ADVANCED TRANSMISSION LINE DESIGNS FOR HIGH ROW UTILIZATION

March 2022

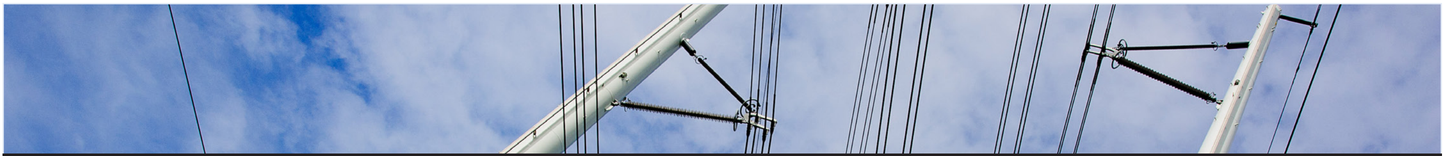


Table of Contents

Introduction

Increasing transmission system capacity is an important enabler to meeting U.S. and global decarbonization goals. There are numerous technical challenges that must be addressed by the electric utility sector for transmission capacity to be increased to the required levels. The Electric Power Research Institute's (EPRI's) recent white paper: *Increasing Transmission Capacity on Transmission Lines and Rights-of-Way* (3002023004) discusses options for increasing transmission capacity by upgrading existing transmission lines or new construction. This white paper provides a more detailed discussion of advanced transmission line designs that can be utilized for new construction to increase capacity.

Transmission Capacity Limitations

For alternating current (AC) lines, power flow, also referred to as capacity, is limited by one of the following:

- Thermal limits. The rated current of the conductor system.
- Voltage-drop limits. The voltage at the end of the line drops below the established operational limits due to current flowing through the line impedance.
- Stability limits. On long lines, small changes in load can result in unstable receiving-end voltage due to the relatively large series impedance of the line.

The underlying phenomenon that limits line loadability varies with line length, as illustrated in Figure 1.

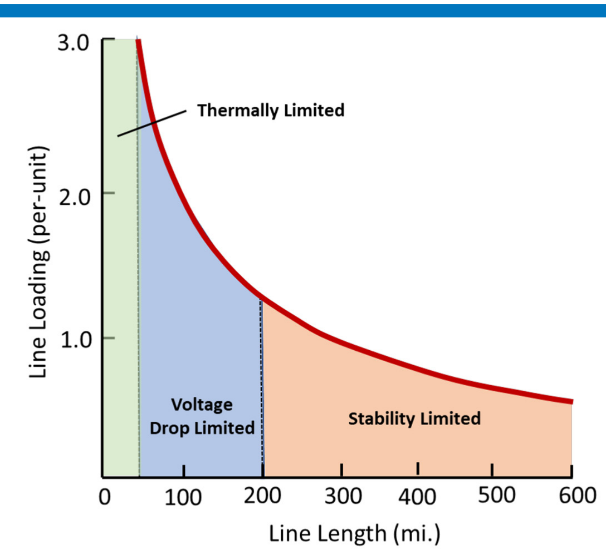
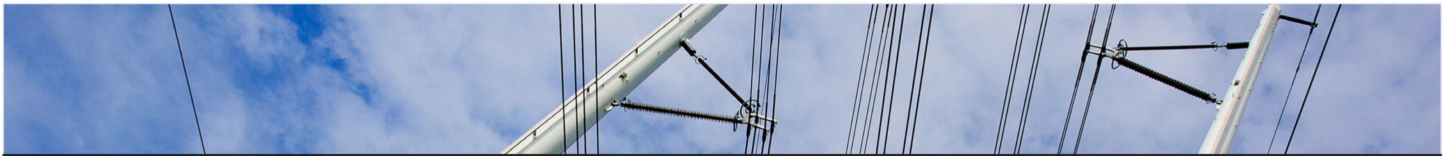


Figure 1. Universal loadability curve of AC lines [1]



The thermal limit of a line can be addressed by increasing the number and/or diameter of the conductors installed, or by increasing the conductor system's rated temperature.

Volt drop or stability limitations can be addressed by reducing the impedance of the line, which is primarily a function of the diameter of conductors and the distance between phases, with the latter being the dominant factor. Decreasing the distance between phases and/or increasing the conductor diameter decreases the impedance of the line.

What is an Advanced Line Design?

Advanced, high-capacity transmission lines, as illustrated in Figure 2, may incorporate several features and technologies, including:

- Phase and bundle configurations that enable increased transmission capacity on the same right-of-way (ROW).
- Incorporation of monitoring to maximize current flow based on current conditions (dynamic rating).
- Compact structure configurations that reduce the footprint and facilitate multiple use ROWs potentially including underground cables, photovoltaic-based generation, and other infrastructure.
- Aesthetic, or low-visibility designs that promote public acceptance.
- Designs that minimize the impact to the environment.
- Designs that have long life expectancy and have reduced maintenance costs.

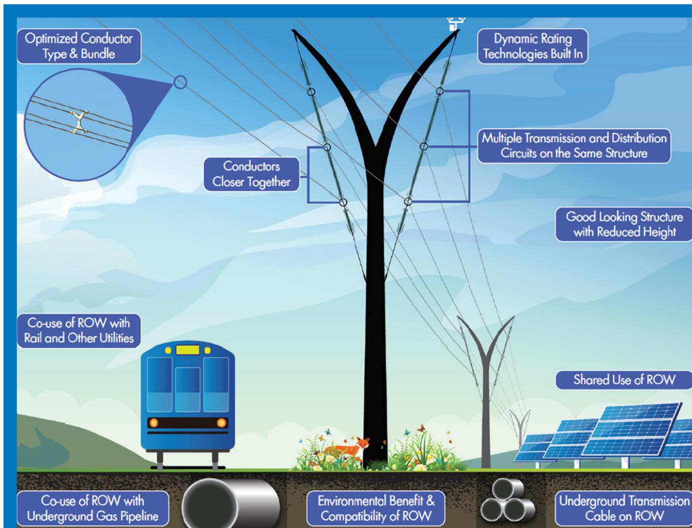


Figure 2: Advanced Transmission Line design features

Objectives of an Advanced Line Design

An advanced line design can have one or more of the objectives listed below:

- Higher level of capacity compared to a traditional line design on the same right-of-way
- Increased public acceptance
- Increased utilization by other infrastructure and the public

In pursuing these objectives, specific design, maintenance, and environmental compliance challenges present themselves. Design approaches to manage these issues are briefly discussed below.

Design Features to Increase Transmission Capacity

Phase Compaction and Bundle Expansion

For longer lines, typically more than 50 mi (80km), that are voltage constrained, additional transfer capacity may be achieved by reducing the distance between phases (also known as the GMD or geometric mean distance), and/or increasing the distance between subconductors in a bundle (geometric mean radius or GMR) or conductor radius in single conductor lines.

Changes in the GMD and GMR affect both the inductance and capacitance of a line, which affect the natural loading of a transmission line, or surge impedance loading (SIL). Where optimally configured, such transmission lines have been referred to as high surge impedance loading (HSIL) lines. [2]

Effective phase compaction can be achieved by positioning the phases within the same tower window, as seen in Figure 3.

