RECONDUCTORING, TENSIONING, AND ADVANCED CONDUCTOR TECHNOLOGIES FOR INCREASING THE CAPACITY OF TRANSMISSION LINES

April 2022

Introduction

The need and range of options for upgrading the capacity of existing overhead transmission lines or building new high-capacity lines is reviewed in The Electric Power Research Institute's (EPRI's) White Paper: Increasing Transmission Capacity on Transmission Lines and Rights-of-Way [1]. The upgrade options discussed in the paper included re-rating, dynamic and ambient adjusted ratings [2], voltage upgrades [3] and AC to DC conversion [4]. This White Paper provides a more in-depth discussion on conductor technologies and techniques for both increasing the capacity of existing lines or building new high-capacity new lines.

Capacity increases from conductors may be achieved through the following (in order of increasing cost):

- Re-tensioning
- Span-specific clearance enhancement
- Applying high emissivity coatings
- Reconductoring with either standard or non-proprietary high temperature low sag (HTLS) conductorsReconductoring with proprietary HTLS conductors

Each option is discussed in this paper.

Conductor Types

For many transmission lines (that are not thermally limited), conventional conductors (Figure 1) such as ACSR (Aluminum Conductor Steel Reinforced), AAAC (All Aluminum Alloy Conductor), and ACAR (Aluminum Conductor Alloy Reinforced) provide adequate performance. Continuous operating temperatures range from 90-95°C for ACSR and 80-100°C (for AAAC and ACAR). [5]

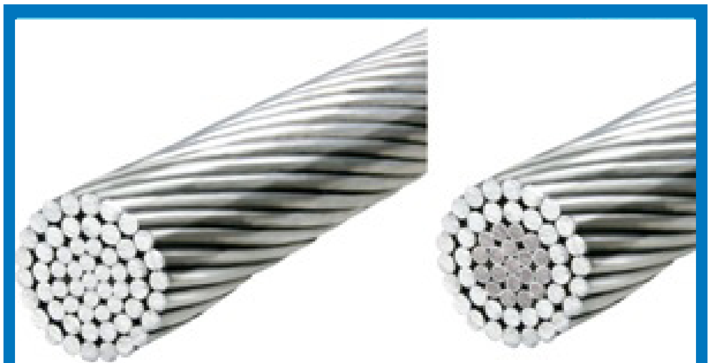


Figure 1. Conventional AAAC, ACAR and ACSR Conductors

High Temperature, Low Sag (HTLS) conductors are designed for applications where continuous operation is above 100°C.

HTLS conductors may include both Non-Propriety Conductors, on which patents have expired making them often more cost-effective alternatives, as well as Propriety Conductors (Advanced Conductors), which generally have a cost premium.

Non-Propriety Conductors are typically standard conductors with the addition of different alloys enabling higher temperature operation, e.g., Zirconium may be added to an aluminum (Al) alloy to provide resistance against annealing, at the expense of conductivity. An example is Gap-type GZTASCR conductor (Figure 2) that uses a Zirconium aluminum alloy decoupled from the steel conductor core, which is coated in high temperature grease.

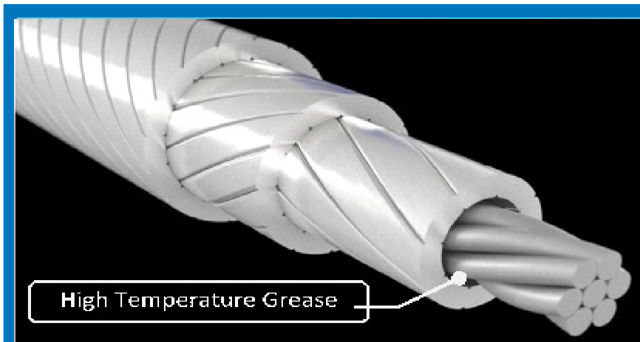


Figure 2. Gap-Type Conductor [Courtesy of Lamifil]

Table of Contents

ACSS (Aluminum Conductor Steel Supported) is a Non-Propriety Conductor that uses fully annealed Al strands. Construction includes round or compact trapezoidal Al strands that are fully supported by a variety of high strength steel cores (Figure 3).

