Enhancing Load Capacity of Braced Line Post Insulators for High-Strength Applications

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Objective – Composite braced line post insulators are commonly preferred for compact transmission lines. However, the working load capacity of traditional braced line posts is limited by standard core diameters of post insulators and conventional connection hardware. This paper explores methods to enhance load-bearing capabilities for high-strength applications by incorporating reinforced fitting hardware, larger post insulator core diameters, and triangulated insulated cross-arms.

Findings – Increasing the core diameter of composite post insulators to 110 – 130 mm and using reinforced hardware significantly enhance braced line post strength. Further improvements with triangulated insulated cross-arms enable higher load capacities, supporting up to 500 kV transmission, improving stability, reducing structures, and lowering construction costs by allowing longer span lengths.

Originality – This work introduces innovative enhancements to braced line post insulators by overcoming traditional limitations in core diameter and connection hardware. By employing reinforced fittings and larger core diameters, along with triangulated insulated cross-arms, the proposed designs significantly enhance mechanical strength, enabling compact transmission up to 500 kV and reducing infrastructure costs.

Keywords - Braced insulator assemblies, braced line posts, compact lines, composite insulators, insulated cross-arms.

1. Introduction

In power transmission, insulators constitute a small fraction of the installation, both in visibility and cost, compared to support structures and conductors. However, they play a crucial role in determining the overall dimensions, performance, and cost of a transmission line.

The growing demand for minimizing environmental impact and maximizing corridor utilization has driven interest in compact transmission lines. In North America, composite braced line post (BLP) insulators have become the preferred choice for 115 kV to 230 kV applications. As line compaction efforts extend into the extra-high voltage (EHV) range, new designs are needed to accommodate increasing mechanical loads and longer insulator sections, particularly at 345 kV and above. Standard braced line posts with conventional components are increasingly recognized as a limiting factor, restricting span lengths and raising project costs.

This paper explores feasible strength upgrades for composite braced line post insulator assemblies to enhance their working load capacity. Key improvements include post insulators with core rod diameters exceeding 88 mm, reinforced hardware and end fittings, and triangulated tripod braced line posts featuring dual post insulators. These high-strength designs address the limitations of conventional braced line posts and pivoting horizontal vees, significantly improving transverse and longitudinal load handling. As a result, they enable longer span lengths, enhance structural efficiency, and reduce overall construction costs.

2. Traditional braced line posts designs

Figure 1 illustrates the standard braced line post design, highlighting its key components. The brace suspension insulator connects at one end to the line post and at the other to the transmission support via connection hardware. The brace primarily carries tension loads, while the post supports compression (or tension) and longitudinal forces [1][1].

Various end fitting combinations are available for the suspension insulator forming the brace. The Eye-Eye end fitting combination [2] is a common choice, as its interface with anchor shackles provides the highest degree of rotational freedom. Alternatively, the Y Clevis-Ball combination [2] offers a balanced trade-off between articulation and live-line maintenance needs. Adjustable turnbuckles in the brace hardware can further enhance flexibility by allowing height adjustments in the assembly connection.

The standard line post insulator assembly features a drop tongue line end fitting and a bendable base pole mount, oriented at either 0° or 12° up-sweep [3]. The bendable base, available in gain or flat-type designs, is typically made from aluminum alloy or steel.

Composite brace insulators conform to ANSI C29.12 [2]and are classified as Class 60 or Class 70, with specified mechanical loads (SML) of 111 kN (25,000 lbs. = 25 kip) and 160 kN (36,000 lbs. = 36 kip), respectively. Composite post insulators adhere to ANSI C29.17 [3] and fall into Class 250, Class 300, or Class 350, featuring fiber-reinforced plastic (FRP) core rod diameters of 63 mm (2.5 inches), 76 mm (3.0 inches), and 88 mm (3.5 inches), respectively. The selection of insulator section lengths is based on the required dry arc distance for a given voltage level and the overall geometry of the assembly. 1 lbf = 4,448N.