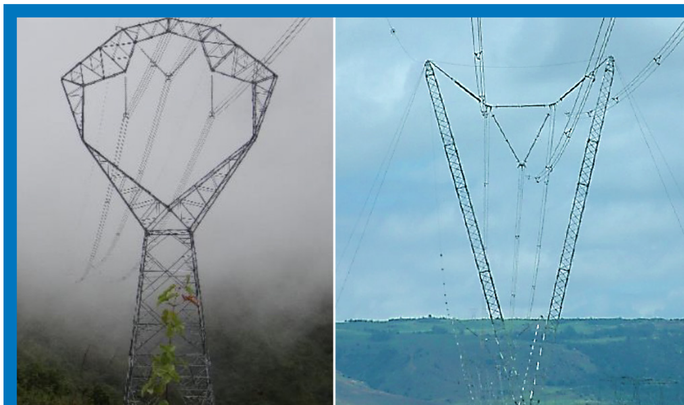
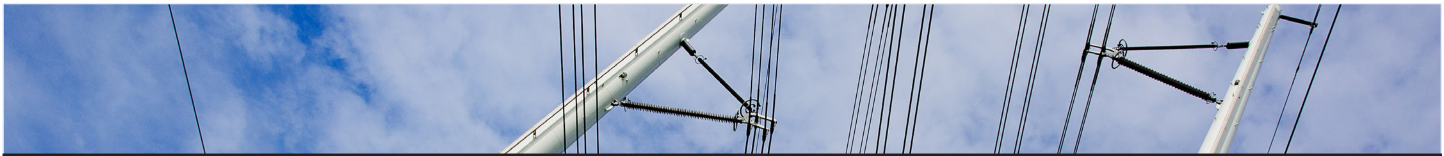


Figure 3:500kV and 400kV structures with compacted phases



Increasing the conductor bundle spacing, although less common, has been used in several 500kV lines in Brazil. As illustrated in Figure 4, the standard bundle spacing has been increased from 18 in (0.46m) to 43 in (1.1m). In recent designs, expansion has been increased even further to form a "super-expanded bundle" measuring 102 x 83 in (2.6 x 2.1m).

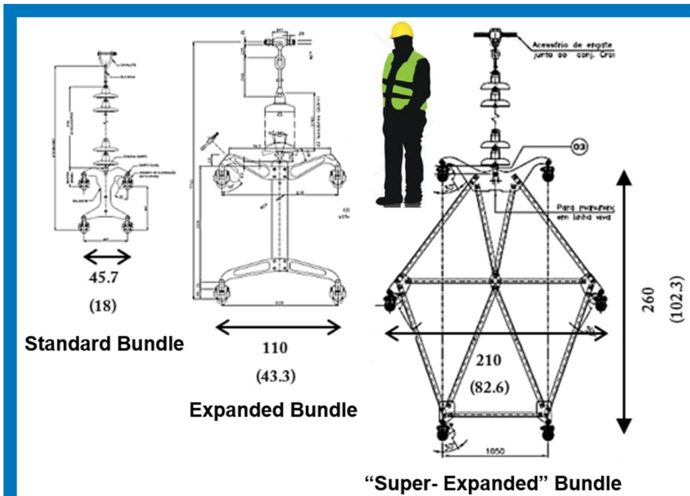


Figure 4: Conventional and expanded bundles

Significant increases in transfer capacity have been achieved using phase compaction and conductor bundle design techniques. A recent comparative study performed by EPRI [3] showed that phase compaction and bundle expansion increased the SIL by 20% and 19%, respectively. The same study showed that phase compaction and bundle expansion combined increased SIL by 48% for an expanded bundle, and 67% for a "super-expanded bundle."

As with any design modification, there are challenges that must be addressed. Design and operational challenges for utilities adopting compact phase configurations include:

- More detailed insulation design procedures are required to compact insulation distances while maintaining an acceptable outage performance. This may necessitate the implementation of additional overvoltage control measures.
- Increased probability of phase-to-phase flashovers accounting for asynchronous conductor swing, galloping, and wildfire events.
- Increased corona activity due to smaller phase spacing, which results in audible and radio noise.
- Live working challenges when considering insulator replacement due to reduced clearances.

An advantage of reduced phase spacing, and increased bundle size, is that the smaller spacing results in lower electromagnetic fields on the ground for the same voltage and current levels. This opens opportunities for narrower ROWs, shorter structure heights, and increased currents and voltages.

The surge impedance of a line can also be compensated for by additional substation equipment in the form of capacitor banks, reactors, or Static Var Compensators. Cost-benefit analyses including maintenance, reliability, and capital cost need to be compared to the cost of the advanced line design.

Dynamically Rated "Smart Structures"

For shorter lines, where transfer capacity is constrained by thermal limitations, lines may be designed for higher ampacity. Such lines may incorporate advanced conductors, discussed in the companion white paper in this series: *Reconductoring, Tensioning, and Advanced Conductor Technologies* (300202023335).

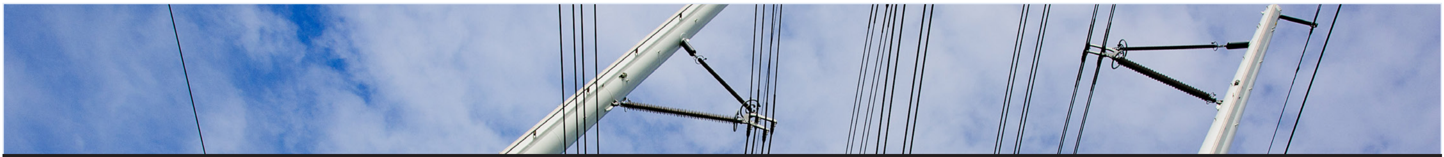
An alternative strategy for thermally constrained lines involves maximizing the rating for the line based on ambient weather conditions. This is the subject of the companion white paper: *Dynamic and Ambient Adjusted Ratings* (3002023333).

More utilities are beginning to adopt periodically adjusted ratings, which allow traditional, fixed ratings to be re-computed either seasonally, monthly, weekly, or even hourly (real-time or dynamic ratings) based on expected weather conditions. Full implementation of dynamic ratings requires the use of online monitoring technologies to know the condition of the line and the local weather conditions.

Online monitoring does not need to be implemented at every span, rather at the critical spans that limit capacity. For example, spans that have smaller ground clearance or at locations where the conductors are shielded from the wind.

What makes real-time ratings attractive is a relatively low capital installation cost. In a future where dynamic real-time ratings are widely adopted; new, advanced structures will account for the technology in the structure designs:

- Mounting points for transducers and electronics cabinets.
- Integration with communications systems such as wireless and fiber optics.
- Access to perform maintenance by staff that has a different skill set from traditional line personnel.