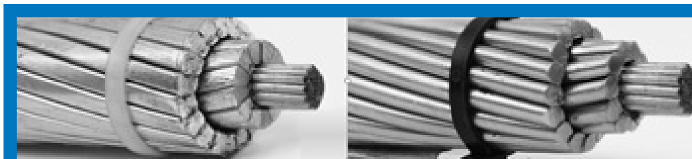


Figure 3. Trapezoidal vs. Conventional Stranded ACSS Conductor

The maximum allowable conductor temperature (MACT) of ACSS is constrained to the degradation limits for the steel core, ranging from 200°C for galvanized strands to 250°C for mischmetal alloy coated strands. Fully annealed, or zero temper Al strands are used in Proprietary HTLS options using solid composite cores such as ACCC (Aluminum Conductor Carbon Core) and ACPR (Aluminum Conductor Polymer Reinforced), as well as stranded composite cores like ACFR (Aluminum Conductor Fiber Reinforced) and C7® (Figure 4). In these variants, the MACT is typically governed by thermal limits of the core material, typically 200°C.

Before discussing uprating options, it is useful to understand fundamental thermo-electrical and thermo-mechanical aspects affecting conductor performance.

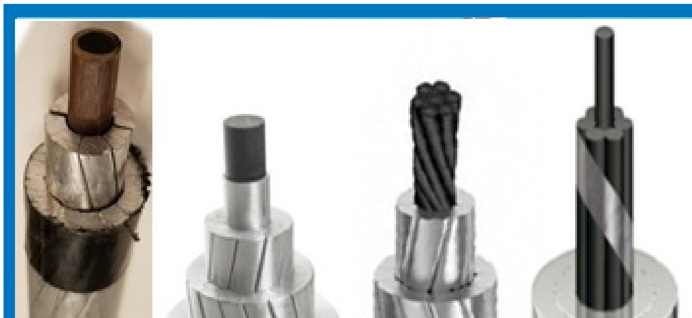


Figure 4. Proprietary HTLS conductors utilizing carbon cores (ACCC, ACPR, ACFR, C7 ®)

Thermo-Electrical Response of Conductor

The basis of all conductor uprating initiatives is the heat balance equation (Figure 5), which equates input energy (current and solar radiation) with dissipated energy (convective and radiative cooling).

While traditional thermal rating methods require the assumption of conservative values for solar radiation, convective and radiative cooling, re-rating initiatives seek to maximize current by providing greater certainty on these variables. [2]

Since the main source of thermal input energy is proportional to the square of current flowing in the conductor, large increases in the conductor operating temperature are needed for useful increases in rated ampacity (Figure 6).

Such large temperature elevations potentially impact the strength of the Al stands in ACSR conductors, typically limiting their continuous operating temperatures to 90-95°C (while short duration-MACT values of up to 140°C have been permitted).

