



BOLD®: Breakthrough Overhead Line Design

Transmission Line Design Considerations

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BOLD® (Breakthrough Overhead Line Design) is a high-capacity, high-efficiency transmission line design that optimizes structure geometry through the use of curved steel arms and compact conductor phase spacing. The unique geometry and electrical characteristics of a BOLD transmission line can be designed and constructed in a manner similar to typical transmission line projects; however, there are several considerations that line engineers need to consider with BOLD projects.



The inaugural BOLD line constructed in Ft Wayne, Indiana was designed by American Electric Power using a process similar to developing a new structure or tower series. The BOLD structures developed are fully compatible for use in PLS-CADD™ and PLS POLE™. One key transmission line design requirement for long lines, which are limited by voltage or stability considerations, is that 95% of the line needs to retain the compact phase spacing to maintain the electrical benefits of the BOLD technology. The compactness of the conductor requires additional consideration for the line engineer with regards to galloping criteria, rolling clearances, and structural geometry. The unique electrical characteristics of BOLD also provide a line engineer with a solution to install EHV transmission lines in a narrower right-of-way corridor.

Introduction

AEP has been a pioneer in extra high voltage (EHV) transmission technology, developing and constructing the first 345-kV and 765-kV lines in the United States in the 1950s and 1960s, respectively. AEP continues to lead this trend in transmission line innovation with the BOLD initiative.

With BOLD, or Breakthrough Overhead Line Design, AEP engineers set out to create a cutting edge generation of transmission lines that could achieve greater capacity and efficiency by increasing the utilization of right-of-way (RoW) corridors. This more effective use of the RoW would reduce visual and environmental impacts. BOLD offers both electrical and geometric benefits.

The BOLD technology leverages physics to maximize electrical performance. The phase separation is reduced into a compact “delta” configuration (Figure 1) and the conductor diameter, number of sub-conductors, and bundle spacing are optimized. Figure 1 shows the BOLD insulator assembly for one 345-kV circuit for a 3-conductor bundle.

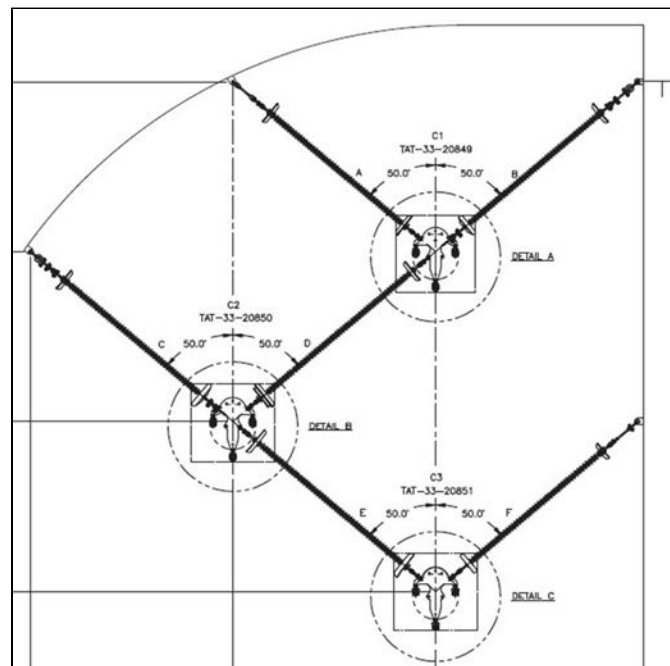


Figure 1

The electrical benefit of the compact configuration is a line with reduced inductance and increased capacitance, which results in higher surge impedance loading (SIL). SIL is a measure of the relative loadability among alternative line designs. By bundling with multiple subconductors per phase, the SIL capacity increases and electric stress decreases to achieve desired corona and audible noise performance. A 345-kV double-circuit BOLD 3-bundled conductor design offers a 43% improved surge impedance loading over a traditional double-circuit 2-bundled conductor design of the same voltage class [1].

When BOLD was developed, a goal of the project team was to address more than just optimizing the electrical properties. The team also considered aesthetics and structural optimization to support the delta-configured phase conductors in a visually appealing way to appeal to the general public and facilitate public acceptance during siting. The compact delta-conductor configuration is attached to a curved arm that also offers geometric benefits by minimizing the structure height. This feature of BOLD is most beneficial to transmission line engineers.

The end result of BOLD is a highly efficient line operating on shorter structures with less visual impact to the general public (Figure 2). BOLD has been developed for 345-kV tubular and lattice designs and current efforts are underway to fully develop 230-kV and 138-kV designs.