To date, limited adoption of dynamic rating is evident, despite decades of study and analysis on numerous experimental real-time installations. A key hurdle limiting wider-spread adoption is that most lines in a network are not thermally constrained, making the introduction of such advanced control systems specific to a small number of lines on the grid. Grid operators may be understandably reluctant to adopt different rating and control approaches for lines on the same network.

Multi-Circuit Structures

Adopting multi-circuit and multi-use configurations is the most widely adopted strategy currently employed to accommodate more than one circuit on constricted rights-of-way (Figure 5).

Figure 5: 400+132kV multi-circuit configuration, and multi-use structure supporting 138kV,11kV under-build, telecoms, and streetlighting

Multi-circuit structures are most commonly used when additional space adjacent to an existing ROW is not available. Often, this necessitates combining a higher voltage circuit with existing lower voltage circuits on the new structure. Supporting multiple circuits on the same structure can also be cost effective, in comparison to separate supports for different circuits.

While attractive from a land-use perspective, multi-circuit structures do translate into significant design, operational, and public liaison challenges, which are discussed later.

Public liaison efforts to secure the re-use of the ROW may be significantly impacted where the superposition of a higher voltage circuit necessitates larger, highly visible structures. The use of aesthetic designs may offer one solution to ameliorate public opposition.

In one study [4], a proposal to recycle an existing ROW with two 66kV double circuit lines into a 2x400kV+2x132kV design, would have translated into a six-fold increase in power transfer, but necessitated a structure with more than double the existing structure height. A size increase of this magnitude would trigger significant opposition, which led to the proposal of aesthetically pleasing V-Pole structures as illustrated in Figure 6.

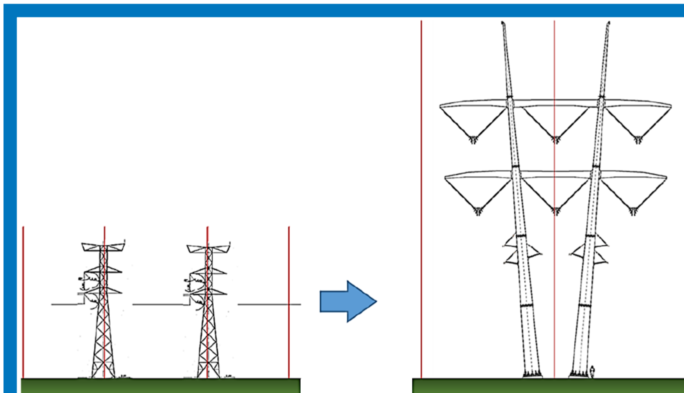


Figure 6: Upgrade of 2 x 88kV lines to multi-circuit (2 x 400 + 2 x 132kV) tower on 118ft (36m) wide ROW

Increasing Public and Environmental Compatibility: Aesthetic Designs

As public resistance opposing the construction of new overhead lines grows, utilities are becoming interested in improving aesthetics and reducing visual impact. Options for improving public acceptance range from low cost, low visual impact structures, decorated towers, sculpture towers, and aesthetic lines can be seen below.

Design competitions have been successfully employed by utilities to generate aesthetically pleasing concepts. There is, however, a need for overhead line design engineers to provide appropriate guidance in the development of such lines to ensure the architectural concepts are practical.

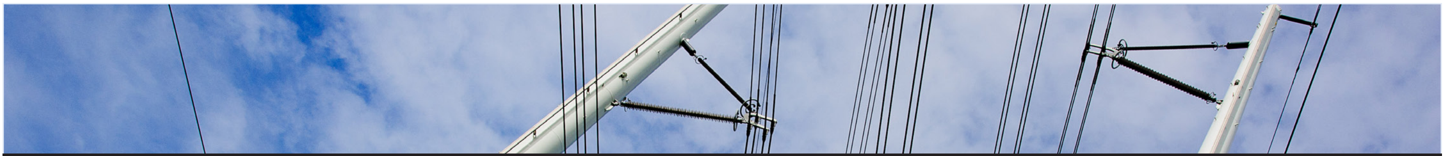


Figure 7: Examples of aesthetic transmission lines [Images courtesy of Nigel Young/Foster + Partners and RTE]

A significant challenge for utilities wanting to adopt aesthetic design relates to the cost of fabrication, which can be more than double the cost of a conventional superstructure. When juxtaposed against the cost of undergrounding, however, the increase may still be justified.

Also significant are operational and maintenance challenges introduced by unusual configurations, which often employ compacted phase assemblies that may have an impact on the ability to perform live-line maintenance.

Sculpture Towers in Public Areas

When placing towers and poles in public areas, the use of sculpture towers can provide an interesting and positive impression of overhead lines, which may benefit the public image of a utility.

Several innovative and interesting sculpture towers have been adopted in the past, and some (such as the famous Mickey Mouse tower in Orlando, FL) are widely known iconic structures.

Naturally, significant engineering challenges may accompany the adoption of such unusual designs, including the incorporation of electrical clearances, structural loads and insulation arrangements.

Low Magnetic and Electric Fields

Both phase compaction and bundle expansion have a beneficial effect on magnetic and electric fields. When phase configurations are compacted, both electric and magnetic fields close to and on the surface of the phase conductors are increased, which leads to a decreased electric and magnetic field at ground level.

Figure 8: Goalpost sculpture tower [Image courtesy of AEP]

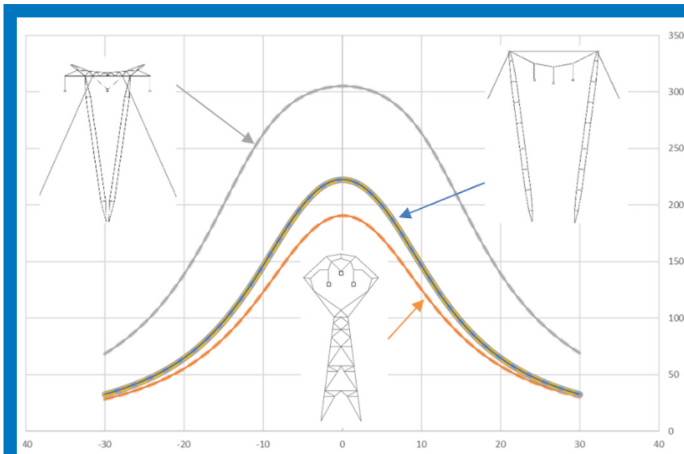
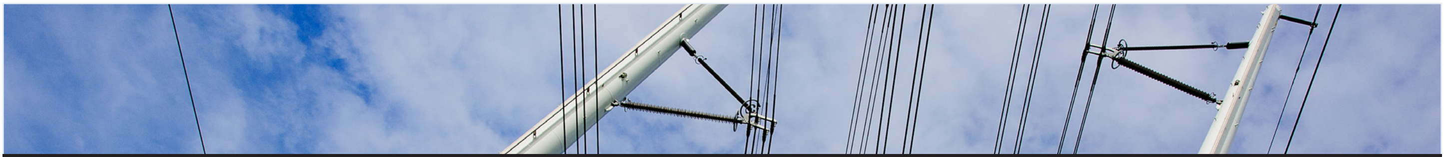


Figure 9: Comparison of magnetic fields for conventional vs. compact phase configurations

The extent of phase compaction is limited when phases are separated by structural members of the tower, while a high degree of compaction is possible when all phases occur within the same tower window. (As illustrated in Figure 3, Figure 22, Figure 23, and Figure 24). Such compaction produces significant reductions in magnetic and electric fields at ground level, while bundle expansion also produces a moderate beneficial effect, as illustrated in Figure 9.



