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Breakthrough Overhead Line Design (BOLD): System and Performance Considerations

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SUMMARY

Electric utilities today are engaged in many transmission projects to enhance reliability, integrate new sources of power generation, and modernize the nation's electric grid. Continued load growth, combined with renewable generation built in remote geographic areas and ongoing retirements of coal-fired stations serving largely native load, calls for efficient transmission capable of carrying bulk power over long distances. Concurrently, public opposition to new line construction, particularly where highest operating voltage and capacity are involved, necessitates new thinking with regard to power transmission design that will minimize the land use, environmental impact and system costs. Despite the need for a modern and efficient extra-high-voltage transmission system, regulators and communities often resist such new infrastructure construction, citing concerns about higher utility costs, falling property values, landscape distractions, loss of property for easements, and the effects of electromagnetic fields (EMF).

A new and innovative, American Electric Power (AEP)-developed, double-circuit 345 kV line design, called Breakthrough Overhead Line Design™ or BOLD™, offers more intrinsic power-carrying capability than three circuits of the same voltage class using conventional designs. BOLD, which is also available in other voltage classes, presents a portfolio of performance and aesthetic benefits that can be tailored to specific requirements of a broad variety of new and rebuild transmission projects. By packing more energy in a compact, efficient, and appealing design than traditional structures, BOLD can help utilities overcome restraints with a long-term and cost-effective solution for service reliability and customer satisfaction.

Improved electrical characteristics and performance are the primary benefits realized by BOLD, but are not the only advantages of the technology. BOLD was originally designed with long, heavily loaded transmission lines in mind. The low-impedance, high-capacity characteristics allow BOLD to carry heavier loads across long distances without the need for series compensation. Additionally, the compact nature of the design also allows BOLD to be installed in populated urban areas with less impact to residents while also offering similar electrical benefits for short length lines. Phase compaction allows BOLD towers to fit into less right-of-way than would typically be needed to accommodate high voltage lines. The aesthetic appeal of the design also lessens the visual impact of the line, easing community objections.

KEYWORDS

Insulation coordination, lightning overvoltage, switching overvoltage, power transfer analysis.

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The Loadability Challenge

The power flow of an alternating-current transmission line is affected by the thermal, voltage-drop and steady-state stability limitations. Thermal rating, which is an outcome of the conductor or terminal equipment selection process, is usually most limiting for lines shorter than 50 miles. For longer lines, voltage-drop or stability considerations are the key limiting factors, both of which are affected by length-dependent line impedance [1].

Power engineers commonly employ per-unit system to express line impedance, which varies with the line's voltage class and design. Although the most effective way to reduce line impedance and improve loadability is to raise the transmission voltage class, this solution is typically opposed by the public, particularly at the highest available transmission voltage. This is a key reason why utilities tend to choose lower-voltage options supported with series compensation to reduce transmission path impedance and attain required power-transfer objectives.

Series compensation traditionally has been utilized in the system as a short-term remedy to stretch system capability until a longer-term solution is implemented or as a substitute for higher-voltage transmission. However, operational issues such as sub-synchronous resonance (SSR) and sub-synchronous control interactions (SSCI), which pose a risk to electric machinery and can lead to system instabilities, are quite common to series compensation applications. Other concerns include system protection complexities, maintenance or spare equipment requirements, limited life expectancy, electrical losses and future grid expansion issues (for instance, the difficulty with tapping a compensated line).

The BOLD Solution [2]

BOLD features a streamlined, low-profile structure with phase-conductor bundles arranged into compact delta configurations (see Figure 1). The structure of BOLD comprises of an arched cross-arm supporting both circuits set atop a tubular-steel pole, which imparts a more favorable aesthetic appearance. Single-circuit or double-circuit lines can be supported by BOLD. Single-circuit construction can be expanded in the future to incorporate double circuit. Initial BOLD projects feature the 345 kV design, but the design series now includes 230 kV and is being expanded into additional voltage classes.