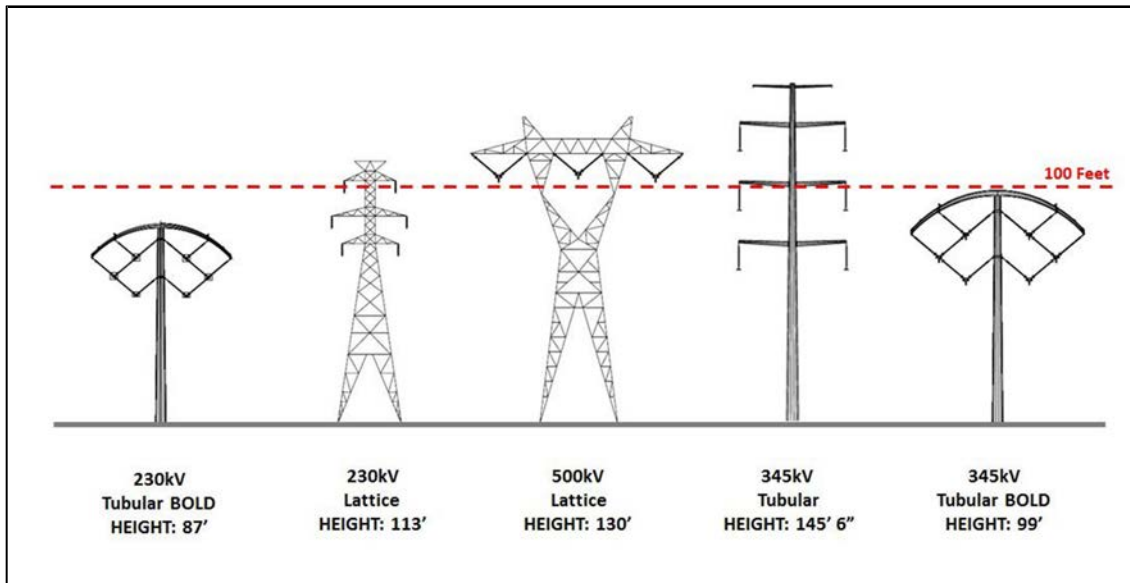


Figure 2

BOLD—Transmission Line Design Considerations

The responsibility to successfully implement the BOLD technology in real world transmission line projects ultimately falls on the transmission line engineer. Once a project has been identified as a candidate for BOLD, the transmission line process will be similar to a traditional line design project. As with any new structure family or technology, there are some key considerations the line engineer needs to keep in mind as the project is advanced from concept to construction.

This paper will provide a high level overview of the inaugural BOLD project process and then discuss key topics for a line engineer, such as PLS-CADDTM modeling, compact spacing requirements, galloping and rolling clearances, RoW width, and geometric considerations.

Inaugural BOLD Project- Structure Development

The challenge of turning the BOLD concept into reality began with the identification of a candidate project in Fort Wayne, Indiana. Several planning solutions were analyzed before deciding that the optimal solution was to rebuild the 22-mile double-circuit, 6-wired, 138-kV existing tower line as a double-circuit BOLD construction with one circuit operating at 138kV and the other circuit at 345kV. It was decided that the project would be a structure-for-structure replacement to minimize impacts to property owners. Average span length for the existing towers was 900' with a maximum span length of 1219' in a flat terrain environment. Figure 3 shows the optimized BOLD 345-kV tubular structure overlaid on the existing 138-kV tower. The 345-kV circuit uses a 3 bundle 954 kCM ACSR conductor and the 138-kV circuit uses a 2 bundle 954 kCM ACSR conductor.

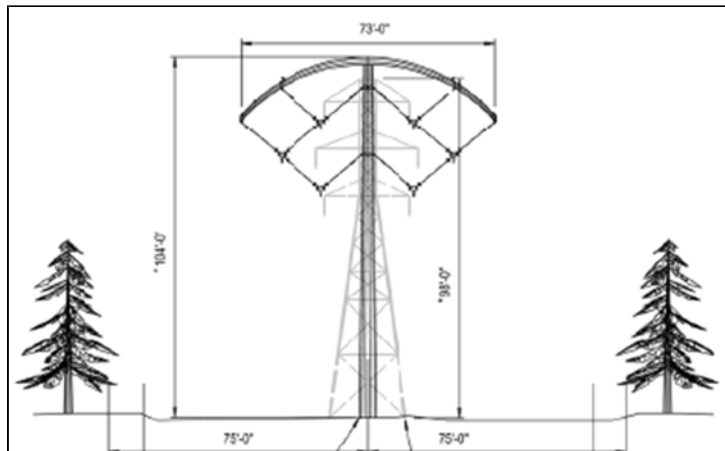


Figure 3

BOLD structure development started with a conceptual design based on the optimized phase spacing in the compact delta configuration. The optimized design was an iterative process to balance the electrical benefits, and the associated impacts on audible noise, corona, and EMF, with the geometric constraints of insulating lengths, arm length, and real world conductor motion from wind and ice.