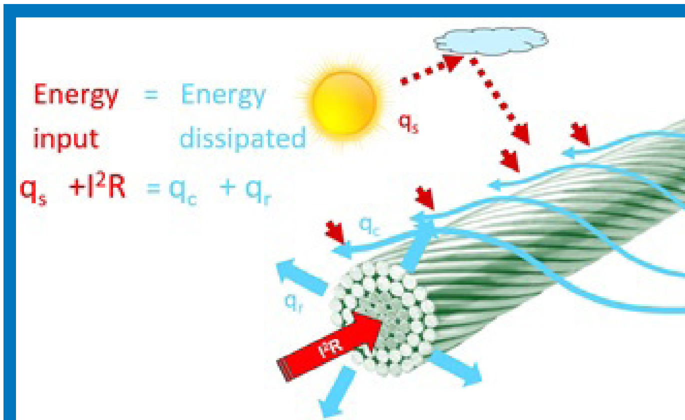


Figure 5. Heat Balance on a Conductor

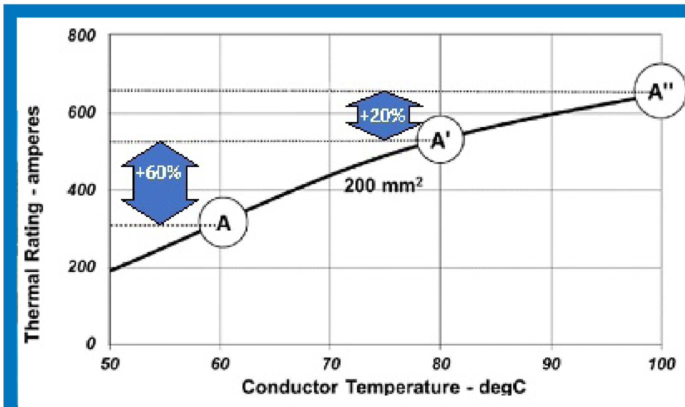


Figure 6. Ampacity vs. Conductor Temperature

Thermo-Mechanical Response of Conductor

Most conductor uprating initiatives are not constrained by the thermal limits of the material, but by the available clearance to ground. Simply put, higher currents result in higher conductor temperatures and expansion. This expansion increases conductor sag resulting in smaller conductor to ground clearances. Consequently, two important components are creep, and the effective thermal expansion coefficient.

ACSR conductors rely on the supporting strength of both Al strands and steel core, and consequently the medium- and long-term sag is characterized by non-recoverable Aluminum plastic deformation (creep). Although prestressing has been used to eliminate creep, time and safety implications during construction typically preclude this option.

Since the thermal expansion coefficient of Al is twice that of steel, the rate of expansion can be significantly reduced by using the steel core to carry the entire mechanical load. In Gap-type conductor or GZTACSR (Figure 2), this is achieved by a greased, de-coupled steel core. In non-decoupled constructions, such as ACSS, improved sag performance is achieved solely via a reduction in creep.

The lowest amount of MACT sag is achieved in carbon core variants (Figure 4), which are typically the only HTLS variants capable of leveraging the full thermal capacity limits of the conductor, since additional sag at MACT is often low enough to prevent clearance violations.

Conductor Options to Increase Capacity

Re-Tensioning of Conductors

Establishment of the precise conductor position, calibrated with respect to the concurrent conductor temperature, is the essential starting point for all capacity increase studies. This is often achieved through field or LiDAR surveys.

Re-tensioning of conductors involves removing the slack in spans that accompanies permanent stretch (creep) induced by years of service under thermal and mechanical load events.

Removing excess slack in conductors may be achieved by placing suspension points in travelers (Figure 7), pulling up the conductors to the appropriate level and taking up the slack at tension insulator assemblies. This procedure requires minimal new material and has a relatively low cost of implementation.

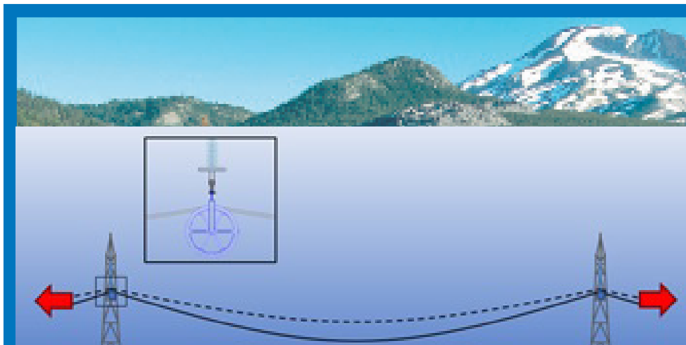


Figure 7. Re-tensioning of conductors

Re-tensioning may provide a moderate increase in capacity but is sometimes also required for safety code compliance and is also an appropriate technique when used in conjunction with voltage upgrading [3].