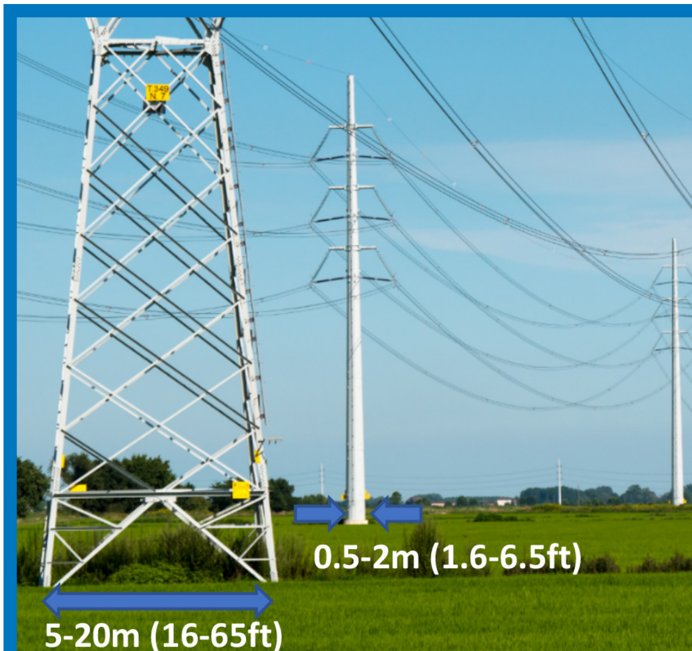


Figure 10: Comparison of conventional lattice vs. steel monopole footprint

Compliance to electric and magnetic fields are further discussed below.

Increasing Co-Utilization of the ROW

Structure Footprint

Reducing the structure footprint facilitates co-utilization of the ROW for public and private use (e.g., parking lots, agriculture, etc.). In this aspect, the use of steel monopoles has proven to be particularly valuable, characterized by a tenfold decrease in footprint, as illustrated in Figure 10.

Railways and Roads

Compact structures close to both railways and roads (Figure 5b) are in many cases unavoidable. Co-location of overhead line structures in roads and railways require specific additional considerations. For supporting structures in close proximity to roadways, vehicle collisions are a key consideration. To reduce the potential for injury and impact damage to structures, crash barriers for heavier structures have been adopted, while for lighter structures, the use of breakaway poles has been suggested.

For railways, the management of electromagnetic interference with railway signaling infrastructure and stray current is a key consideration. Special grounding or shielding arrangements may be needed and DC stray currents may be blocked by insulating shield wires from the towers for a specified distance on either side of the railway crossing (refer to EPRI railway book [10] for more information).

Access to both the railway line and to the transmission structure for maintenance needs to be considered.

Distribution

Distribution circuits can be added below the transmission conductors on the same structure to increase utilization. This has the advantage of potentially reducing the electric fields on the ROW and improving the lightning performance of the transmission circuits. However, lightning performance on the distribution circuit may be impacted as the transmission line structures are much taller, attracting more lightning strikes.

Operationally, the combination of distribution circuits on a transmission structure may pose additional challenges on both distribution and transmission field crews within the same utility, where equipment and work methods may not be compatible with maintenance of both voltages. In addition, live (energized) work methods may need to be carefully re-evaluated to accommodate both voltages on the structure. Grounding, clearances, and arc flash are all topics to be addressed.

Use of ROW for Solar Installations

As the cost of solar generation decreases, utilities continue to identify suitable space for solar photovoltaic (PV) installations within the proximity of existing transmission and distribution infrastructure, which includes the potential use of portions of the overhead line ROW.

When co-locating solar PV installations on existing ROWs, the impact of access to, and maintenance of the overhead line needs to be considered. Maintenance practices may be adapted to allow utilization for substantial portions of the ROW.

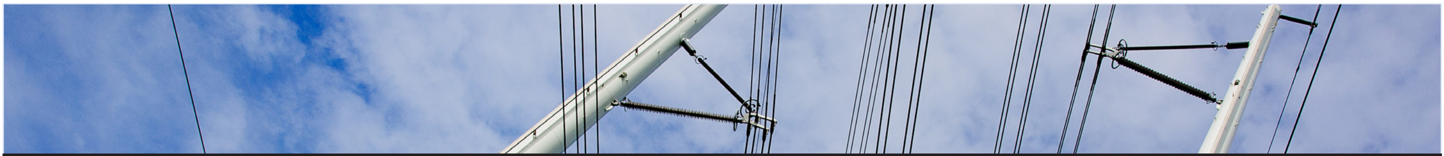


Figure 11: Can the ROW be used for solar generation?

Midspan clearances may be sufficient to accommodate panels without clearance violations. However, consideration for solar installation and maintenance equipment, such as cranes, is a key safety risk management area, which may require specialized (insulated) equipment. In addition, the impact of induced currents and voltages on the solar installation, as well as potential lightning and fault currents need to be considered. Solutions include earthing and shielding strategies.

Addition of Underground Cables to Overhead ROW

While underground cables usually constitute the most expensive option, in some cases this may be the only workable solution, especially in urban areas (Figure 12). The installation cost factor applied to an equivalent overhead line (excluding the cost of ROW procurement) associated with undergrounding is a function of voltage, ranging from around a factor of 2 for 11kV cables, to around 20 for some 500kV installations. Nevertheless, the cost of ROW procurement and practicality in high-value urban environments may dominate and render undergrounding as the most cost-effective option.

Where a ROW has already been acquired for an overhead line and extra capacity is needed, the addition of a cable to the ROW may be a feasible option as it has limited visual impact. Concepts have been suggested where the underground cable is installed in a conduit (pipe) elevated above the ground to reduce cost and increase access.

Figure 12: Installation of underground cable in an urban area

For AC cables, the power transfer capacity reduces as the line length increases due to the shunt capacitance (15 to 40 times higher than equivalent overhead lines [5]), as shown in Figure 13. This is not a limitation for direct current (DC) cables. However, the cost of DC terminal equipment is much higher.

Installing long AC cables may also have negative influences on the performance of the surrounding system, such as introducing system resonance at lower harmonic frequencies that can result in significant sustained temporary overvoltages. This necessitates extensive system and insulation coordination studies to ensure the successful integration of such cable systems.