The average 100-foot, 345 kV BOLD structure is about one-third shorter than a traditional double-circuit design. Each phase may contain multiple conductor bundles 18 to 32 inches in diameter. The separation distances among the three phases are as low as 14 feet and are maintained using two interphase insulators per circuit. Non-ceramic, glass or porcelain insulators attach each of these bundles to the cross-arm and tubular structure bodies. The cross-arm itself supports two shield wires positioned to provide zero-degree shield angle to protect the outmost phases from being exposed to direct lightning strikes.

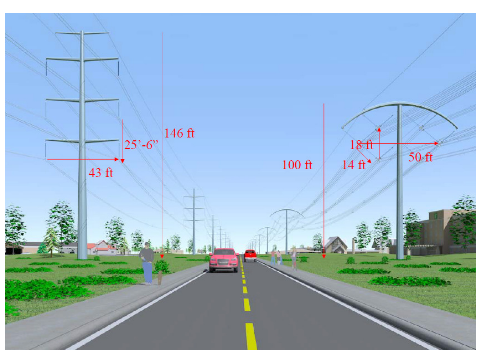

Figure 1: BOLD (right side) and traditional 345 kV double-circuit line designs.

BOLD employs large, multi-conductor phase bundles. Large phase bundles placed in close proximity to each other reduce line reactance (X) and increase line charging (B), resulting in lower surge impedance (√X/B) and larger surge impedance loading (reciprocal of surge impedance, in per unit). By using multi-conductor phase bundles, high transmission efficiency and ampacity is ensured. The ground-level magnetic field exposure from the line is reduced by utilizing the compact-delta configuration.

Significant gains are attained in thermal capacity and line efficiency, resulting in lower operating temperatures by incorporating three-conductor phase bundles. Overall system performance is improved by unloading higher-impedance/lower-capacity lines. Alternative phase bundle designs are possible, typically using between two and four conductors per phase.

BOLD's 3-Cardinal per phase design (see Table 1) adds 50 percent more capacity into a right-of-way (ROW). Additionally, BOLD markedly improves line surge impedance loading (SIL), lowers series impedance and reduces ground-level electromagnetic field and audible noise effects when compared to traditional designs. SIL is a convenient yardstick for measuring relative loadability among line design solutions. BOLD typically uses three conductors per phase at 345 kV, which offers significant gains in line loadability and energy efficiency for long-distance and local applications.

Table 1

Comparison of BOLD and Typical 345 kV Line Designs

	TYPICAL 345 kV DESIGN	**BOLD 345 kV DESIGN**	
Phase Conductor Bundle	2-954 kCM ACSR Cardinal (18" Bundle Dia.)	**3-954 kCM ACSR Cardinal (29" Bundle Dia.)**	
Phase Spacing (Feet) (ϕ1-ϕ2/ϕ2-ϕ3/ϕ3-ϕ1)	25.5 / 25.5 / 51.0	**15.0 / 15.0 / 19.3**	
Structure Height (Feet)	145.5	**99**	**-32%**
EACH CIRCUIT:			
Surge Impedance (Ω)	284	**198**	**-30%**
Surge Impedance Loading (MW)	419	**601**	**+43%**
Thermal Rating (A)[1]	2,358	**3,537**	**+50%**
BOTH CIRCUITS COMBINED:			
Resistive Loss (MW/100 Miles)[2]	84	**56**	**-33%**
Corona Loss (MW/100 Miles)[3]	1.0	**1.1**	**+10%**
Audible Noise @ ROW Edge (dBA)[4][5]	43	**41**	**-5%**
Electric Field @ ROW Edge (kV/m)[4]	0.5	**0.8**	**+60%**
Magnetic Field @ ROW Edge (mG)[4]	112	**55**	**-51%**

Notes:

(1) Summer rating for continuous operation in AEP Eastern Region
(2) Line loss based on 1000 MVA loading in each of two circuits
(3) Yearly average corona loss (rain 20%, snow 2%, fair 78% of time)
(4) Results are shown for "superbundle" phase arrangement (1-2-3/1-2-3, top-to-bottom); other arrangements are possible. Right-of-way (ROW) width is 150 feet (46 m)
(5) Mean value of audible noise in rain at sea level

BOLD's low-height, visually appealing profile can fit 345 kV lines within a 105-foot ROW instead of the 150-foot ROW commonly required by traditional 345 kV lines, a potential reduction of nearly one-third of typical ROW width. The smaller ROW coupled with the visual benefits are expected to improve public acceptance of new transmission projects.