In some studies, especially those where lines are old and have a high probability of having experienced extreme climatic events, the allowable increase in transfer capacity following an uprating study may be negative (necessitating de-rating) if conductor creep has stretched conductor beyond limits assumed during design. Since re-tensioning operations have a minimal capital cost in comparison to other options, it may be an option where smaller increases in capacity are required. Re-tensioning is more likely to be used to complement other techniques such as re-rating studies and voltage upgrades.

Span-Specific Clearance Enhancement

The capacities of some transmission lines are limited by the clearance on only a few spans. These spans can sometimes be addressed by adopting HTLS conductors on that span, more compacted insulator assemblies, or obstacle removal. Significant advancements have been made to facilitate raising of structures under live conditions (Figure 8), which may be a cost-effective option where sufficient structural capacity is present in existing supports and foundations.

Figure 8. Raising of lattice tower for clearance enhancement [Courtesy of Ampjack]

Coated Conductors

Coatings on conductors have been developed to reduce absorptivity, and increase the emissivity of conductors, allowing greater heat dissipation, and theoretical increases of 10-20% in current for the same conductor temperature. The durability of such coatings is not proven and a subject of current EPRI research and future investigation. [2]

Reconductoring – Conventional Conductors

It may be possible to re-conductor overhead lines using larger traditional ACSR and AAAC conductor options where additional structural capacity is available. The original design parameters together with a condition assessment is required to establish structure limits to accommodate additional loads from larger conductors.

Transverse wind loads may potentially be reduced by using trapezoidal stranding (Figure 3) which enables approximately 20% of additional aluminum cross sectional area for an equivalent diameter.

More difficult to control, however, is the reduction of conductor weight, which translates into higher longitudinal loads, affecting both strain structures at angles and broken conductor loads.

Reconductoring – Non-Proprietary HTLS

Gap-type ACSR (GZTACSR) and ACSS conductors may offer efficient capacity increases in conditions where sufficient ground clearance exists. Gap-type conductor offers a lower expansion coefficient (1/2 that of Aluminum conductors), while ACSS expands at the same rate as ACSR, but with significant reductions in creep. Where clearance is not a constraint, increases of up to 100% are achievable.

Reconductoring – Proprietary HTLS

Proprietary HTLS conductors incorporate several aspects that enable increased power flow:

- The ability of conductor materials to accommodate temperature increases
- Reduced thermal expansion characteristics
- Reduced conductor weight and installed tension (in carbon core and ceramic composite core conductors)

While these conductors have been on the market for several years, there are still knowledge gaps regarding the installation, long-term performance and inspection methods for these conductors and their associated hardware. Many of these HTLS conductors have different installation requirements when compared to the traditional steel core conductors. Most failures of HTLS conductors experienced to date have been attributed to improper installation.

Despite being significantly more expensive (typically between 2.5 to 5 times the cost of equivalent ACSR), the majority of proprietary HTLS options offer capacity increases which would otherwise not be achievable with conventional or non-propriety conductors.

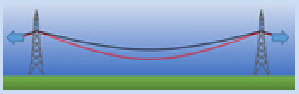
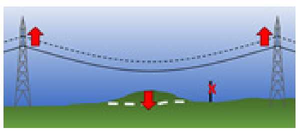
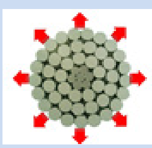
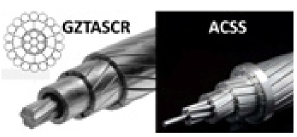
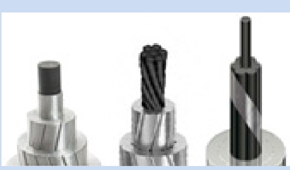
Where a carbon core is used, the expansion coefficient becomes negligible, allowing maximum operating temperatures of 180-200ºC.

Reconductoring an existing line with new HTLS (High temperature Low Sag) conductor has mostly been adopted when rebuilding the line is prohibitive from a network constraint perspective. In some cases, the cost of proprietary HTLS options may be comparable with the cost of building a new line.