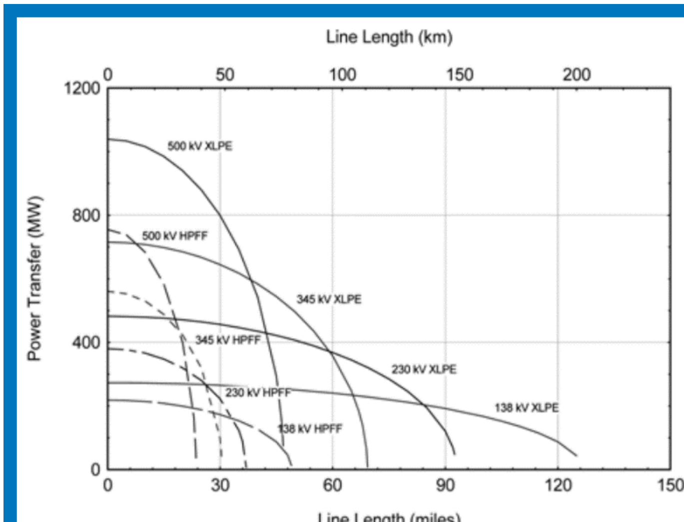
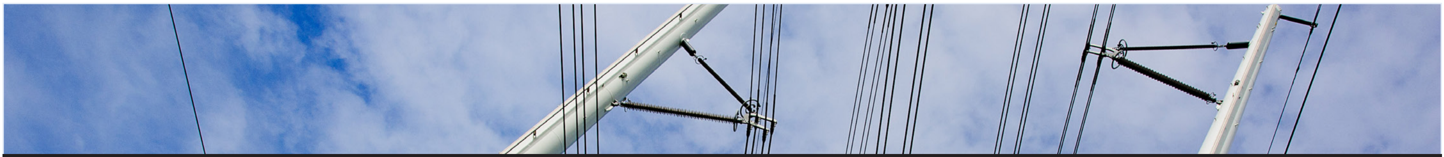


Figure 13: Maximum real power transfer for AC cables [5]



Considerations of adding cables to the ROW include:

- The impact of circuiting current on the corrosion of both the underground and overhead lines
- Impact of fault currents from the overhead line on the underground line
- Induced currents and voltages
- Maintenance practices when one or both lines are energized

From a public acceptance perspective, undergrounding may be the most attractive option to consider, with the least amount of opposition. In multiple instances, strong public opposition and litigation have resulted in extensive delays or cancellation of overhead line projects in favor of undergrounding. These experiences underscore the need to consider this option seriously from the outset on time-sensitive projects.

Undergrounding cables in a shared ROW, whether adjacent to other overhead lines, roads, or pipelines constitute an effective public use of land, and may be pursued with minimal impact to the existing power supply.

Finally, underground transmission installations, which are virtually impervious to extreme weather, enjoy a higher level of reliability compared with overhead lines. However, when they do occur, faults in the cable system are usually permanent in nature, with long outages needed to replace a faulted section.

Maintaining Compliance

Electric and Magnetic fields

While the levels of both magnetic and electric fields imposed by transmission lines to humans is relatively low in comparison to everyday household appliance exposure, much emphasis has been placed on the management and reduction of exposure levels of both magnetic and electric fields for those living adjacent to overhead lines, with a bias towards management of magnetic fields in recent years. Most utilities aim to comply with the limits suggested by ICNIRP [6], while some utilities have adopted even more conservative limits.

EPRI has collaborated with utilities to achieve compliance to stringent magnetic and electric field limits. The starting point for such studies involves modelling of fields in software such as EPRI's Transmission Line Workstation - Generation 2 (TLW-Gen2).

The TLW tool can aid engineers in identifying options for reducing the resulting electromagnetic fields. For example, magnetic fields have been successfully reduced following the installation of passive induction loops under phase conductors.

Audible Noise and Radio Interference

When compacting phases, increased electric field stresses at the conductor surface may lead to increased levels of corona, which in turn give rise to both audible noise and radio interference (RI). Electronic devices have evolved towards higher frequency digital devices, largely ameliorating the impact of radio interference. However, audible noise remains a key issue to manage.

To manage corona levels, a number of options are available, including the use of larger conductors, expanded conductors, changes in phasing arrangements, conductor bundles, or asymmetric bundles.

TLW Gen 2 may be used to evaluate audible noise conditions in dry or wet conditions. An important step in the verification of corona-related impacts involves electrical testing, as discussed below.

Clearances

Statutory clearances to conductors may be impacted by permanent stretch (creep) following extreme climatic events or vegetation growth. The periodic use of LiDAR to verify compliance has been widely adopted to comply with FERC mandates to manage clearances.

Most of the focus relates to the impact of vegetation encroaching on overhead lines and is a key risk for utilities in areas prone to wildfires. Coupled with LiDAR, the use of predicted growth models and data analytics have been used to identify and prioritize ROW management, as illustrated in Figure 14.

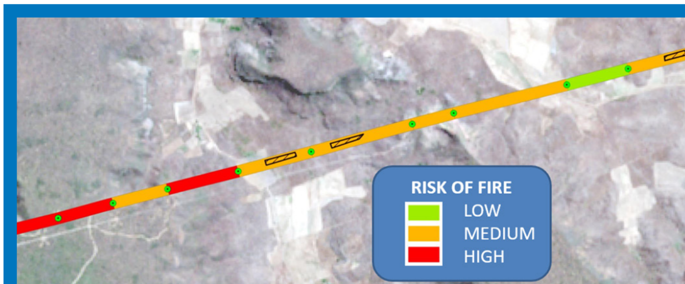
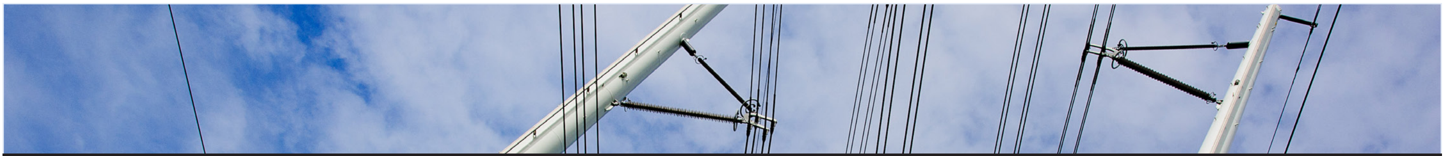


Figure 14: Data Analytics may be used to identify and prioritize critical vegetation clearing zones



Maintaining Reliability and Resiliency

Providing a reliable electricity supply is one of the key focus areas in the EPRI mission. In the context of advanced line design, several electrical, structural, and environmental aspects require specific attention.

Lightning

Lightning is a major cause of outages in the U.S. and is, therefore, an important factor to consider in line design. Tall, slender structures, favored in advanced line designs, typically have a worse lightning outage rate than short, squat structures. Improvement in the performance can be achieved by carefully positioning shielding wires, to protect phase conductors from direct strikes, selecting an appropriate insulation level, and by designing a low-impedance grounding system. Some advanced line designs may incorporate surge arresters to achieve acceptable performance.

Switching

Switching overvoltages occur due to system operations or faults in the network and are an important design parameter for compact lines and in power systems at and above 230 kV. The flashover strength as a function of insulation length is nonlinear, resulting in unexpectedly low flashover strengths for gaps of over 2 mi in length. Achieving compact insulation distances in most cases is only possible by considering overvoltage control measures such as controlled switching, closing, or opening resistors on breakers or surge arresters.

