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BOLD[TM] Development – Mechanical Considerations for the Design of a Compact EHV Transmission Line

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SUMMARY

Conductor motion must be given due consideration when designing transmission lines. Unexpected movement can lead to flashovers, breaker operations, and overloading of structural and electrical components. These effects can be magnified when the line is both extra-high voltage (EHV) and is compacted. This paper describes how these mechanical considerations were addressed during the development of AEP's new EHV compact Breakthrough Overhead Line Design, or BOLD.

BOLD is a high-capacity, high-efficiency transmission line design. A single steel pole with two curved arms was desired for the first BOLD suspension structure, combining a simple, elegant appearance with performance. Two BOLD circuits are symmetrically supported, with the bundled conductor phases of each circuit chained together by an innovative arrangement of V-string insulator assemblies. Each individual phase consists of three conductors, optimized in a 29 inch (74 cm) bundle configuration. The phase spacing of 345 kV BOLD is as low as 15 feet (4.6 m) for the first BOLD application, the Sorenson–Robinson Park 345/138 kV Line. Two ground/shield wires are positioned on top of the arched beam assembly providing a zero-degree shield angle to the outermost phases. The average structure height is 50 feet (15.2 m) shorter than traditional double-circuit 345 kV line designs.

AEP has been a pioneer in the development of EHV transmission lines. With the experience derived from designing over 39,000 miles (62,800 km) of transmission lines in over 11 states in the United States of America – including over 8,000 miles (12,875 km) of EHV lines of which 2,100 miles (3,380 km) are 765 kV – AEP has been able to push the design envelope. As the voltage levels of transmission lines have increased over the decades, the ratio of the phase-to-phase spacing to the spacing required to prevent power frequency voltage flashover has been reduced by half when comparing these ratios at 138 kV to 765 kV. This reduction in physical space and electrical margin provides the basis for the compactness of BOLD.

In addition to withstanding the larger electrical stresses due to phase compactness, BOLD lines must also function under weather related mechanical stresses. To evaluate the effects of conductor motion near mid-span, extensive analytical studies were performed using AEP transmission line mechanical loading criteria for both every day and extreme weather conditions. The minimum electrical clearances, both phase-to-phase and phase-to-ground, to be maintained during conductor movement are determined by insulation coordination studies and three phase electrical testing performed at ERPI.

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Clearances for switching overvoltage are maintained for conductor motion under every day conditions, and clearances for power frequency voltage under extreme weather conditions.

The conductor motion studies addressed include conductor gust response differential (blowout), galloping, ice shedding, and fault current induced mechanical loading. The calculated movements were determined by the loading criteria and design limitations were determined by the acceptance criteria that are discussed in subsequent sections of this paper. To address situations outside of acceptable limits of conductor movement, the application of In-span Interphase Insulators (I^3) is required. Additionally, this paper summarizes the effects of this conductor motion study on the strength requirements of the insulator assemblies at the structure location.

The results of conductor motion study led to the decision to move BOLD from concept to implementation. This unique design was ready for construction after approximately two years of development. The first 345 kV BOLD line (see Photo 1), located in Fort Wayne, Indiana, USA, will be in service in 2016. A long-term line monitoring program is being undertaken to evaluate both the mechanical and electrical performance of this new design.


Photo 1 BOLD in Fort Wayne, Indiana

KEYWORDS

Compact, extra high voltage, conductor motion, galloping, gust response differential, ice shedding, fault current, aesthetic, 345 kV, transmission line, expanded bundle, aspect ratio, phase spacing

BOLD Configuration

345 kV BOLD was envisioned as a double-circuit line(C1-C2-C3, C4-C5-C6), with each phase of each circuit consisting of two, three, or four conductors at an optimized bundle diameter forming a “delta” using three traditional V-string suspension insulator assemblies (see Figure 1). The compact phase spacing, combined with the optimized conductor bundle, provides superior electrical performance in terms of surge impedance loading (SIL), significant reductions in magnetic fields, and moderate reductions in audible noise when compared with traditional designs. The number of sub-conductors used is based on the desired electrical loading capacity of the line. Although originally conceived as double circuit, BOLD may also be installed as single circuit construction.