Once the geometry was conceptually developed, the next step was electrical and structural modeling of the conductor and structure to refine a prototype structure to be used for full scale structural testing, hardware testing, and electrical testing.

Full scale structural testing was conducted at the Valmont-Newmark structural testing facility in Valley, Nebraska. Figure 4 shows the structural test setup. The full scale testing confirmed the structure strength was consistent with the calculated values and confirmed that some of the unique aspects of the BOLD construction, such as the curved arm bending process (Figure 5) and interconnected insulator assemblies, could be accurately modeled and had no impact on structural performance. The structural testing was conducted using the actual insulator assemblies.



Figure 4



Figure 5

Hubbell Power Systems conducted single phase testing on the prototype insulators and hardware to conclude that they met AEP’s design criteria. Three-phase electrical testing was also conducted at the EPRI Power Delivery Laboratory in Lenox, Massachusetts, for power frequency, corona effects, audible noise, lightning surges, and switching surges.

Completion of the prototype testing series allowed the project development team to move into the next design phase of the structure development to produce an optimized BOLD structure family in PLS-CADDTM. It was determined that the line would require a range of tangent and dead end structures, as well as a running angle structure. The lightest and most frequently used tangent structure was designed for wind spans up to 900’ and 0-2° line angles (Figure 6). Two heavier tangent structures were designed for longer wind spans and line angles up to 6°. The running corner structure was developed for wind spans up to 1,000’ and 5-15° line angles (Figure 7). One dead end structure was designed for line angles of 0-30° and a heavier dead structure was designed for 30-60° line angles (Figure 8).

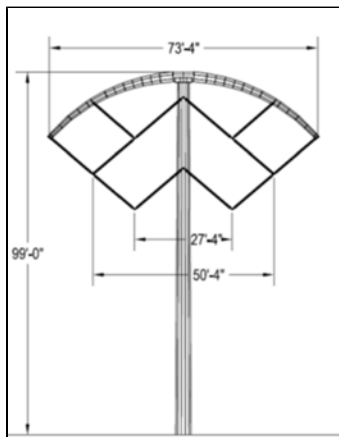


Figure 6

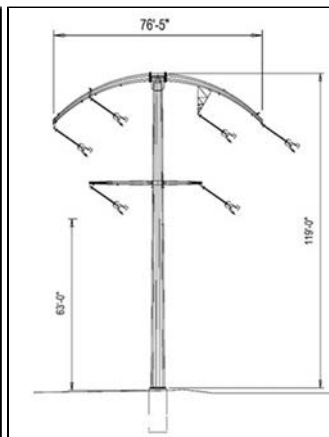


Figure 7

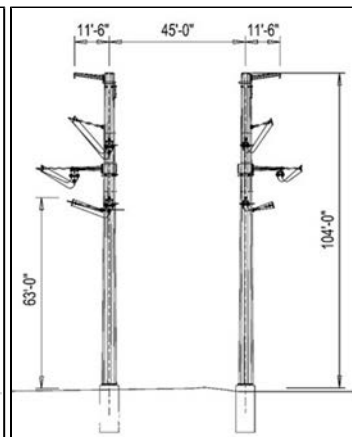


Figure 8

PLS-CADD Modeling

The BOLD PLS-CADD models are developed using standard functions within the program and are a collaborative effort between the line engineer and pole manufacturer. The line engineer delivers structure performance drawings—which provide load case, geometry, and attachment details—to the pole manufacturer. The pole manufacturer then develops the pole shaft model and provides the dimensions of the curved BOLD arm. At this time, the pole manufacturer cannot provide PLS pole models of the curved arm but can provide the arm dimensions. The line engineer then uses the arm dimensions provided by the

manufacturer to create the arm, similar in PLS-CADD to a typical davit arm, using a series of short tangent segments and tapering the arm diameter (Figure 9). The process is similar to ordering a typical davit arm structure but designing the davit arms as a separate component not provided by the pole manufacturer.