Contamination

Insulator contamination is the result of salt deposits on insulators, which significantly lower the power frequency flashover strength of insulators. This is usually only a concern in areas close to the coast, salted roads, or industry, and is mitigated by the appropriate selection of insulators. Important characteristics in this regard are: if the insulating material is hydrophobic or not, the shape of the insulator profile, and the insulator dimensions – including the axial length and leakage distance.

Aging

Advanced line designs often favor the use of polymeric materials, both as structural and insulating materials. These materials allow for a greater flexibility in achieving complex designs due to their low weight and the possibilities of manufacturing non-standard shapes. However, a concern with utilizing these products is their ability to withstand the anticipated environmental and electrical stresses over the expected lifetime of longer than 50 years. As of yet, there are no standards or formalized test procedures to qualify materials for this use and EPRI is actively working to fill this void.

Wind, Rain, and Ice

Extreme weather-related impacts in recent years have significantly interrupted electricity supply, which emphasizes the need for continuous improvement in the creation of a more robust and hardened grid.

Previous aspects not necessarily covered in design standards include the impact of flooding (Figure 15), and changes in the nature of extreme events due to climate change, such as the magnitude of icing events.

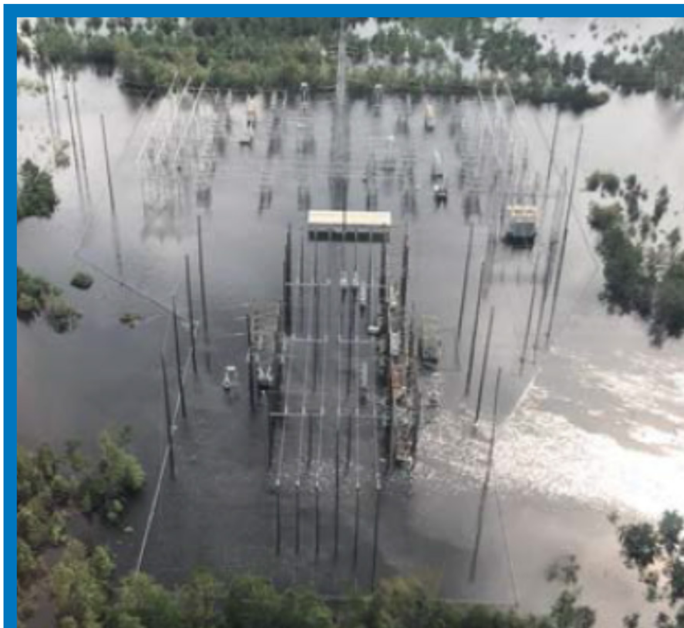
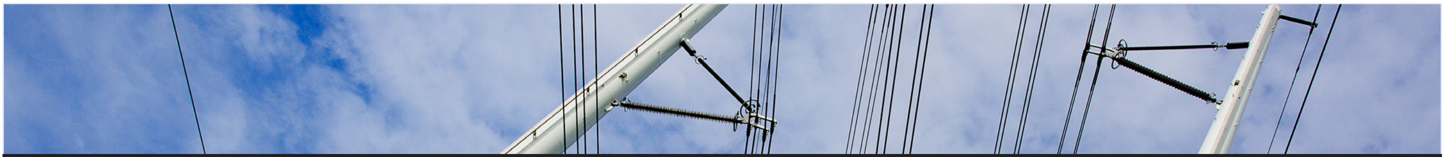


Figure 15: Climate change impact trends include an increase in flooding events

Another aspect not extensively covered in design standards relates to the prevention of cascading failures, a secondary effect following initial structural failure due to extreme weather or degradation. In this space, EPRI has suggested changes to design philosophy, and has created the CASE Tool, software that identifies this susceptibility of lines to overhead cascades.



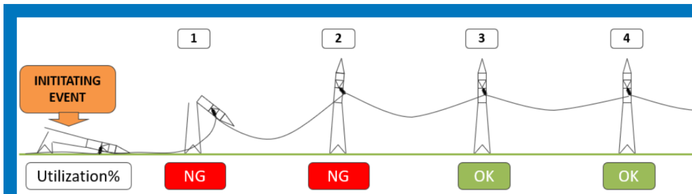


Figure 16: EPRI's CASE Tool aims to predict the length of cascade events

Maintaining Maintainability

When developing advanced structures with compact phase arrangements, maintenance and tower top access are often challenging design areas.

Live Working

Compact phase arrangements may well impact live working techniques. For this reason, integration of maintenance specialist input into the design process is a key component for advanced line development.

Technologies that may facilitate live working on compact lines include the use of portable protective arresters that have been demonstrated to provide improved safety in comparison to portable protective air gap devices (Figure 17).

Figure 17: Installing a Portable Protective Arrester [7]

Structure Access and Climbing

Architecturally pleasing structures may also present access and climbing challenges, particularly on designs that call for smooth surfaces with no external visible attachments.

In these arrangements, access may still be possible using underslung airborne maintenance, insulated lifting platforms, or ascender devices. EPRI is currently engaged in the evaluation of several ascender systems for ground-based maintenance crews (Figure 18).

Figure 18: Battery-powered ascender devices for direct access to conductors

Advanced Monitoring for Maintenance, Reliability, and Physical Security

The use of smart structures is particularly relevant for facilitating reliability and physical security. Vibration monitors may be used to detect specific vibrations relating to structure tampering or impact to the structure. Vibration sensors have also been used to detect ground acceleration due to blasting activity.

RF monitors have also been used to improve reliability during contamination or galloping events

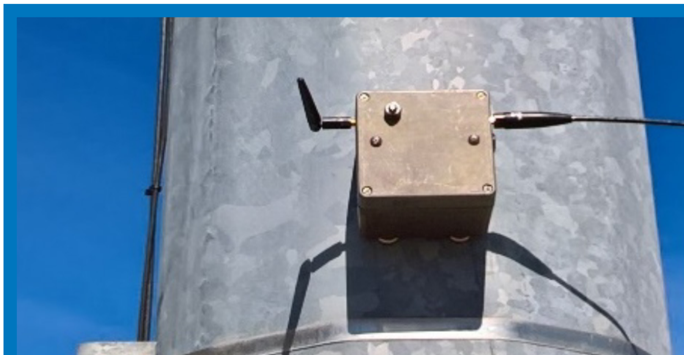


Figure 19: Structure vibration monitors have multiple applications to aid operational reliability

Developing an Advanced Structure

Advanced Structure Development Process

A value engineering process has been adapted for the development of high-value overhead line assets (Figure 20), which aims to identify and create ways to improve transfer capacity, reliability, and safe operation at the lowest cost and environmental impact.[5]

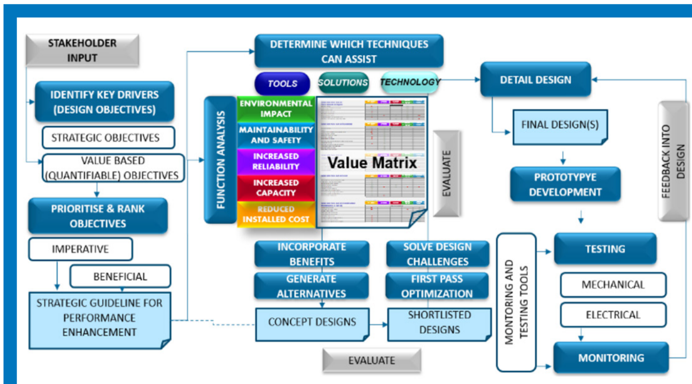


Figure 20:Application of Value Engineering to Overhead Line Design [3]

Value engineering describes the creation of high-value assets, where value is maximized by increasing the benefit-to-cost ratio. Applied to overhead line design, value may be expressed as the ratio of a line's transfer capacity to its risk-adjusted life-cycle cost.