The conductor motion studies discussed in this paper use the phase arrangement shown in Figure 1, which is the configuration used in the first BOLD project. The phase spacing is 15 feet, 15 feet, and 19.33 feet (4.6 m, 4.6 m, and 5.9 m). Each phase configuration consists of three 954 KCM 54/7 ACSR Cardinal conductors with phase bundle diameter of 29 inches (74 cm). The aspect ratio between sub-conductor spacing and the conductor diameter is 21. The unique “netting” appearance requires two insulators in an uncommon phase-to-phase position per circuit. That is, the circuit on the left has interphase insulators between C1 and C2, and between C2 and C3. The overhead ground wire GW1 is directly above phase C2, and GW2 is directly above C5. The distance between GW1 and C2, and GW2 and C5 is 23 feet (7 m).

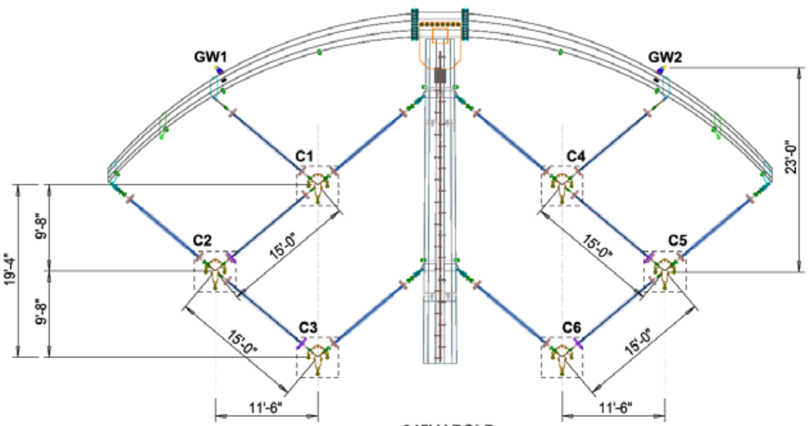

Figure 1 345 kV BOLD Phase Configuration

BOLD is an EHV line designed for bulk power delivery over long distances. The conductor motion study is mainly focused on the phase spacing for span lengths between 600 feet (183 m) and 3,000 feet (914 m).

Loading Criteria

The AEP service territory covers 197,500 square miles (511,500 sq.km) in Arkansas, Indiana, Kentucky, Louisiana, Michigan, Ohio, Oklahoma, Tennessee, Texas, Virginia and West Virginia (see Figure 2). These weather conditions range from heavy ice in the mountains of West Virginia, to high wind and ice in the central plains (Indiana, Oklahoma, and west Texas), to extreme wind in the coastal area of Texas. These weather and geographical conditions are representative for most transmission lines built in the United States.

AEP transmission line design criteria meets or exceeds the current industry standards (see Figure 3 and Figure 4). AEP transmission lines are designed for the following distinct weather cases: 1.25” (3.2 cm) heavy ice, 25 psf. (1200 Pa) wind, 50 psf. (2400 Pa) wind in coastal areas, and 6.25 psf (300

Pa) wind concurrent with 1.0” (2.5 cm) ice. These weather conditions form the basis for the conductor motion studies.