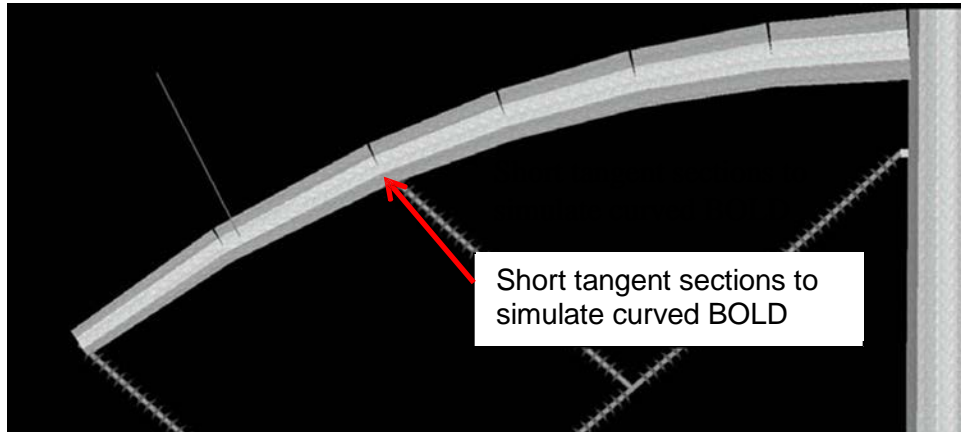


Figure 9

Connections, such as the insulator vangs and the “knuckle,” or the top section of the pole shaft where the arms attach, are structurally designed and checked by the pole manufacturer. The line engineer designs the insulators using the 2-part insulator function in PLS-CADD. Limits should be set within the model to check that insulators do not go into compression under wind cases, as dictated by the project design criteria, similar to typical V-string insulators. The insulator attachment points will be vangs on the structure or the vertex of an adjacent V-string insulator, depending on which insulator is being modeled. Figure 10 shows a typical BOLD 2-part insulator connectivity table from PLS-CADD.

						Model Check Report								
						No errors or relevant warnings detected.								
2-Parts Label	Side A Str. Attach	Side B Str. Attach	Tip Label	Property Set	Down Right	Cond. 1 Min Load Angle (deg)	Cond. 1 Max Load Angle (deg)	Cond. 2 Min Load Angle (deg)	Cond. 2 Max Load Angle (deg)	Cond. 3 Min Load Angle (deg)	Cond. 3 Max Load Angle (deg)	Cond. 4 Min Load Angle (deg)	Cond. 4 Max Load Angle (deg)	
1	C1	Arm1:rb5	V1	C1	230kv-1-R2SCA (SDove)	Down/Right	-45	45	-45	45	-45	45	-45	45
2	C2	Arm1:rb5	C1	C2	230kv-2-R2SCA (SDove)	Down/Right	-45	45	-45	45	-45	45	-45	45
3	C3	C2	V2	C3	230kv-3-R2SCA (SDove)	Down/Right	-45	45	-45	45	-45	45	-45	45
4	C4	Arm2:rb3	V3	C4	230kv-1-R2SCA (SDove)	Down/Right	-45	45	-45	45	-45	45	-45	45
5	C5	Arm2:rb5	C4	C5	230kv-2-R2SCA (SDove)	Down/Right	-45	45	-45	45	-45	45	-45	45
6	C6	C5	V4	C6	230kv-3-R2SCA (SDove)	Down/Right	-45	45	-45	45	-45	45	-45	45

Figure 10

It should be noted that due to the interconnected property of the BOLD insulators, some of the insulator strings will be subjected to loads that are doubled in magnitude. As shown in Figure 11, two insulator strings, with the load magnitude labeled 2*TL and 2*TR, will support the load from the conductor attached to the vang and the load from an interconnected insulator attached to the same vang.

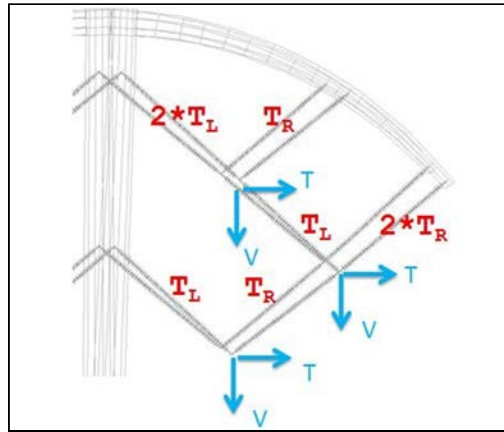


Figure 11

95% Phase Compaction Requirement

One key requirement for all line engineers working on a long BOLD transmission line project, limited by voltage or stability considerations, is to maintain the compact phase spacing for 95% of the overall line length. Typically, lines in excess of 50 miles are considered “long” transmission lines, and are therefore subjected to the 95% phase compaction requirement. Increasing phase-to-phase clearances is a possible design option that may be considered for long spans, at dead end structures (due to increased dead end spacing needs), or when rolling to a horizontal configuration. However, electrical modeling of long transmission lines has shown that the compact phase spacing is required for 90-95% of the line length to maintain the electrical benefits discussed previously. Setting the requirement at 95% will conservatively ensure that the line will operate as intended. Deviation from this requirement would require additional electrical modeling to ensure intended performance of the line is achieved.