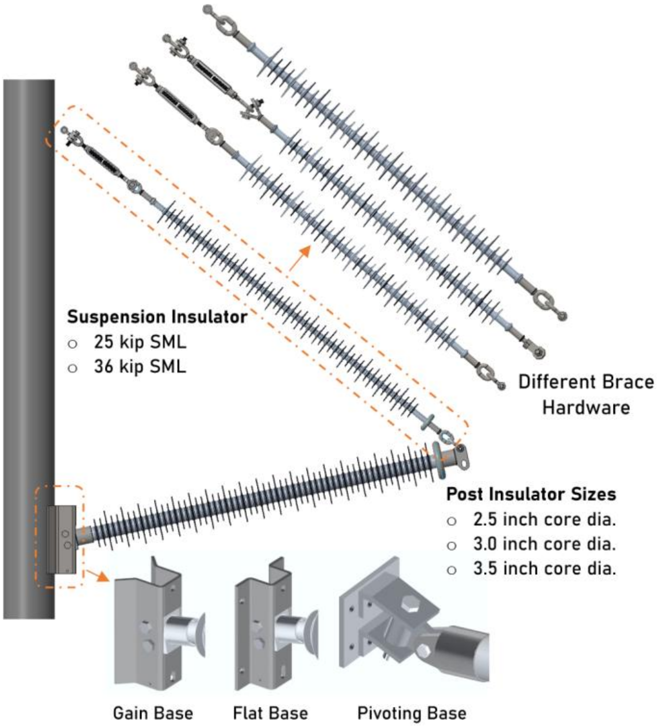

Figure 1 : Braced line-post design options with standard components

Depending on the application, electric field grading rings (commonly known as corona rings) may be required for braced line posts. Traditionally, manufacturers recommended their use only for voltages of 230 kV and above based on past criteria and application practices. However, recent studies on water droplet-induced corona (WDIC) and EPRI's guidelines [4], which suggest limiting electric field stress on composite insulator housings to 4.2 kV rms/cm, have led to revised recommendations advocating for corona rings at lower voltages.

This is particularly relevant for line posts and braced line post insulators used in compact transmission lines, where increased electric field stress is a concern. To ensure compliance with stress limits, finite element analysis (FEA) and three-dimensional modeling are now widely employed to evaluate electric field distribution and optimize designs.

3. Working application load curves

The electrical ratings for a braced line post are relatively straightforward to define. Flashover voltages are primarily determined by the assembly's strike distance, which is the shortest arcing path between the energized hardware (or phase conductor) and grounded hardware (or support structure). The housing profile of the insulators and the assembly's leakage distance, which is the minimum of the post and suspension insulator leakage, influence pollution withstand performance. With composite insulators, the hydrophobic properties of silicone rubber enhance reliability in contaminated environments. Finally, the radio influence voltage (RIV) and visible corona onset voltages depend on the setup and electric field grading of the assembly.

On the other hand, the mechanical ratings of braced line posts are much more complex. Their mechanical capacity is influenced by various factors, including the overall geometry of the assembly, the SML rating of the suspension insulator, the strength of the brace hardware, the size and section length of the post insulator, and the strength and type of the post end fittings and connection base. In service, braced line posts experience combined vertical loads from conductor weight and potential ice accumulation, transverse loads from wind or line deflection angles, and longitudinal loads due to differential horizontal tensions between adjacent spans. Transverse loads are further categorized into compression (toward the assembly line end fitting) and tension (away from the assembly line end fitting), as the braced line post may exhibit different load capabilities in each direction.

While maximum single working loads in each direction are often specified in manufacturer drawings, these values have limited practical use for transmission line designers. Instead, working load curves are generated, which combine the effects of multi-axis loads. For a given longitudinal load, the combined working load curve defines the allowable combination of vertical and transverse loads that can be applied without exceeding the damage limit of the insulators or connection hardware [5]. Figure 2 illustrates the basic structure of typical working load curves for a braced line post. The complete boundary conditions for these curves consider tension loading in the brace assembly as well as the bending (cantilever), compression, and tension load magnitudes for the post insulator, including end fittings and bases [6].