Figure 2 AEP Service Territory

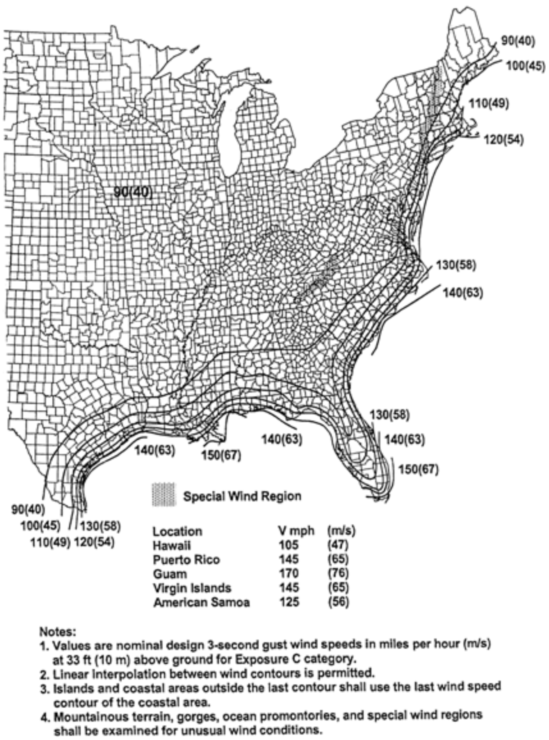

Figure 3 ASCE 10-05 Basic Wind Speed

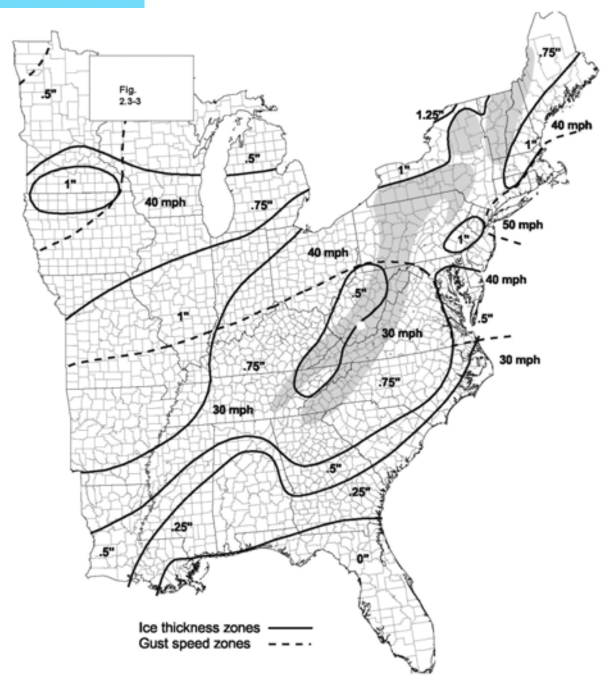

Figure 4 ASCE 10-05 ice with Concurrent Wind

Table 1 defines the weather conditions used for each type of conductor motion considered in the study.

Table 1 Weather Conditions for BOLD Conductor Motion Studies

	Weather Conditions		
Conductor Motion Types	Temperature (°F/°C)	Ice Thickness (in./cm)	Wind Pressure (psf/pa)
Gust Response Differential (Bare Wire)	60/16	0	2/100, 6/300, 12.25/600, 25/1200, 50/2400
Gust Response Differential (Loaded Wire)	0/-18, 32/0	0.5/1.27	4/200, 6.25/300
Galloping	32/0	0.5/1.27	2/100
Ice Shedding	32/0	0.5/1.27	0
Sag Differential under Unequal Ice	32/0	0.5/1.27, 0.75/1.91, 1.0/2.54	0, 4/200
Fault Current Induced Motion	60/16	0	2/100

Acceptance Criteria

Phase spacing under normal weather conditions should be larger than the necessary separation for withstanding switching surge overvoltage. An insulation coordination study and three-phase electrical testing performed at EPRI confirmed that the critical flashover strength of a 9.25 feet (2.82 m) phase-to-phase strike distance will exceed the electrical stress resulting from switching over-voltages induced by the AEP system on 345 kV BOLD. The phase-to-ground strike distance of BOLD of 8'-11" (2.72 m) is governed by lightning protection requirements, as are as traditional designs.

The conductor motion must be limited to prevent a flashover during 60 Hz operation. This requires a withstand clearance of 3.5 feet (1.07 m) between phases, and 2.5 feet (0.76 m) from phase to ground. Table 2 summarizes the minimum phase spacing required for the different types of conductor motion and weather conditions, under either power frequency or switching over-voltage conditions.