BOLD technology greatly reduces the need to install, maintain, or replace series compensation equipment (including SSR or SSCI mitigation), a substantial financial benefit considering the long life expectancy of a transmission line.

Insulation Coordination Studies

Transmission line insulation coordination is the process of determining the appropriate line insulators, tower clearances, hardware, tower grounding, and terminal equipment in relation to the operating and transient voltages that can appear on a power system. Specifically, lightning insulation coordination assesses the overvoltage stresses from shielding failures or lightning strikes to the tower or shield wire system relative to a transmission line's insulation strength. Such a study is essential in determining if the strike distances (tower clearances) are appropriate enough to keep any flashover rate (e.g. flashes per 100 km per year) to a minimum desired value. Similarly, studies are conducted to assess the risk of switching surge flashovers.

Comparative lightning and switching overvoltage studies for BOLD and traditional 345 kV designs were carried out using PSCAD™ electromagnetic transient simulation software. Similar studies examined BOLD and traditional 230 kV designs. The goal of these studies was to ensure reliable performance of BOLD's highly-compact configuration and to provide a basis for the development of line insulators, hardware and terminal equipment. Lightning overvoltage studies utilized the generic lightning impulse strength characteristics from the EPRI Red Book [3]. The main conclusions of these studies are summarized below.

Lightning Overvoltage:

1. The BOLD tower is lower in height than a traditional tower. This results in a lower number of lightning flashes to a BOLD line per year.
2. BOLD's compact configuration has shown a significant improvement of the lightning backflashover rate, whether a strike hits the shield wire at the tower or mid-span. This is because the minimum phase-to-ground strike distance in BOLD is greater than that in a traditional design of the same voltage class.
3. While the conventional line's shielding failure flashover rate is low, BOLD virtually eliminates shielding failure flashovers in flat terrain.
4. Overall, it can be concluded that the estimated lightning performance of BOLD is as good as – or better than – that of conventional line designs.

Switching Overvoltage:

1. Simulations of BOLD 345 kV and 230 kV lines without shunt reactors resulted in high phase-to-ground and phase-to-phase flashover probabilities. Adding a shunt reactor at the receiving end of the line reduced the flashover probabilities essentially to zero.
2. Using pre-insertion resistors in 345 kV circuit breakers of BOLD is an effective way of controlling the phase-to-ground and phase-to-phase switching overvoltages. For BOLD 230 kV, line-end surge arresters can be used to reduce the risk of switching surge flashovers.
3. System strength at the switching location has a marginal impact on the switching overvoltage level. The impact on the estimated switching surge flashover rate is negligible.

Prototype Development and Testing

BOLD development began with exhaustive analysis and design efforts, followed by extensive laboratory testing. AEP teamed with Hubbell Power Systems and Valmont Industries on some aspects of the development to ensure the new line design met established performance requirements and would have the requisite structures, insulators, and hardware ready for practical installation. Hubbell Power Systems tests conducted at the Wadsworth, Ohio, facility confirmed the modelled insulator hardware corona performance. Valmont Industries fabricated the tubular-steel structure. BendTech and American Pipe Bending, which are Valmont subcontractors, provided cross-arm bending services using an induction heating process. Mechanical tests of the structure were conducted at Valmont's facility in Nebraska.

The Electric Power Research Institute's (EPRI) Power Delivery Laboratory in Lenox, Massachusetts, tested a full-scale single-circuit prototype of BOLD for power frequency, corona effects, audible noise, lightning and switching surges, and phase-to-phase insulation.

Project Application – Fort Wayne, Indiana

In 2010, PJM (a Regional Transmission Organization, of which AEP is a member, which covers 13 states plus the District of Columbia) identified widespread low-voltage conditions and multiple 138 kV line overloads in the Fort Wayne, Indiana area as part of its annual Regional Transmission Expansion Planning (RTEP) analysis process.