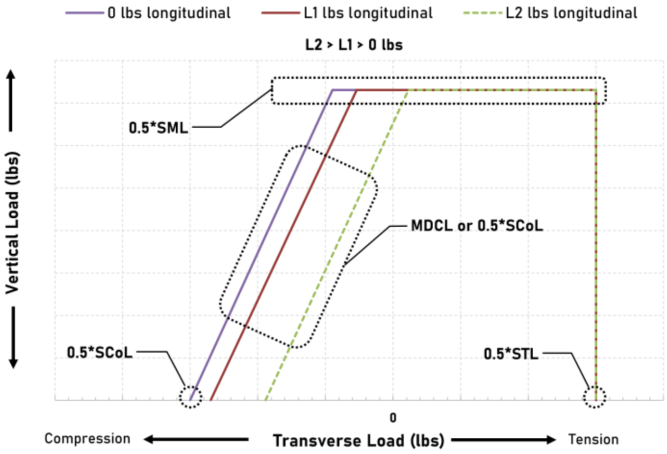

Figure 2 : Example of braced line post working load curves

In Figure 2, STL represents the specified tensile load of the post insulator assembly, which includes the capacity of the associated hardware, connecting bolts, and the integrity of the compression crimping or glued connection at the insulator end fittings. SCoL denotes the specified compression load of the post insulator, defined by its buckling capacity, and must also account for any limitations in hardware strength. The MDCL refers to the maximum design cantilever load of the post insulator, typically taken as 50% of the SCL or the specified cantilever load rating of the post insulator.

The vertical working load is governed by the SML rating of the brace insulator. The transverse tension load is limited by STL rating of the post insulator, while the transverse compression load is constrained by SCoL or MDCL limits of the post insulator. Figure 3 illustrates the typical failure modes of the post insulator, including compression buckling and damage to the FRP core under bending stresses.

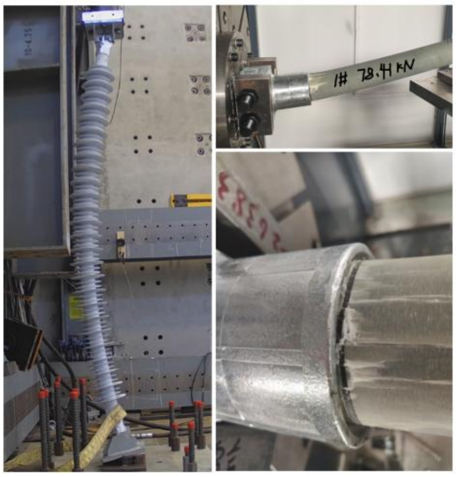

Figure 3 : Line post insulator failure modes under compression buckling (left) and bending stresses with FRP core damage (right)

During application and line design, the actual service loads must remain within the limits defined by the working load curves to ensure that insulators and hardware are not subjected to stress beyond their damage threshold. However, exceptions can be made for scenarios such as broken wire or other security-related load cases, where line loads may be aligned with the ultimate load curves. In these cases, the goal is not to prevent insulator damage but to avoid complete detachment of the assembly, which could lead to cascade failures. While load-strength coordination is sufficient for rigid braced line posts, additional verification of wind stability is required for pivoting horizontal vee assemblies [1]. Figure 4 illustrates a wind stability analysis using a finite element model for a three-tower, four-span (3T4S) section of a 345 kV line. Span lengths ranging from 400 m to 550 m were examined under various wind directions, and the maximum rotation angle of the pivoting horizontal vee assemblies, along with overall system stability, was confirmed.

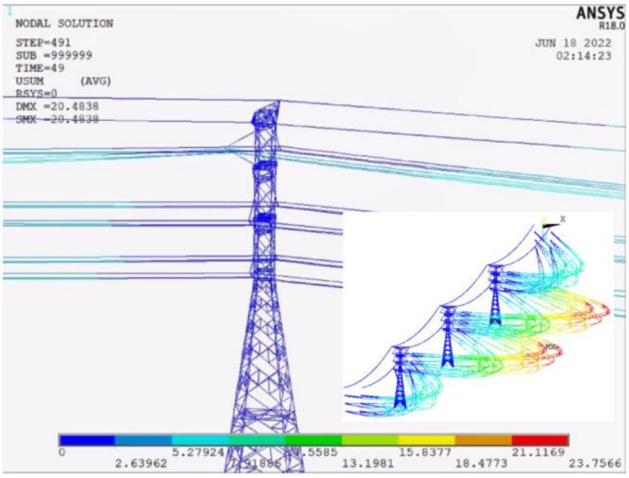

Figure 4 : Wind stability analysis of 345 kV pivoting horizontal vees

4. Strength upgrades

Before proposing any strength upgrades, it is essential to first understand the traditional limits of braced line posts. All components must be evaluated to identify the weakest link in the assembly, which can then be reinforced or upgraded. Figure 5 displays the working load curves for a typical contemporary design of a 345 kV braced line post with an 88 mm diameter post insulator (currently the largest standard size in North America), paired with a 160 kN rated suspension insulator. The post insulator is fitted with a common drop tongue line end fitting and bendable type base (post hardware). The post insulator has a section length of 3,2 m, a mounting angle of 0 degrees, and a vertical assembly height of 4,3 m.