Table 2 Minimum Withstand Phase Spacing

Conductor Motions	Weather Conditions	Operation Conditions	Clearance (feet/m)	Min. Phase Spacing (feet/m)*
Gust Response Differential	2, 4, 6, 6.25 psf wind	Switching over-voltage	9.25/2.82	12.25/3.73
	12.25, 25, 50 psf wind	Power Frequency	3.5/1.07	6.5/1.9
Galloping	32°F, 0, 2 psf	N/A	No Overlap	3/0.91
Unequal Ice Sag Differential	0.5" ice vs. bare	Switching over-voltage	9.25/2.82	12.25/3.73
	1" ice vs. bare	Power Frequency	3.5/1.07	6.5/1.9
Ice Shedding	200 feet (61 m) of 0.5" ice drop	Power Frequency	3.5/1.07	6.5/1.9

Note:
1. Minimum phase spacing is equal to the sum of clearnance, bundle diameter,
   and 0.5 feet (15 cm) representing sag differential between adjacent phases to account for construction tolerances.
2. Bundle diameter is 2'-5" feet (74 cm).

Gust Response Differential

The effects of gusting wind will vary in velocity, direction, duration, and area covered from point to point. Gusts will not reach each phase bundle at the same time. Additionally the sag and tension between phase conductors can vary slightly due to construction tolerances. All these factors will result in different wind loading on each of the phase conductors. The resulting conductor response differential can generate a momentary reduction in design phase spacing.

AEP has a successful operational history in terms of limited momentary outages for 138 kV lines with 15 feet (4.6 m) horizontal phase spacing at average spans of 1,200 feet (366 m) and maximum spans of 2,000 feet (610 m). The calculations show that 15 feet phase spacing allow 10% differential movement in horizontal direction between the adjacent phases. This aligns with the results of published studies by Dianna et al. 1990 and Tsujimoto et al. 1982. These studies show that the differential movement between phases comprised of triple bundles crossing a valley is about 9% of the total horizontal displacement due to wind, and 10% for phases comprised of single conductors. The differential movement used to evaluate the BOLD line performance was based on 10% of the total horizontal displacement due to gusting winds.

The longest span that maintains the clearances listed in Table 2 is 1,200 feet (366 m). This occurs when the middle phase swing is 10% less than the top or bottom phases for 25 psf (1200 Pa), 50 psf (2400 Pa) and 6 psf (290 Pa) wind pressures (see Figure 5 and Figure 6). Span lengths longer than 1,200 feet (366 m) may require the installation of I^3 assemblies to maintain the desired phase spacing.