The planning criteria violations stem from several contributing factors:

- The Fort Wayne area relies on several 345/138 kV transformers to serve the local load.
- There is a very limited amount of local generation in the area to serve load.
- Area fossil unit retirements combined with new generation (primarily wind) reduced the availability of reactive power in the area, exacerbating the low voltage conditions.

This base generation change in the area, combined with heavy power flows into Michigan, all were factors in the PJM identified reliability violations.

The solution was two-fold. A new 765 kV source was introduced to Sorenson substation on the southwest side of Fort Wayne. The expanded station acts as a source of reactive power into the area, helping relieve some of the voltage concerns. However, the addition of increased flows from the 765 kV system required a complementary solution to mitigate overloaded lines in and around Fort Wayne. There were several options available to accomplish this, all with multiple pros and cons associated with each.

First, the overloaded 138 kV lines could be rebuilt or reconductored at 138 kV. This avoids any complications introduced with converting or building to higher voltages and reduces right-of-way costs associated with new construction or larger right-of-way requirements for higher voltages. However, the cost to rebuild the nine 138 kV lines was prohibitive. Outage constraints would not allow for each line to be taken out of service as it was rebuilt, and the age and condition of the existing towers on the identified lines left the advisability of reconductoring each line questionable at best. Furthermore, rebuilding and leaving the 138 kV system in place would require additional reactive compensation to meet system needs on the lower voltage network.

Second, a new, greenfield, 345 kV double circuit line could be constructed from Sorenson station to Robison Park station, which would complete a 345 kV loop around the greater Fort Wayne area. Greenfield construction eliminates the need for long-duration outages when replacing existing lines. This option also allows for full utilization of double circuit 345 kV capability with no need to convert existing stations to 345 kV. Unfortunately, this greenfield option would require additional cost for new right-of-way for the line. The line route would be forced outside the suburban areas around Fort Wayne, resulting in 40+ miles of new construction. Since the construction would be on all new right-of-way, significant landowner impacts would be introduced by constructing a line where no line had previously been.

Third, the existing 138 kV corridor that already exists between Sorenson and Robison Park could be rebuilt as a 345 kV double circuit line. While this option has the advantage of eliminating the need for new right-of-way, thereby reducing overall cost, there is still a need for existing right-of-way expansion due to the size and requirements of traditional 345 kV construction. This option would also require the conversion of several existing 138 kV stations to 345 kV operation in order to fully utilize the capacity and capability of a double circuit, 345 kV line.

The three options presented above each have unique challenges associated with the benefits they provide. A fourth option was developed utilizing BOLD technology to rebuild the existing 138 kV line as a double circuit line, with one side operated at 345 kV and the other side at 138 kV. In this option, BOLD 345/138 kV hybrid would supplant the existing 138 kV line in a phased manner, while maintaining one-way service to step-down stations and customer loads located along the way.

The fourth option allows for the full capacity utilization of a typical 345 kV double circuit corridor while not requiring the station conversions along the existing 138 kV path. Due to the compact nature of BOLD, it was anticipated that the higher voltage line could be more easily installed within the existing right-of-way than a conventional 345 kV double circuit line. Landowner impact would be lessened with BOLD from both right-of-way acquisition and visual impact standpoints. The reduced line impedance plus increased line charging provided by BOLD would eliminate the need for additional voltage support in the area, especially on the 138 kV system. However, since BOLD was still a new technology, there would be a small price premium for the line itself that would need to be considered versus other options.

For the Fort Wayne line, ROW and landowner impact were particularly important factors in developing solutions to the PJM identified issues. The existing Sorenson to Robison Park 138 kV corridor passes through some heavily developed and well established areas. AEP held several open houses in the area to discuss the project with residents and business owners who stood to be affected by the project development.