This requires positive collaboration across utility stakeholders in the transmission space, which spans transmission planning, engineering, and operational divisions.

A value engineering process requires exploration of all new concepts with potential merit, and naturally lends itself to advanced overhead line development.

The development process entails refinement of conceptual designs into a final workable product, which includes testing and development to validate designs.

Testing and Development

EPRI has partnered with several utilities to contribute to the development and testing of advanced configurations.

Figure 21: Mechanical testing of 115kV compact assembly [Courtesy of National Grid USA]

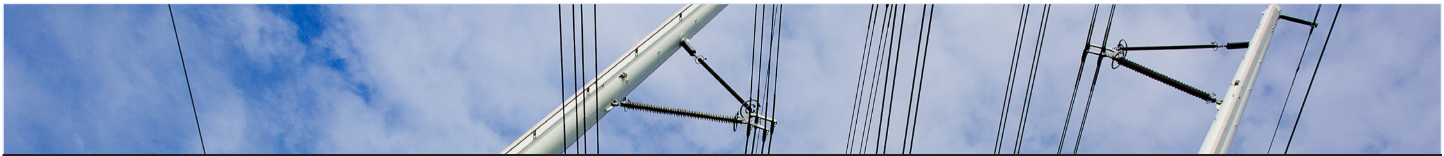
For example, a new compact 115kV assembly (Figure 21) was subjected to both electrical and mechanical tests to vet corona performance and load capacity of the assembly.

Mechanical testing enabled several design modifications to improve load capacity, which were implemented in the final design.

EPRI's Advanced Line Design Supplemental Project [8] was initiated to provide guidance on how state-of-the-art solutions and technology can enhance the value of overhead line designs to maximize transfer capacity, reliability, safe operation, environmental impact, and cost efficiency. This initiative gave rise to the Advanced Transmission Structure Concept Design Supplemental Project [9], which will aim to develop two new scalable advanced overhead line designs in the voltage range 69-138kV, and 235-380kV.

Field Monitoring to Verify Performance

EPRI's Sensor suite has been effectively used to evaluate multiple aspects on advanced overhead line designs, affecting mechanical and electrical performance. For example, stress monitoring was used to vet the mechanical performance of a new curved 345kV cross arm design, and ongoing monitoring on selected test spans continue to vet the performance of anti-galloping mitigation devices on sections of line with shorter than normal phase spacing.



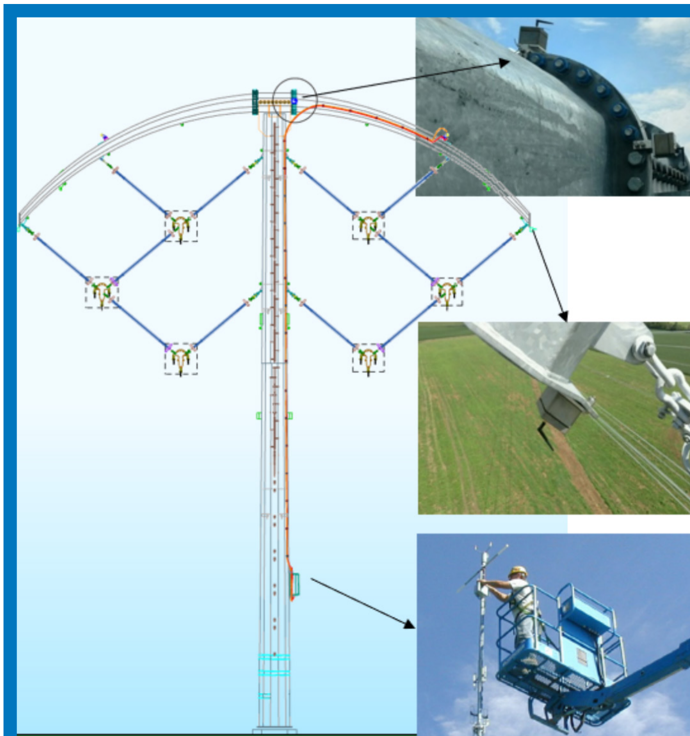


Figure 22: EPRI RF Sensors applied to the BOLD structure to assess dynamic stress performance

Figure 23: Hybrid implementation of BOLD, including 138kV and 345kV circuits [Courtesy of BOLD Transmission, LLC]

Figure 24:400kV T-Pylon double circuit [Courtesy of National Grid]

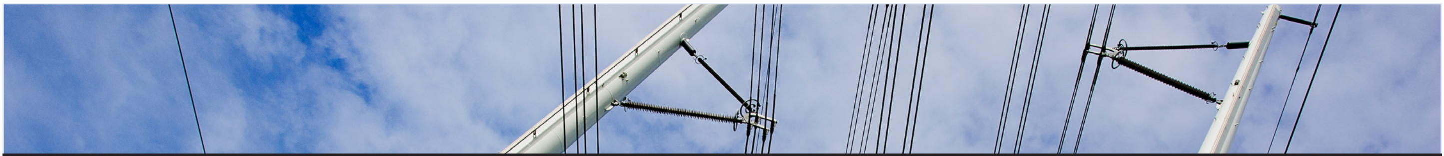
Examples of Implementations

AEP's Breakthrough Overhead Line Design (BOLD) embodies multiple design elements previously enumerated. This aesthetic design is scalable, presented in 116, 138, 230 and 345kV formats, which can also be adopted in a multi-circuit configuration (Figure 23). It features a horizontally and vertically compact phase configuration, which facilitates both increased power transfer and reduced visual impact. The unique assembly utilizes tension-only insulators that may be replaced with adapted live-line techniques, depending on utility work practice.

Following a well-publicized design competition, National Grid selected the T-Pylon (Figure 24) as the winning concept. This 400kV design features a smooth, seemingly jointless configuration, facilitated by internal flange connections, and advanced fabrication techniques. The compacted phase configuration is supported in a diamond pattern suspended from single support points, and utilizes specially designed hollow core post insulators as the central compression insulator.

In Southern Africa, Eskom has developed several long-distance 400kV AC links using compact phase arrangements, which can be supported on cross-rope structures, since ROW space restrictions are typically absent in sparsely populated rural terrain.