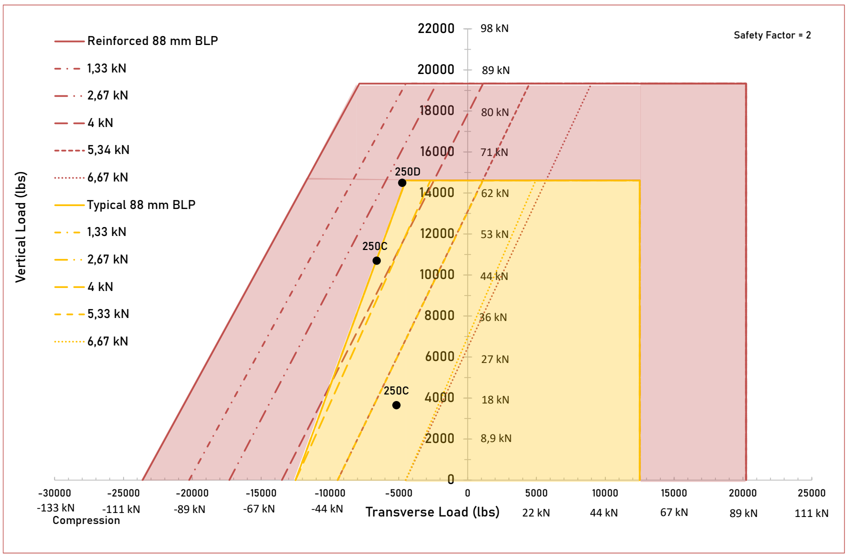

Figure 5 : Working load curves of 345 kV braced line post assembly composed of 88mm post insulator with typical and reinforced hardware (1 lbf = 4,448N).

The transverse load capacity of this assembly is limited by the conventional post hardware, which has a maximum working load of 55 kN. These hardware components were originally designed for nominal line post loads. However, in braced line post applications, typical hardware failure (rupture or deformation) occurs before the bending stress or buckling threshold of the post insulator is reached, limiting the assembly's ultimate strength [7]. To unlock the full potential, the line end fitting and base of the post insulator, identified as the weak links, should be upgraded. The common drop tongue line end fitting can be replaced with a high-strength, reinforced version made from high-grade steel. At the other end, the bendable base can be substituted with a fixed bolt circle connection.

To increase the capacity for vertical loads, the strength rating of the suspension insulator can be upgraded from 160 kN to 220 kN or even higher, based on the specific application needs. Additionally, the strength of the brace connection hardware should be upgraded to align with the SML rating of the suspension insulator. An example of such reinforcements is shown in Figure 6, along with corresponding stress distribution plots derived from finite element analysis. An alternative to the reinforced drop tongue line end fitting is an integrated yoke, which allows direct connection of conductor clamps, further compaction of the transmission structure.

To provide a clearer perspective, the working load curves for the 345 kV braced line post with upgraded hardware components are shown to be overlaid in Figure 5. At a minimum, transmission line facilities must be designed to meet the loading conditions outlined in Rules 250B, 250C, and 250D of the National Electrical Safety Code (NESC) [8]. The NESC loads for a twin-bundle 1033.5 kcmil ACSR Curlew with a 365 m (1200 ft) span and 2-degree line angle are also plotted in Figure 5. The NESC 250B load corresponds to heavy district loading, NESC 250C accounts for a 156 km/h (97 mph) basic wind speed, and the NESC 250D load is calculated for a 64 km/h (40 mph) wind speed combined with 25 mm (1-inch) conductor ice thickness. It is evident that the traditional braced line post design is limited in its working capabilities and can barely meet the NESC loads for a typical transmission line.