Ultimately, the BOLD option was chosen for several reasons:

- The high capacity, low impedance nature of BOLD enabled the use of a single line to help alleviate the PJM identified violations.
- By rebuilding along a single 138 kV line corridor, outage constraints associated with rebuilding or reconductoring multiple 138 kV lines in the area are alleviated.
- BOLD achieves nearly five times the capacity in the same corridor that already existed, and the self-compensating nature of the BOLD design helps boost system voltages without the need for additional voltage support.
- As mentioned previously, ROW considerations played a heavy part in the final project selection. Land development and encroachments limited the ability to expand the existing Sorenson to Robison Park corridor and left little choice in creating new line routes.
- Feedback gathered from public open houses indicated that most in the affected communities had a positive impression of the BOLD tower design and profile.

Other factors went into the decision to rebuild the existing Sorenson – Robison Park 138 kV line as well, though they did not directly relate to mitigating the reliability violations. By utilizing a three-conductor bundle on the BOLD line, losses will be reduced by approximately 33% compared with a standard two-conductor bundle. The existing Sorenson – Robison Park line was constructed in the 1940s. A separate rehabilitation project for the line would be needed in the near future regardless of the project option selected to solve the voltage and thermal violations in the area. Combining the line rehabilitation needs with the ability to install a 345 kV line to solve the PJM identified issues while also maintaining the 138 kV circuit was the best option for the Fort Wayne area.

Project Application – Western Indiana

Two portions of other AEP lines were identified by PJM as overloaded in other RTEP studies, including the Meadow Lake – Reynolds 345 kV line and the Meadow Lake – Dequine 345 kV lines. These two line sections are part of a long 345 kV double circuit corridor that runs from Reynolds station in western Indiana to Sullivan station in southwestern Indiana, approximately 120 miles in length.

Reynolds station is owned by NIPSCO and is the site of a future 765/345 kV project approved by Midwest ISO (MISO, an RTO covering much of the central United States) and PJM that will connect NIPSCO's Reynolds station to Duke's Greentown 765 kV station. Sullivan is an AEP-owned 765/345 kV station serving as one of two outlets for AEP's Rockport Plant, a major generating station in southern Indiana. Additionally, two large wind farms are connected to the AEP system in this area. Meadow Lake currently has a capacity of 600 MW (nameplate) with an additional 200 MW in the PJM queue. Fowler Ridge wind farm, 750 MW (nameplate), is connected at Dequine 345 kV station.

PJM has already approved a rebuild of the 7-mile section of line between Meadow Lake and Reynolds 345 kV stations as a baseline project in 2013. In 2014, with the implementation of FERC Order No. 1000 competitive requirements in PJM, a reconductoring project for Dequine to Meadow Lake was chosen. AEP is currently working with PJM to convert the reconductoring to a rebuild project offering significant incremental benefits associated with a complete rebuild.

AEP plans to utilize BOLD technology in the proposed rebuilds on the Meadow Lake – Reynolds and Meadow Lake – Dequine 345 kV lines. The nature of the interconnected system at Reynolds and Sullivan essentially creates a 765 kV connection across the 345 kV double circuit corridor, which is limited due to the age and configuration of the existing line. An original project, of which the Reynolds – Greentown 765 kV line is a part, was proposed to connect Reynolds station to Sullivan station at 765 kV along with a third line connecting west out of Reynolds. Presently, only the initial portion between Reynolds and Greentown has been approved. The Reynolds – Greentown 765 kV line along with the wind generation at Meadow Lake and Dequine are contributing to the PJM-identified issues on the 345 kV system. These factors led AEP to work towards rebuilding the entire 120 mile corridor with double circuit 345 kV BOLD technology.

