)	-62.8 (-206)	25 (82)	25.7 (84)	2.46%	10409 (2340)	10155 (2283)	-2.50%
5	670.6 (2200)	-23.5 (-77)	61.1 (200)	58.3 (191)	-4.81%	10409 (2340)	10898 (2450)	4.49%
6	176.4 (579)	43.2 (142)	4.3 (14)	4.3 (14)	-0.79%	10409 (2340)	10489 (2358)	0.76%
7	575.5 (1888)	37.3 (122)	44.9 (147)	43.9 (144)	-2.40%	10409 (2340)	10653 (2395)	2.30%
8	231.2 (759)	27.9 (91)	7.2 (24)	7.6 (25)	5.27%	10409 (2340)	9866 (2218)	-5.50%
9	91.6 (301)	-17.8 (-59)	1.1 (4)	1.2 (4)	6.47%	10409 (2340)	9755 (2193)	-6.70%
10	398.3 (1307)	-33.1 (-109)	21.4 (70)	22.5 (74)	4.63%	10409 (2340)	9933 (2233)	-4.79%
11	441.8 (1449)	10.6 (35)	26.3 (86)	27 (89)	2.64%	10409 (2340)	10137 (2279)	-2.68%
12	153.6 (504)	-0.4 (-1)	3.2 (10)	3.3 (11)	3.08%	10409 (2340)	10089 (2268)	-3.17%
13	526.2 (1726)	8.9 (29)	37.4 (123)	36.7 (120)	-1.94%	10409 (2340)	10609 (2385)	1.89%
14	15.2 (50)	-2.7 (-9)	0.03 (0.1)	0.03 (0.1)	0.00%	10409 (2340)	10809 (2430)	3.70%
15	679.4 (2229)	25.6 (84)	62.7 (206)	59.6 (196)	-5.13%	10409 (2340)	10934 (2458)	4.80%
16	115.7 (380)	23.9 (78)	1.8 (6)	1.9 (6)	4.29%	10409 (2340)	9964 (2240)	-4.46%
17	110.2 (362)	0.7 (2)	1.6 (5)	1.8 (6)	9.48%	10409 (2340)	9426 (2119)	-10.43%
18	182.8 (600)	-27.9 (-92)	4.5 (15)	5.1 (17)	11.52%	10409 (2340)	9212 (2071)	-12.99%
19	319.4 (1048)	-27.7 (-91)	13.8 (45)	15.2 (50)	9.11%	10409 (2340)	9466 (2128)	-9.96%
20	465.7 (1528)	34.7 (114)	29.3 (96)	30.9 (101)	4.95%	10409 (2340)	9902 (2226)	-5.12%
21	133.4 (438)	35.9 (118)	2.5 (8)	2.7 (9)	7.41%	10409 (2340)	9639 (2167)	-7.98%
22	499.3 (1638)	23.6 (77)	33.7 (111)	34.2 (112)	1.49%	10409 (2340)	10258 (2306)	-1.47%
23	422.8 (1387)	-30.8 (-101)	24.2 (79)	25.1 (82)	3.89%	10409 (2340)	10008 (2250)	-4.00%
24	337.8 (1108)	-5.2 (-17)	15.4 (50)	16.6 (55)	7.69%	10409 (2340)	9613 (2161)	-8.28%
25	283.5 (930)	2.3 (8)	10.8 (35)	12 (39)	10.07%	10409 (2340)	9368 (2106)	-11.11%
26	347.3 (1139)	28.4 (93)	16.3 (53)	17.9 (59)	9.22%	10409 (2340)	9426 (2119)	-10.43%

Consider the fifth span of our previously mentioned example line. It has 2.8m [9 ft] of additional sag at the 149º C [300º F] emergency operating temperature when analyzed with the real span method as opposed to the ruling span method. While in this case ruling span is dangerously liberal, it can be overly conservative in others. For example the 15th span actually has 3.1m [10 ft] less sag than predicted by ruling span. In addition to this startling difference in sag we also find longitudinal loadings of 4337 N [975 lbs] per static wire and 1864 N [419 lbs] per phase for a total of 14265 N [3207 lbs] of additional longitudinal load for the NESC heavy load case (even 10098 N [2270 lbs] of longitudinal load under the 149º C [300º F] case). The discrepancies between ruling span and real span are due to a combination of uneven span lengths and elevation changes [Motlis '98, Motlis '99]. Perhaps a more intuitive ruling span problem can be seen at structure three which despite being a suspension structure and thus under the ruling span assumptions capable of perfectly equalizing tension, has a vertical load of 50665 N [11,390 lbs] under NESC heavy that must be lifted in order for the insulator to swing and equalize tension.