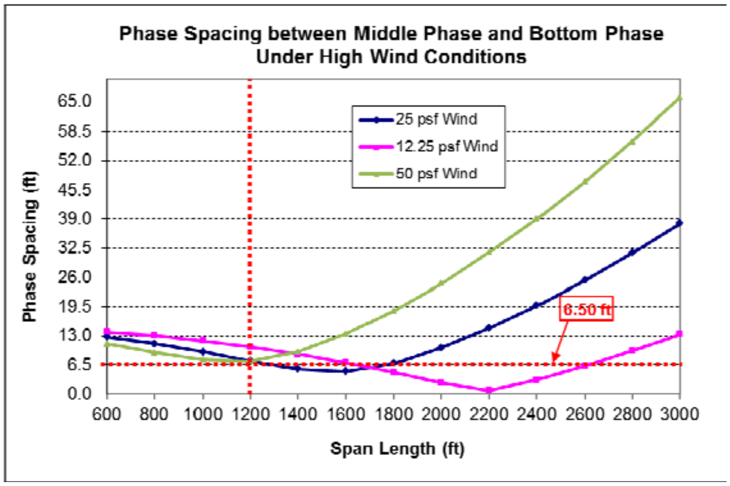

Figure 5 Phase Spacing under High Wind Conditions

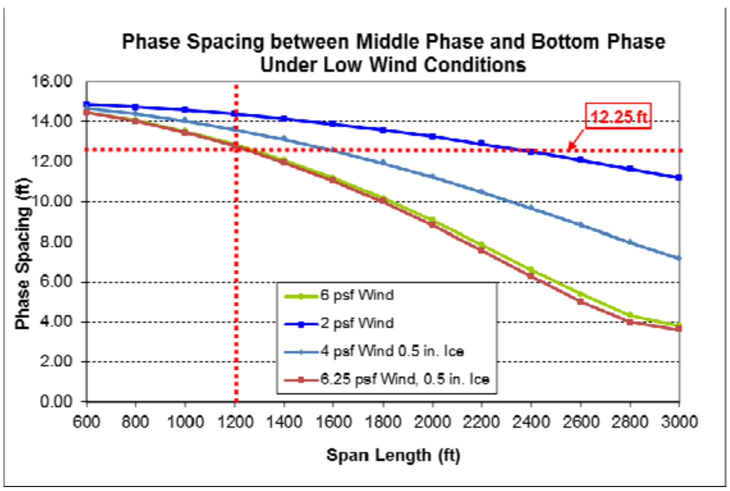

Figure 6 Phase Spacing under Low Wind Conditions

Galloping

Most AEP EHV lines use round-shaped conductors in two bundle, three bundle, four bundle, or six bundle phase configurations, of which aspect ratios are in the range from 13 to 15.5. The typical span length is 1200 feet (366 m) in which some vertical galloping has been observed. The magnitude of this vertical galloping is usually less than 20 feet (6.1 m), except when the aspect ratio is less than 12. In this case, the maximum magnitude of vertical galloping is larger than 25 feet (7.6 m).

BOLD has an expanded bundle configuration. The aspect ratio is about 21, which is significantly larger than traditional designs. Large aspect ratios will reduce vertical galloping, however very little research has been done on the galloping performance of expanded bundle configurations. The galloping envelopes of BOLD were determined by AEP field operational experience, which are approximately 50% smaller than what the Cigre method predicts. The galloping envelope defined in the Cigre Report 322 for bundled conductor phase configurations was included in this study for comparison.

The size of the galloping envelope is predicted to be about 16 feet (4.9 m) for a 1,200 foot (366 m) span (see Figure 7) based on AEP experience. This means that the phase conductors will not contact each other while galloping when the span length is less than 1,200 feet (366 m). When the span lengths are longer than 1,200 feet (366 m), I^3 assemblies can be installed to control the magnitude of galloping. Studies (Havard, 2008) show that I^3 assemblies usually can reduce the galloping magnitude by half. Twisted pair conductors can also be used to reduce or eliminate galloping.