Short lines, or lines which are thermally limited and not limited by voltage or stability considerations, are not subject to the 95% phase compaction requirement. For these lines, the compact phase spacing should be maintained for structure height minimization and aesthetic reasons, but the electrical performance will not be affected by increasing the phase spacing in more than 5% of the line.

Galloping Criteria

For areas where galloping is either historically known to occur or is expected, the line engineer will need to consider the potential for galloping in the design. Special consideration is required for BOLD projects due to the compact phase spacing of the conductors.

Several galloping analysis methods are used in the transmission industry and the results of these different methods can vary dramatically. Studies have shown that installing in-span interphase insulators, or I3 insulators, can reduce the galloping magnitude by half [2]. Figure 12 shows a picture of a typical mid-span insulator. Depending on the project span lengths and galloping specifications, the line engineer has several options to mitigate galloping concerns. The following mitigation options can be applied to lessen other forms of conductor motion:

- Decrease span lengths (also may allow narrower corridor, as discussed in RoW considerations)
- If only a few of the longer spans have excessive galloping ellipses, phase spacing can be increased on those spans only, keeping in mind the 95% compact spacing requirement
- Install I³ insulators at the time of initial construction
- Install conductor with compact spacing and monitor performance over time; install I³ insulators at a later date, if deemed necessary
- Use anti-galloping conductor



Figure 12

Rolling Clearances

Rolling from a compact vertical BOLD configuration to a horizontal configuration, such as a station bay, can also require some consideration from the line engineer. Depending on the span lengths and geometry, the line engineer has several options to meet the design criteria minimum phase-to-phase rolling clearances:

- Increase phase spacing at a dead end structure outside the station, keeping in mind the 95% compact spacing requirement
- Install an intermediate suspension structure between a BOLD dead end and the station bay, keeping in mind the 95% compact spacing requirement (see Figure 13)
- Vary the tensions in each phase for the entrance span into the station (i.e., install the top phase with higher tension than the middle phase and the bottom phase with lower tension than the the middle phase)
- Install I3 insulators on the rolling spans at the time of initial construction

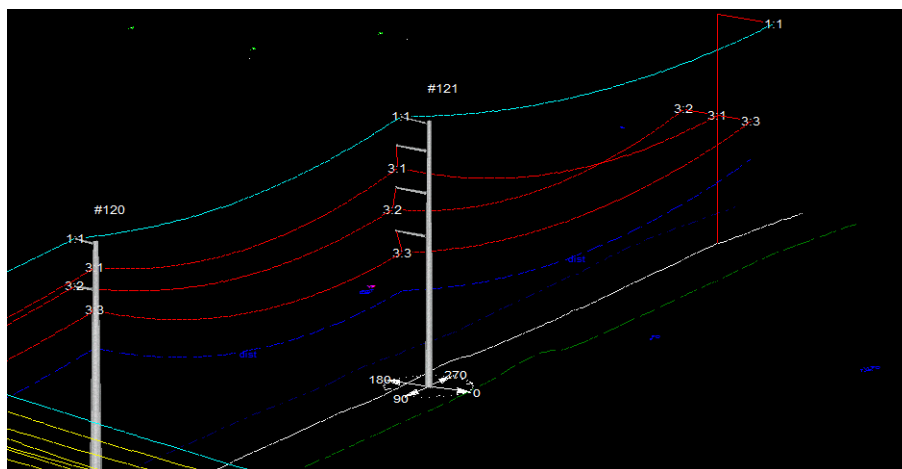


Figure 13

Right-of-Way (RoW) Requirements

One additional benefit to a BOLD line is the flexibility it provides a line engineer to install EHV lines using a narrower RoW width due to lower audible noise and magnetic fields. This can be a particularly useful solution for RoW constrained areas, such as urban settings, or if the engineer intends to limit the galloping ellipses.