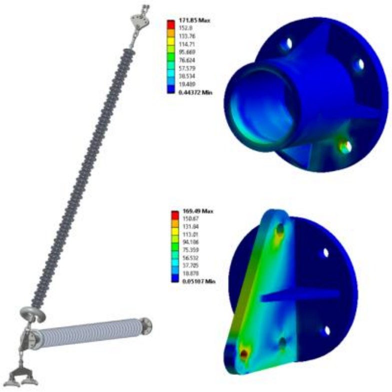

Figure 6 : Reinforced drop tongue line end fitting and rigid bolt circle base.

Once the limitations of traditional hardware are addressed through reinforced end fittings and bolt circle base attachments, the buckling load of the 88 mm post insulator becomes the primary factor determining the working strength limits of the assembly. The next logical upgrade to enhance transverse and longitudinal load capabilities for braced line posts is to use a post insulator with a core rod diameter larger than 88 mm. The buckling load is influenced by the post insulator's FRP core rod diameter, section length, and mounting angle. As the section length of the post insulator increases, its buckling stability and MDCL decrease [6] - [7], making a larger core rod diameter more desirable.

With advancements in FRP technology, it is now possible to manufacture high-quality solid core FRP rods with diameters larger than the standard 88 mm. Figure 7 compares the buckling load of a 88 mm post insulator with larger rod diameters of 110 mm and 130 mm. Elastic buckling becomes a limiting factor in designs intended for 345 kV and higher applications. In such cases, using larger post insulator rod diameters allows for achieving the optimal working loads for the braced line post assembly.

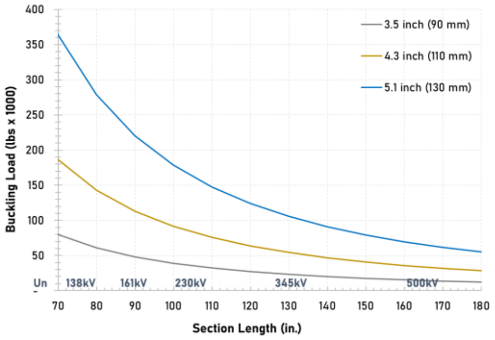

Figure 7 : Buckling load as a function of post insulator core rod diameter and section length (1 inch=25,4 mm, 1 lbf = 4,448N)

Using the same dimensions and geometry as the 345 kV braced line post with the 88 mm post insulator, designs have been developed using larger post insulator rod diameters of 110 mm and 130 mm. To maximize the strength of the assembly, the post insulator hardware is reinforced to the point where the buckling limit of the post insulator becomes the determining factor. The 110 mm post insulator is paired with a 220 kN suspension insulator, while the 130 mm post insulator is combined with a 300 kN suspension insulator. The working load curves for this high strength (HS) braced post designs are shown together in Figure 8, illustrating that using larger post insulator diameters significantly increases both compression and longitudinal load capabilities.

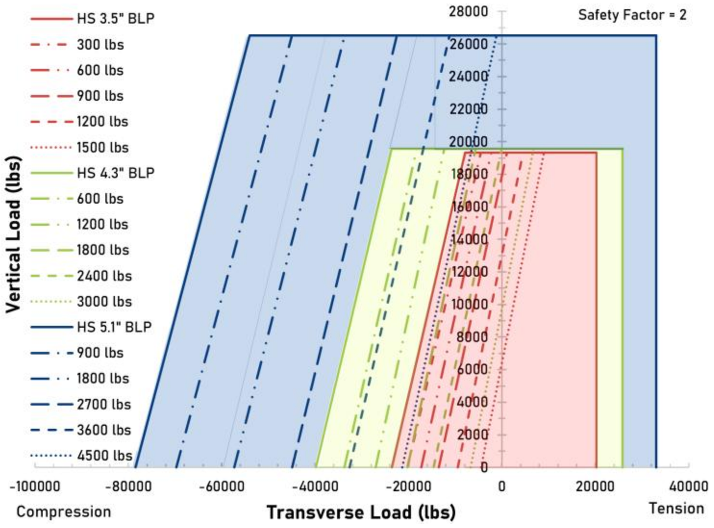

Figure 8 : Working load curves of high strength 345 kV braced line posts (1 lbf = 4,448N)

These working load curves are validated by full-scale combined mechanical load testing, where multiple load cases are applied to verify the damage and ultimate load limits of the assembly. An example of such testing is shown in Figure 9, where a 345 kV braced line post assembly with a 110 mm post insulator and 220 kN brace is subjected to the combined effects of vertical and compression loads until buckling onset of the post insulator is observed.