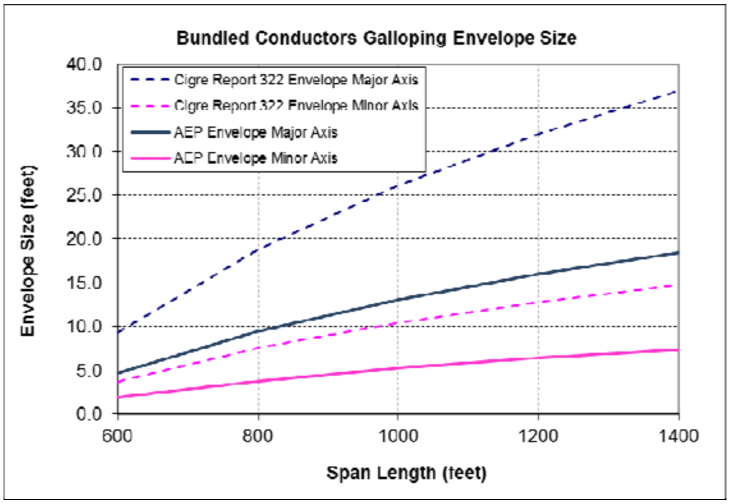

Figure 7 Galloping Envelope Size

Unequal Ice Sag Differential

The top phase of BOLD is directly above the bottom phase, and the ground wire is directly above outside middle phase (see Figure 1). The sag differentials are examined for the case where the top phase conductors have more ice than the bottom phase conductors to ensure there is enough clearance between the phases. The results show that the minimum phase spacing listed in Table 2 can be maintained when subjected to 1.0 inch ice loading on the top phase with the bottom phase bare. The resulting phase spacing between the ground wires and outside middle phases is greater than 11 feet (3.35 m) under the same icing conditions, which is large enough to withstand the switching and lightning overvoltage for span lengths up to 3,000 feet (914 m) (see Figure 8). Table 3 summarizes the study results.

Table 3 Summary of Sag Differential under Unequal Ice between Top and Bottom Phases

Span (feet)	Phase Spacing (Feet) 1.0" Ice v.s Bare	0.75" Ice v.s. Bare	0.5" Ice v.s. Bare	1" Ice v.s. 0.5" Ice	0.75" Ice v.s 0.5" Ice
600	14.0	15.5	16.8	16.54	18.04
800	12.8	14.9	16.5	15.69	17.75
1000	12.0	14.5	16.3	15	17.54
1200	11.3	14.2	16.2	14.46	17.36
1400	10.8	14.0	16.1	14.04	17.21
1600	10.4	13.8	16.1	13.69	17.1
1800	10.1	13.7	16.0	13.4	17.01
2000	9.8	13.6	16.0	13.17	16.94
2200	9.6	13.5	16.0	12.97	16.87
2400	9.4	13.4	15.9	12.79	16.82
2600	9.2	13.3	15.9	12.63	16.77
2800	9.0	13.3	15.9	12.48	16.73
3000	8.8	13.2	15.8	12.35	16.68

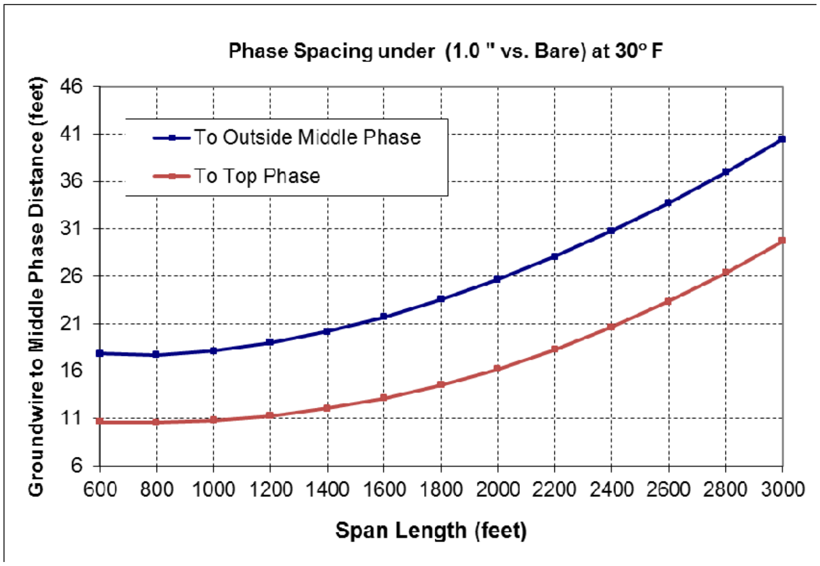

Figure 8 Phase Spacing between Groundwire and Middle Phase under Unequal Ice

Ice Shedding

Ice shedding can cause vertical motion of phase conductors and overhead groundwires. The magnitude of the vertical motion depends on the span length, conductor sag, conductor size, ice thickness, the amount of ice shedding at any one time, and the position of the ice being shed in the span.