As shown in Figure 14, audible noise and magnetic fields of a 345-kV BOLD line with three subconductors at the edge of 105' RoW compares favorably to traditional 345-kV designs at the edge of 150' RoW. The audible noise from BOLD is more than 1-2 dBA lower than that of conventional design at the edge of 105' RoW and less than that of traditional designs measured at the edge of the 150' RoW. The magnetic field from BOLD is 50% of that produced from traditional designs at equal electrical loading at the edge of each RoW. The magnetic field from BOLD at the edge of the 105' RoW is less than that of traditional designs at the edge of the 150' RoW. If the electric load of BOLD is doubled, the resulting magnetic field at the edge of either the 105' or 150' RoW will equal the magnetic field of traditional designs with the base loading.

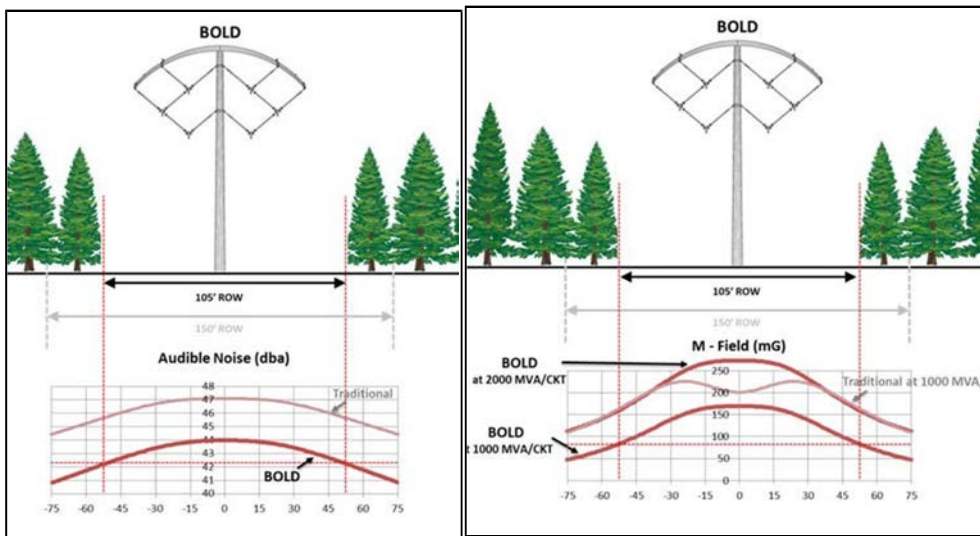


Figure 14

For a greenfield project without a constrained RoW, the line engineer will typically determine structure locations to optimally minimize the number of structures and project costs. For these projects, RoW width will be determined by conductor blowout. Conductor blowout for BOLD structures is similar to the blowout of a typical suspension I-string insulated conductor, even though the BOLD arm is longer and the middle phase is further from the pole shaft than traditional designs. For typical transmission span lengths, the I-string insulator swing on a traditional 345-kV structure will horizontally position the conductor in a vertical plane close to the location of the outermost BOLD phase when both are loaded under 6#/ft wind cases, as shown in Figure 15. In Figure 15, the pink lines represent the BOLD conductor blown out position at midspan and the blue lines represent the traditional conductor in a similar condition for 1,000' span lengths.

Figure 16 shows RoW widths required for a 345-kV double-circuit structure optimized line (150' RoW with optimized structure spacing), a 345-kV double-circuit RoW optimized line (105' minimum RoW with shorter spans to limit blowout), and a 345-kV single-circuit line RoW optimized line (50' minimum RoW with shorter spans to limit blowout). Some structures, which have design features to address galloping concerns, may have middle phase davit arms that are longer than the top and bottom phase arms to reduce or eliminate the galloping ellipse overlap. Structures with this design feature would have greater RoW width requirements due to the increased blowout width. The traditional design selected for the blowout comparison in Figure 15 does not have this design feature.