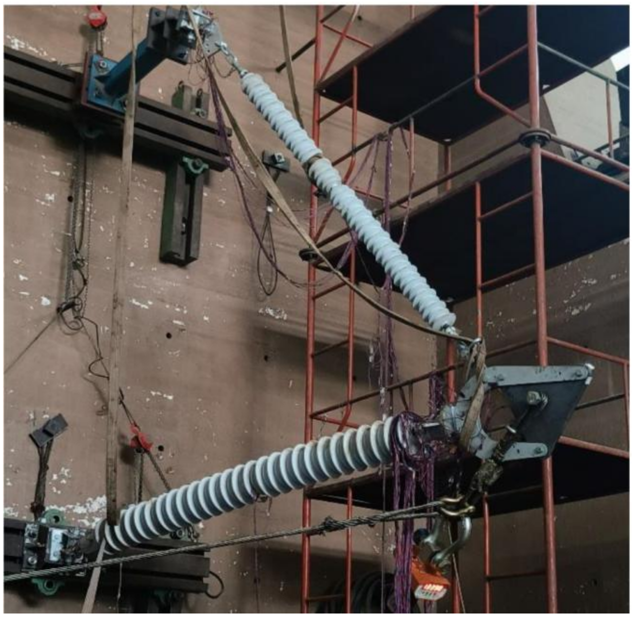

Figure 9 : Full-scale combined load testing of braced assembly with 110 mm diameter post insulator.

In addition to hardware and insulator size upgrades, the working load capabilities of braced line posts can be further enhanced by modifying the assembly's fundamental configuration, such as by implementing a tripod arrangement using two post insulators.

The triangulated braced line post, also known as an insulated cross-arm (CICA), can significantly enhance the ability to withstand higher longitudinal and transverse loads [9]. Figure 10 presents an example comparing the working load curves of a braced line post with a single 88 mm post insulator and a tripod CICA assembly featuring two 88 mm post insulators (with a 1m connection width).

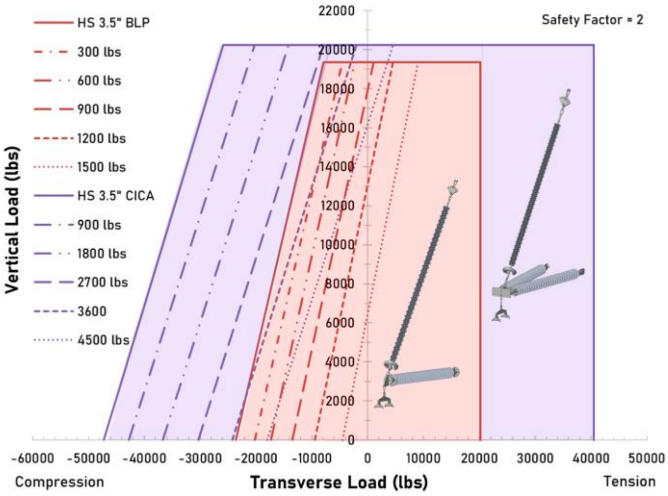

Figure 10 : Comparative working load curves of a 345 kV braced line post and tripod insulated cross-arm (1 lbf = 4,448N)

This tripod CICA design can be utilized on both steel monopoles and lattice towers for high-strength applications, accommodating longer spans, heavier conductors, and larger running angles. For 500 kV and above CICA applications, hollow-core post insulators can be used to optimize both weight and mechanical performance. When applied to monopoles, additional longitudinal davit arms are required to provide the necessary width for post insulator connections. The optimal opening width between the two post insulators is carefully selected to balance longitudinal and compression loading capabilities.

5. Conclusion

Traditional connection end fittings and the limitation of post insulator core diameters to a maximum of 88 mm restrict the capabilities of braced line posts, limiting their use at higher voltages and mechanical loads. By utilizing reinforced hardware and composite post insulators with larger core diameters of 110 mm and 130 mm, the working load capabilities can be significantly enhanced. Further strength improvements can be achieved by integrating composite insulated cross-arms with two post insulators arranged in a triangulated configuration. These high-strength assemblies can surpass the limitations of conventional braced line posts and pivoting horizontal vee assemblies, offering improved longitudinal load security. This enables line compaction up to 500 kV, providing opportunities for reduced construction costs through longer span lengths and fewer transmission structures.

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