



BOLD®: System and Performance Considerations

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BOLD® (Breakthrough Overhead Line Design) is a new transmission line developed by American Electric Power, providing a high-capacity, high-efficiency solution in a low-profile, compact configuration. BOLD's compact phase arrangement, combined with an optimized bundle configuration, provide electrical characteristics that drive superior performance and can provide significant advantages over traditional designs.



This paper reviews the system and performance benefits of BOLD compared with those of a typical 345-kV double-circuit line design. Experiences related to integrating BOLD into transmission planning studies and case studies of specific projects are also discussed.

Introduction:

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. In spite of this 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, double-circuit 345-kV line design developed at AEP, trademarked Breakthrough Overhead Line Design (BOLD®), offers more intrinsic power-carrying capability than three circuits of the same voltage class using conventional designs. BOLD, available in this and 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 than traditional structures in a compact, efficient and appealing design, BOLD can help utilities overcome restraints with a longterm 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 that landowners are typically concerned with.

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

Although the most effective way to reduce line impedance and improve loadability is to raise the transmission voltage class, this method is faced with public opposition, particularly at the highest available transmission voltage. This is 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 shortterm 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 including tapping the compensated line.

The BOLD Solution²

BOLD features a streamlined, low-profile structure with phase-conductor bundles arranged into compact delta configurations. 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 expanding 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 inches 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. Standard 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 installation
near Fort Wayne, Indiana***

BOLD's patented configuration can pack roughly 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 EMF effects. SIL is a convenient yardstick for measuring relative loadability among line design solutions. BOLD typically uses three conductors per phase at 345kV, a configuration that offers significant gains in line loadability and energy efficiency for long-distance and local applications.

While BOLD structures can be used in the typical 150-foot ROW needed for traditional 345-kV lines, BOLD's low-height, visually appealing profile can also fit within a 105-foot ROW, a potential reduction of nearly one-third of typical ROW width. These visual benefits are expected to improve public acceptance of new transmission projects.

BOLD vs. Traditional Design

BOLD offers significant improvements in the three factors that most influence loadability and efficiency and are the key drivers for transmission lines to carry power over long distances: SIL (43 percent increase), impedance (30 percent reduction) and energy loss reduction (33 percent lower resistive loss). Additionally, BOLD lines include a 51 percent reduction in ground-level magnetic field, which is very favorable considering the attention EMF typically receives in line-siting regulatory proceedings.

BOLD features large, multi-conductor phase bundles arranged in a compact-delta configuration suspended from a single cross-arm. Large phase bundles placed in close proximity to each other reduce line reactance (X) and increase line charging (B), resulting in lower surge impedance (VX/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 and 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 technology also 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 to keeping flashover rate (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 were carried out using PSCAD™ electromagnetic transient simulation software for the BOLD and traditional 345-kV designs. Similar studies examined the 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. The main conclusions 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.
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. This statement should be tempered with the fact that these studies utilized the generic lightning impulse strength characteristics from the EPRI Red Book.³

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.



Figure 2: Electrical testing set up

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 its Wadsworth, Ohio, facility—confirmed the modeled insulator hardware corona performance and found it met AEP’s design criteria. 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 Power Delivery Laboratory in Lenox, Mass., 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 covering 13 states plus the District of Columbia, of which AEP is a member) identified widespread low-voltage conditions and multiple 138-kV line overloads in the Fort Wayne, Ind., 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 comprised of 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 to 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, and multiple pros and cons associated with each.

First, the overloaded 138-kV lines could be rebuilt or reconducted at 138kV. This would avoid any complications introduced with converting or building to higher voltages and reduce 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 ability for 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 345kV. 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 previously no line had 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 station 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 construction to rebuild the existing 138-kV line as a double circuit line, with one side operated at 345kV and the other at 138kV. This 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 businesses that could be affected by the project development.



Figure 3: Portions of the existing Sorenson–Robison Park 138-kV line.

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. 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.



Figure 4: 765 and 345-kV line routes for the Sorenson–Robison Park project.

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 had 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 1000 competitive requirements in PJM, a reconductoring project for Dequine to Meadow Lake was chosen. AEP is 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 5:

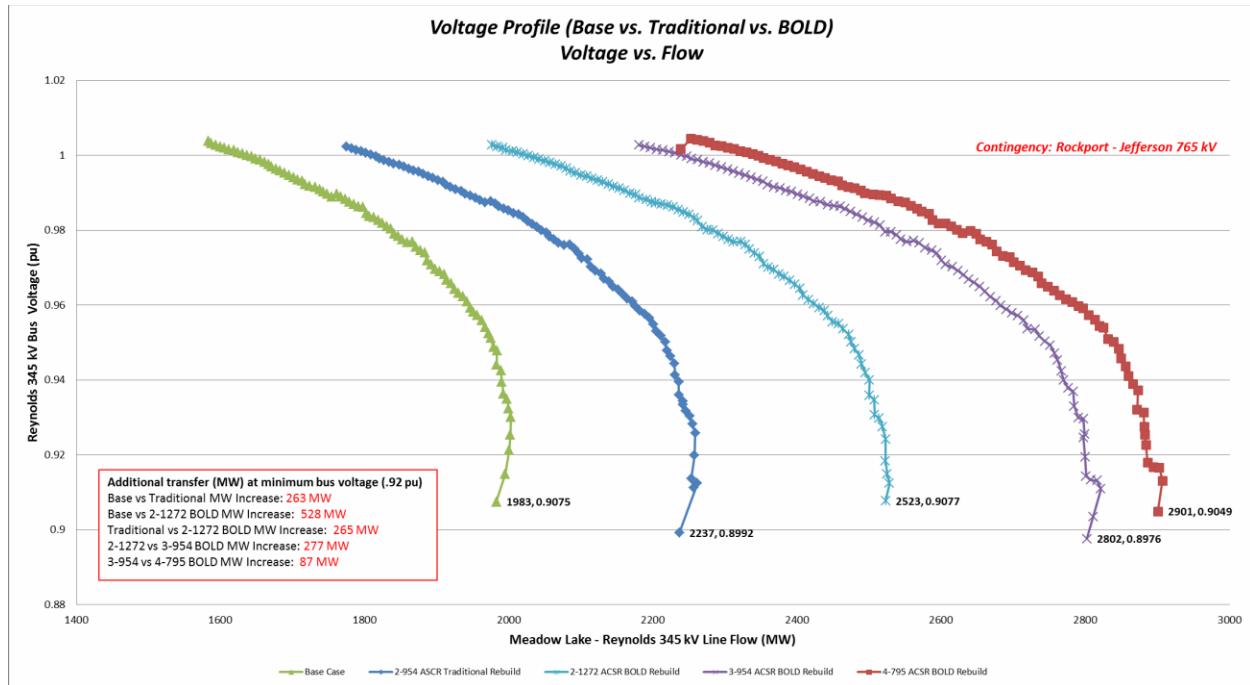


Figure 5: Transfer analysis results on Meadow Lake–Reynolds 345-kV line.

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 allows 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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