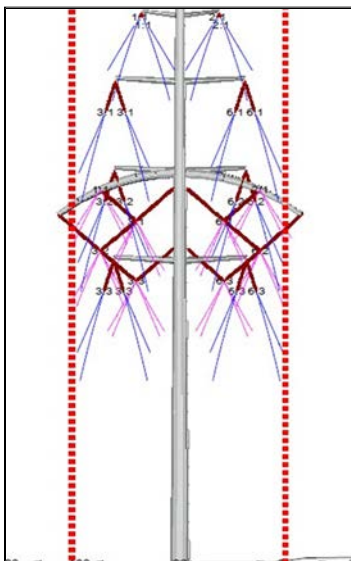


Figure 15

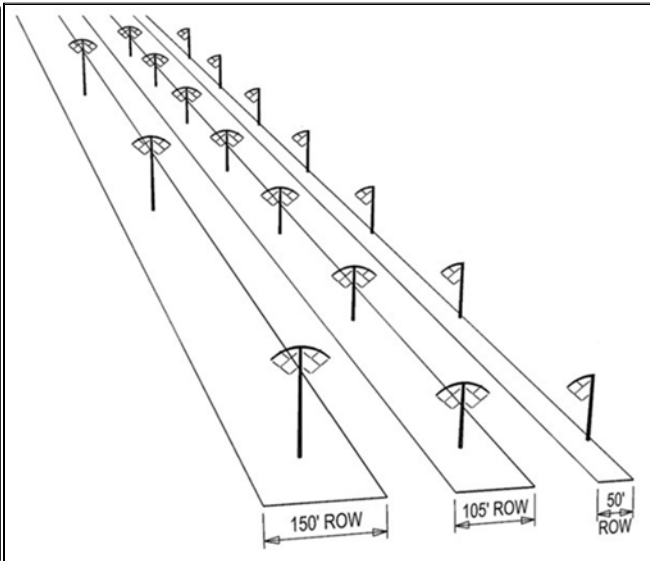


Figure 16

Arm Geometry

BOLD arms are typically longer than traditional steel pole davit arms due to the optimized insulator geometry. Some traditional tubular structures designed for galloping may have a longer middle davit arm, comparable to the length of the BOLD arm, but most traditional designs will utilize davit arms considerably shorter than the BOLD arm. For a 345-kV BOLD structure, the tip-to-tip distance of the arms is 73'-4" compared to 43'-0" for the traditional tubular structure with davit arms shown in Figure 17. The line engineer needs to account for this additional length and may need to adjust typical offsets when placing BOLD structures adjacent to public road RoW or railroads to avoid overhanging these facilities.

Corridor construction, or constructing parallel lines in a common RoW easement, is another situation where the line engineer may need to evaluate typical offset distances between adjacent lines. Depending on the geometry of the lines, the longer BOLD arms may present phase-to-ground clearances that are less than those of traditional lines in corridor construction. In most cases, placing BOLD structures near the adjacent line structures, and not at mid-span where maximum conductor blowout occurs, will alleviate inadequate phase-to-ground clearances.

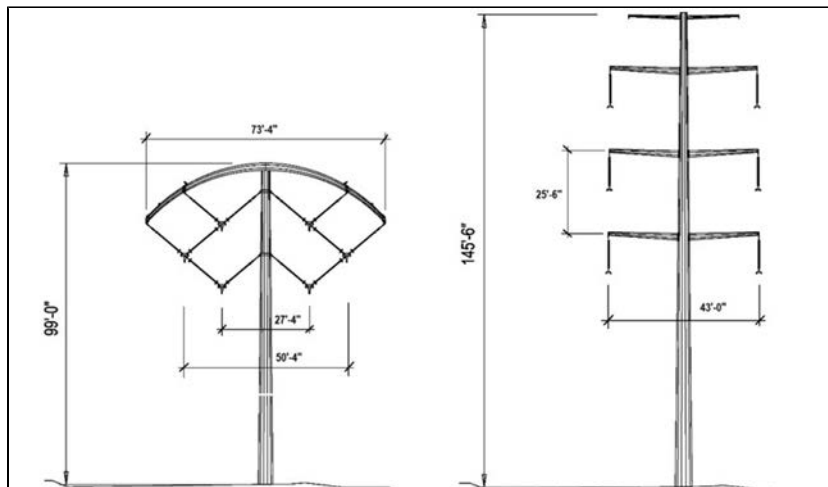


Figure 17

BOLD Dead End Structure Geometry

BOLD dead end structures are similar to traditional dead end structures and consist of two independent poles with one circuit terminated on each pole. Ideally the compact delta phase spacing will be maintained at the dead end structures. For light line angles, this can be achieved by terminating the top and bottom phase on the pole shaft, similar to traditional tubular structures, and installing a davit arm to terminate the middle phase (see Figure 18).