AEP performed power transfer analysis for several variations of construction along the Reynolds to Sullivan 345 kV corridor. The results are seen in Figure 2:

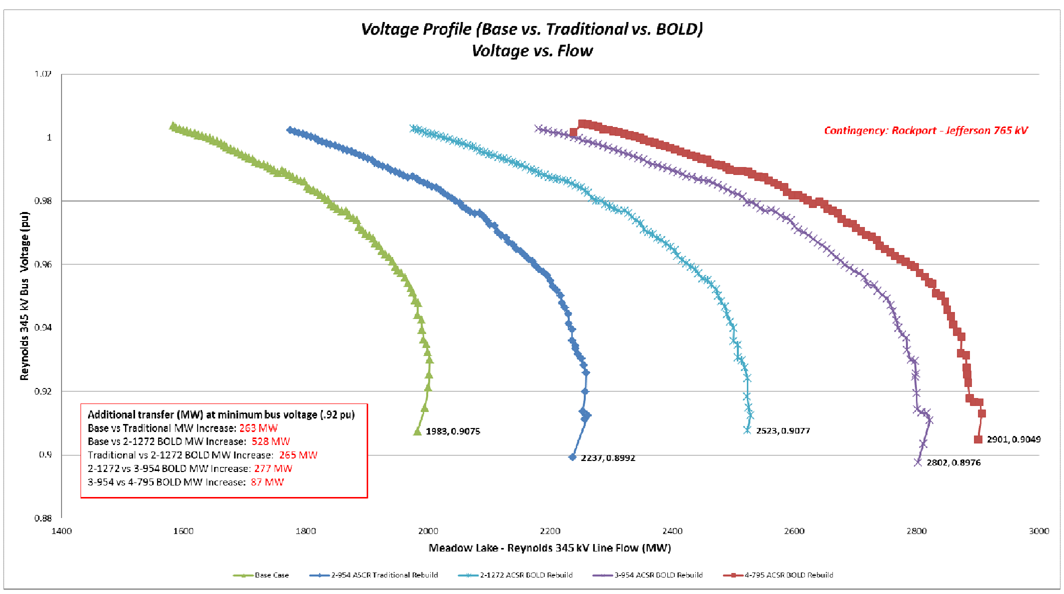

Figure 2: Transfer analysis results on Meadow Lake – Reynolds 345 kV line.

Power transfer analyses relate voltage performance at a certain bus compared to the power flow across a given line under heavy transfer scenarios. In the figure above, AEP compares the voltage performance at Reynolds 345 kV bus (y-axis) versus the MW flow on the Meadow Lake – Reynolds 345 kV portion of the Reynolds – Sullivan 345 kV corridor (x-axis). By reconductoring or rebuilding the line with 2-bundled 954 ACSR conductor as a conventional design, the transfer limit at a voltage violation point (0.92 pu voltage at the Reynolds 345 kV bus) is increased by 263 MW. If the line were rebuilt utilizing a BOLD 2-bundled 1272 ACSR conductor configuration, the transfer limit is increased by 528 MW over the existing line capability. Using a 3-bundled 954 ACSR BOLD configuration increases the transfer limit by an additional 277 MW over the 2-bundled 1272 ACSR BOLD option. A 4-bundled 795 ACSR BOLD design increases the transfer limit another 77 MW.

This analysis indicates that utilizing a 3-bundled 954 ACSR BOLD design allows the 345 kV double circuit corridor to act as a proxy for a 765 kV line between Reynolds and Sullivan stations. When comparing the case with no additional transfers modelled, a 3-bundled 954 ACSR BOLD designed line carries nearly 600 MW more across the Meadow Lake – Reynolds 345 kV corridor.

In contrast to the Fort Wayne area, the western portion of Indiana is very rural. Most of the land along the Reynolds – Sullivan corridor consists of farmland, where ROW restrictions are less of a concern. AEP plans to use BOLD lattice tower design instead of the monopole design in this project. The BOLD lattice tower offers the same electrical and compact advantages as the monopole design, but does so at less cost. The existing tower design is lattice, so BOLD will replace lattice for lattice at a reduced overall tower height.

Conclusion

BOLD offers many advantages over conventional line construction. Reduced impedance combined with increased surge impedance loading results in more efficient power flows across long distances. The phase compaction and reduced height also allow BOLD to be constructed through constrained areas where traditional construction may have a large impact. AEP, partly in association with Hubbell Power Systems and Valmont Industries, has developed and executed myriad test scenarios to ensure that BOLD offers all the advantages inherent in a compact solution without compromising safety or reliability. Two installations are already moving forward in Indiana, with one nearing completion, along with others under development.

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