The span length of an EHV line is usually longer than 800 feet (244 m). The likelihood of an 800-foot (244 m) length of ice shedding at the same time is very low. The EPRI Blue Book recommends using a fixed length of 133 feet (40.5 m) of 0.5 inch (1.3 cm) glaze ice to simulate ice shedding. This study used a 200 foot (61 m) length of 0.5 inch (1.3 cm) glaze ice. Six spans of the BOLD line were modelled with the defined ice loading using PLS-CADD^{TM}. Two hundred feet of ice was released in various spans (one span at a time) and the differences in sag in all spans were calculated. The total upward vertical deflection in the span that experienced the ice shedding is equal to the sum of the corresponding downward deflections in the adjacent spans plus the sag reduction due to the ice drop. The maximum vertical deflection calculated was 6.02 feet (1.8 m). Table 3 shows that the phase spacing between top and bottom phases could be as close as 16.2 feet (4.9 m) when the top phase conductors have 0.5 inch (1.3 cm) of ice and the bottom phase is bare for 1200 feet (366 m) spans. The net phase spacing will be reduced to 10.18 feet (3.1 m) from 16.2 feet (4.9 m). This reduced spacing is still larger than the 6.5 feet (2 m) that is required to maintain 60 Hz power frequency clearance.

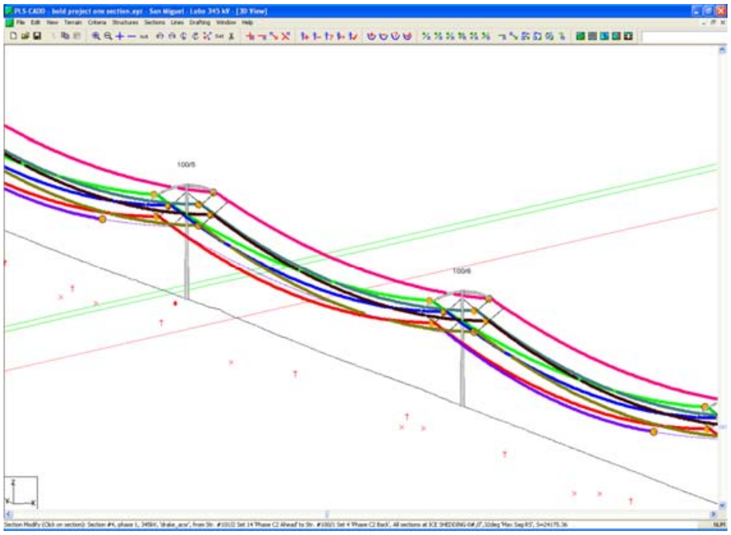

Figure 9 PLS-Cadd Modeling

Other Considerations

The likelihood of a traditional 345 kV transmission line having a phase to phase fault is very low, less than 0.3/100 miles/year (0.19/100 km/year). Fault current induced conductor motion is discussed in the EPRI Orange Book, but detailed analysis was not part of this study because it does not control the design. Minimum phase spacing is maintained at 9.66 feet (3 m) after fault current induced conductor swinging occurs. This is larger than 6.5 feet (2 m) required for 60 Hz operation (see Table 2).

The additional mechanical forces induced by galloping on the three V-string insulator assemblies at the structure location have been studied. Galloping can cause up to a 70% increase in vertical load on the insulator assemblies in an 1800 foot (550 m) span. However, AEP's heavy ice (1.25" (3.2 cm) ice) load case actually controls the insulator strength requirement.

Conclusions

Four main types of conductor motion (gust response differential, galloping, unequal ice sag differential, ice shedding) were considered for the initial conceptual design of BOLD. When the span length is less than 1200 feet (366 m), the performance of a 345 kV BOLD is predicted to be similar to a traditional EHV line design. Span lengths longer than 1200 feet (366 m) may require that I^3 units be installed to maintain the desired electrical clearances under the gust response differential conditions. I^3s can also be added on the spans where galloping is observed.

Conductor motion studies on BOLD are based upon the existing AEP field operational experience and limited published research results. A long-term field monitoring program has been developed to validate the study assumptions used in this paper and further optimize the BOLD line design in terms of line compactness, bundle configuration, and phase arrangements.

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