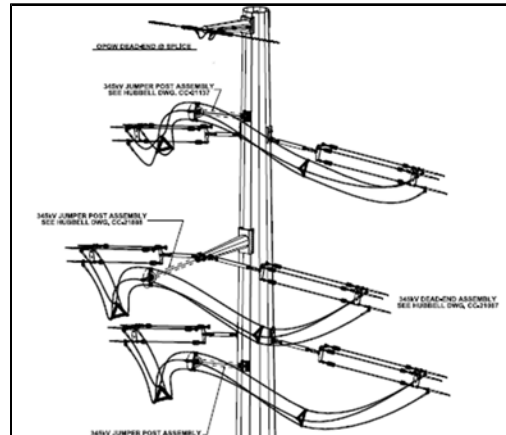


Figure 18

The compact phase spacing presents a unique geometry for the line engineer to consider, particularly for heavy line angles. One clearance to check for medium to heavy line angles is the phase to ground clearance between the middle phase, which terminates on a davit arm, and the steel pole as shown in Figure 19. As the line angle increases, the middle phase davit arm will need to be lengthened to maintain the compact delta phase spacing of the adjacent tangent structures. Installing a second davit arm, with both arms perpendicular to the middle phase conductor, is a solution if the arm length becomes excessive for heavy line angles.

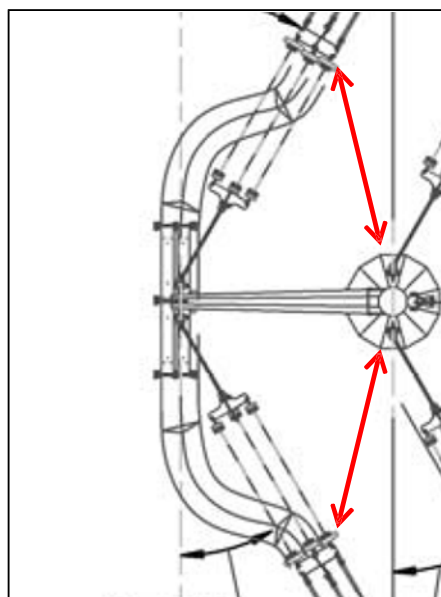


Figure 19

Some projects may require one face of the poles to be “clean” of wires for maintenance access purposes. For these projects, it would be necessary to install all jumper loops on the same side of the pole as the

middle phase davit arm. The compact phase spacing with heavy line angles can create challenges for construction crews to make up jumper loops that maintain adequate clearance between the top phase jumper loop and the middle phase corona rings on the energized end of the insulator (Figure 20). A recommended best practice is to create 3D models of the jumper loops and insulator assemblies to discover where design modifications may be needed prior to finalizing the insulator assembly designs. The line engineer has several options for increasing clearances at the dead end insulators:

- Space the phases out and use a typical dead end vertical configuration with all three phases and shield wire terminated on the pole shaft, keeping in mind the 95% compact spacing requirement. Jumper loops would be installed on the inside angle of the pole, similar to traditional construction.
- Maintain the BOLD delta configuration but increase the vertical distance between the top and bottom phases as required per the 3D model clearance check, keeping in mind the 95% compact spacing requirement. Depending on the line angle, two post insulators may be needed to “walk” the jumper loop around the larger exterior angle.
- If maintaining a clean pole face for maintenance is not a requirement, then installing the top and bottom jumpers around the inside angle of the pole, and installing the middle phase jumper around or under the davit arm, will provide adequate room for all three phase jumpers

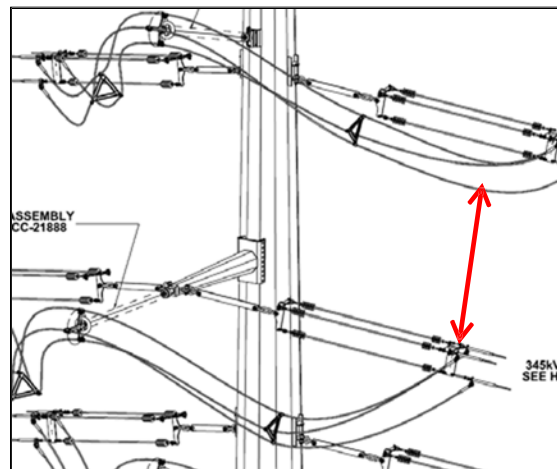


Figure 20

Conclusion

BOLD offers transmission utilities with a solution to address many of the challenges faced in the current environment, including increased public opposition, difficulty obtaining new RoW easements, and cost sensitivities. The transmission line engineer plays an integral role in promoting the BOLD solution [1] and successfully integrating this technology. As discussed in this paper, BOLD technology can be seamlessly integrated with little modification to the traditional transmission line design procedures and tools used by most utilities today. It has been successfully implemented on two 345-kV projects in Indiana and has been conceptually developed for numerous other applications.



Figure 21

References

1. R. Gutman and M.Z. Fulk, "AEP's BOLD Response to New Industry Challenges," *Transmission & Distribution World*, November 2015.
2. D.G. Havard. "Conductor Galloping" IEEE ESMOL and TP&C Meeting. Las Vegas, Nevada. January 2008