Another consequence of the ruling span assumption is the inability to consider differential loading scenarios such as imbalanced ice, slack reallocation schemes like cutting and splicing conductor lengths in a span to reduce sag, or complex behavior due to large displacements of suspension or 2-parts insulators (such as hinged braced posts). These conditions cannot be considered since they either are the result of or themselves induce a longitudinal tension imbalance that by definition cannot occur under the ruling span regime. A structure designer limited to the ruling span method will not be prepared for these additional loads, sags or unstable behavior. This will be demonstrated in the Line Analysis section.

Line Analysis

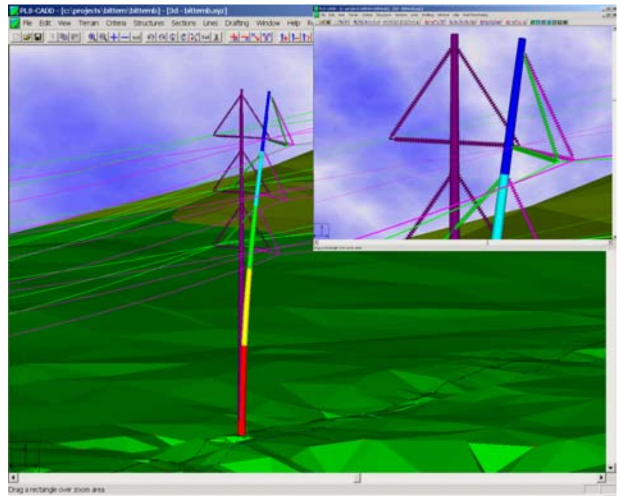

Figure 3

Complete line analysis combines the finite element models of structures, conductors and insulators into a single large model which can be analyzed to provide accurate answers to complex problems such as the effects of structure flexibility, imbalanced loading and slack accumulation over spans. We have analyzed such a model of a line in Western Canada that failed due to flashover [Figure 3]. This model consists of 18 structures, 3 wood H-Frames and 15 steel poles. The intermediate steel poles used hinged braced post insulators. Flashover was caused by a combination of structure deflection adding slack and slack running through several spans until enough slack accumulated in one of the spans to allow a post to swing longitudinally across and flip over the structure resulting in the conductor striking the pole. Figure 3 shows the structure in its undeformed position as predicted by ruling span superposed with the final deflected position predicted by the real span method considering structure flexibility and a complete model of the wire and structure system during the windstorm. Note that the real span method includes the effects of structure deflection, which can be substantial for a steel pole (3.56 m [11.7 ft] for this 30.5 m [100 ft] tall pole).

The utility solved the flipping problem by longitudinally guying several structures. This effectively eliminated structure deflection and prevented the addition of slack by the bending of the steel poles. The original flashover occurred during a strong windstorm, but we do not have weather data for that location and cannot quantify just how strong the winds were. Therefore, we cannot conclusively say that the problem has been fixed since we cannot guarantee that the line has seen the same weather conditions as those that caused the problem. However, in the three years since corrective action was taken the problem has not reoccurred.

Conclusion

We first looked at the classic problem of H-frame stability under a geometrically nonlinear finite element analysis. This instability could be real or due to neglecting to model the supporting behavior of the conductors, shield wires and other structures attached through them to the structure. We demonstrated that an analysis of the frame together with these wires and other structures allows one to determine whether the frame is stable: i.e. whether the restraining influence of the conductors and other structures suffices to support the frame in question or whether it is inherently unstable under the applied loads. We also compared three methods for deriving loads: ruling span, real span and single cable. We then used these loads with four analysis methods: contraflexure, linear analysis, nonlinear analysis and nonlinear analysis including the wires and other structures. We showed that contraflexure produced liberal results, linear analysis neglects second order effects, nonlinear analysis was unstable and nonlinear analysis of the entire system provides both an affirmation of the stability of the structure and the adequacy of its strength.

Next we demonstrated that traditional ruling span assumptions can lead to substantial errors in both sags and loads. These errors can be either liberal or conservative depending on the geometry of the line, the flexibility of the attachments and a variety of other factors. These factors are sufficiently complex and occasionally counterintuitive that one cannot simply "eyeball" a line to determine which spans may be in error. Instead, one must perform a rigorous analysis that does not depend on the ruling span approximation. This analysis can lead to safer, more reliable designs and eliminate costly errors prior to building the line. While traditional methods have served us well and continue to be the most efficient tools for preliminary design, the use of more sophisticated methods that have now become practical, should be encouraged to ensure code compliance. This is of particular importance as the traditional safety buffers that have prevented gross clearance violations are eroded in an attempt to transmit ever more power through the same conductors.

Finally, we investigated another application of the combined wire and structure finite element model: determining whether or not unstable hinged braced post insulators will flip across a structure and cause flashover. In the failure we explored, traditional analysis did not reveal a problem, as it could not account for the additional slack introduced into the problem span by the deflection of the relatively flexible steel poles. Neither could it predict the flipping behavior of the insulators that was caused by longitudinal loading as the ruling span regime assumes that longitudinal loads are perfectly equalized at each intermediate support.

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