This low impedance design has become the norm for applications in Namibia, where long-distance AC Links exceeding 350km (220 mi) are typically required by NamPower. Early iterations adopted star-configuration assemblies, while later versions utilized live-line friendly delta configurations (Figure 25). However, special FACTS devices had to be developed to detune the interconnection and avoid low frequency resonances and associated temporary overvoltages.



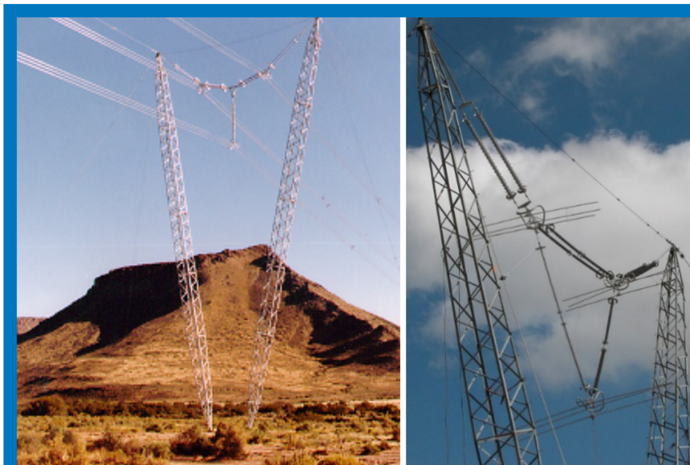


Figure 25:400kV Compact Crossrope Structures [Courtesy of Eskom]

Conclusion

To maximize the power flow in existing corridors, advanced, compacted design concepts may be adopted to support additional circuits. A summary of options is provided below in Table 1. Despite compaction, such initiatives are likely to increase the size of structures, which necessitates the consideration of aesthetic designs.

Since the boundaries of existing technologies are often pursued in advanced designs, rigorous testing and development are recommended to vet reliable performance.

Undergrounding remains a legitimate option for shorter, high land value sections where overhead solutions are untenable, provided that the necessary studies are done to successfully integrate them in the network.

Where successfully deployed, Advanced New High Capacity, High ROW Utilization Designs have the potential to elevate the corporate image of the utility.

Glossary

ROW – The right-of-way is a legal right, established by usage or grant, to pass along a specific route through grounds or property belonging to another.

ICNIRP – The International Commission on Non-Ionizing Radiation Protection, whose activities include determining exposure limits for electromagnetic fields.

Step and Touch Potential – Step potential is the voltage between the feet i.e., one step of a person standing near an energized grounded object. Touch potential is the touch voltage between the energized object and the feet of a person in contact with the object.

LiDAR – Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges.

FERC – The Federal Energy Regulatory Commission is the United States federal agency that regulates the transmission and wholesale sale of electricity and natural gas in interstate commerce.

Smart Structure – In this brief, Smart Structures are defined as those equipped with sensors to record and transmit conductor loads and position, together with real time weather conditions.

References

1. P. Kundur, Power System Stability and Control. EPRI and McGraw-Hill, 1994. ISBN0-07-035958-X.
2. Papailiou, K. et. Al, Cigré Green Book – Overhead Lines, ISBN 978-3-319-31747-2, 2017.
3. *Advanced Overhead Line Design–Interim Report 2: Advanced Solutions for Producing High Value Overhead Lines.* EPRI, Palo Alto, CA: 2021. 3002022070.
4. Marais, JP, Louw, G., Comparison of Multi-Circuit Pylon Options: Overview of support options using steel poles to support a quadruple circuit 2x500kV + 2x132kV multi-circuit pylon, Cigré Paper 114, Cigré Regional Conference, Cape Town, 2015.
5. *EPRI Underground Transmission Systems Reference Book: 2019 Edition.* EPRI, Palo Alto, CA: 2019. 3002015535.
6. ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz – 100 Khz), International Commission on Non-Ionizing Radiation Protection, 2010.
7. Phillips, A.J. et. al, Development of an Overhead Transmission Line Portable Protective Arrester (PPA) for Live Work, Cigré Paper, Paris 2020.
8. *Supplemental Project Notice - Advanced Overhead Line Design.* EPRI, Palo Alto, CA: 2017. 3002011047.
9. *Supplemental Project Notice - Advanced Transmission Structure Concept Design.* EPRI, Palo Alto, CA: 2020. 3002019517.
10. *Power System and Railroad Electromagnetic Compatibility Handbook*. EPRI, Palo Alto CA: 2006. 1012652.

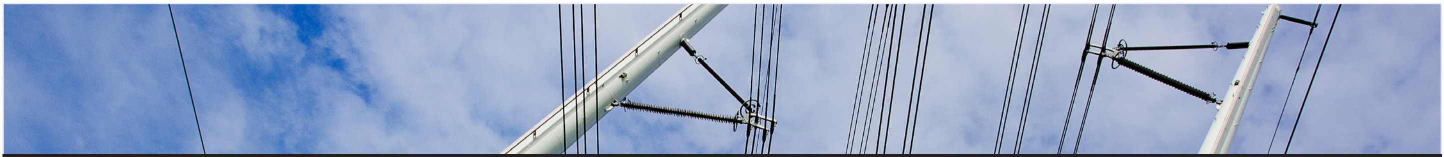
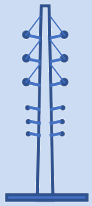
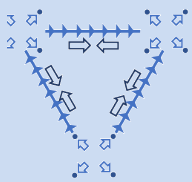
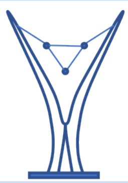
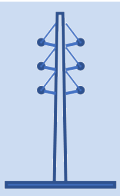


Table 1. Advanced High Capacity, High ROW Utilization Options

Option	Relative Cost*	Typical Increase in Transfer Capacity	Key Considerations
Multi-circuit options 	Low (0.8-1.5x)	1.5-10x	Potentially cost-effective solution. Maintenance challenges. Circuit-to-circuit impacts.
"Smart structures" with built-in dynamic rating 	Low 1.1-1.2 x	1.5-2x	High potential for cost-effective power transfer increase. Integration of dynamically rated lines into network control a key issue.
HSIL Designs (phase compaction, bundle expansion) 	Low/Moderate 0.8 - 1.2 x	1.2-1.7x	Motion control may be required on compacted lines. Live maintenance of compact circuits a key issue. Expanded bundles require additional tower top space and alternative hardware.
Aesthetic structures 	High 1.5 – 3x	N/A	Potentially beneficial to corporate image. Unusual designs often expensive. Maintenance challenges on many aesthetic configurations.
Underground cables in/on common ROW 	Very High 3-20 x	1-2x	May avoid delays in ROW procurement. Additional resilience in comparison to overhead lines. Most expensive option.

* Relative cost in comparison to conventional designs

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

Note

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

EPRI RESOURCES

Jean-Pierre Marais, *Principal Technical Leader*
704.595.2495, jmarais@epri.com

Overhead Transmission

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

3002023331 March 2022

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com