In addition, experience has shown that additional care needs to be exercised when installing composite core conductors, which are more readily damaged than conventional steel core options.

For this reason, older generation, non-proprietary HLTS options, may also be a cost-effective option, and should be considered along with proprietary conductors.

Table 1. Conductor specific uprating options for increasing power flow

Option	Relative Cost	Typical Increase in Transfer Capacity*	Key Considerations
Re-tensioning 	Low	Low - Moderate 5-20%	Useful for compliance to statutory clearance following extreme events causing excessive creep, or in conjunction with re-rating or voltage upgrades.
Span-specific clearance enhancement 	Low-Moderate	Low Variable (<10%)	Obstacle removal not practical for entire line. Useful at specific clearance compromised critical spans. Structure raising may be possible on longer sections.
Coated conductors 	Moderate 1.2-1.5 x ACSR Cost	Moderate 10-20%	Durability of coatings unknown. Benefits reduced at night. Requires reconductoring, not readily applied to in-service conductors.
Reconductoring – non-proprietary HTLS 	Moderate 1.15-1.65 x ACSR Cost	**Moderate - High** **20-100%**	May be the most efficient solution ($/MVA added) Often constrained by clearance considerations
Reconductoring – proprietary HTLS 	High 2.5-5 x ACSR Cost	High 50-110%	Carbon core variants not constrained by ground clearance during MACT Excessive sag during in icing events on carbon core variants. Limited long-term experience Care to prevent damage during installation is critical. End of life Inspection technologies unavailable.

* Capacity increases based on ampacity increases from actual studies. Not including gains from re-rating.

Cost vs. Benefit

Table 1 highlights key aspects for these options. Low, or No-Cost options are potentially attractive where a moderate increase in capacity delays the need for more extensive upgrades.

Moderate cost options, which may utilize established, non-proprietary conductor technologies have been identified as preferred solutions in some studies as they can offer the highest capacity added per dollar spent.

High cost, high capacity re-conductoring options may be attractive as an alternative to underground cabling or other high-cost options, or where clearance constraints dominate.

Physical and Operational Implementation

Increasing power transfer using methods that concern work and upgrades solely on overhead conductor are attractive since they enable reduced outage duration compared to techniques that require more structure modification, such as voltage upgrades.

Reduced supply interruption impacts are also possible where live line construction methods are safely adopted especially on double circuit lines where the existing conductor can be used as the pilot wire for the new HTLS conductor, while the adjacent circuit remains energized.

In cases where live line work is not possible, the use of temporary supported insulated crane mounted lifts (Figure 9) may allow continued supply. In these cases, the management of induced currents and working grounds are important safety considerations.

Implementation Challenges and Maturity

Care needed during implementation is partially a function of product maturity, with the latest products carrying greater implementation risks.

Non-proprietary HTLS conductors are mature technologies with a relatively low installation risk, however there are currently no standards for HTLS conductors. Gap-type conductors do require an additional installation effort due to the need to de-couple the steel core from the outer conducting layers.

The low elastic modulus for carbon core conductors may lead to excessive sag during icing and extreme wind events. In some cases, this may be solved by selection of a larger carbon core.

Experience with installation of both composite ceramic and carbon core conductors has revealed that care to prevent damage during installation is critical, as damage to such conductors has been experienced where the bending radii limits have been exceeded. Recent iterations in some carbon core HTLS options have introduced multiple strand carbon cores (Table 1) to reduce the allowable bending radius, while other variants offer increased protection to the carbon core.

Knowledge Gaps

Notable knowledge gaps for HTLS conductor include:

- Improved installation procedures for newer generation conductors to prevent installation damage.
- Inspection and assessment of new HTLS conductors, including determination of carbon core integrity.
- Long-term durability of factory applied high emissivity coatings to conductors, some of which also purport ice-phobicity.
- Safe installation tensions for ACSS conductors, which have improved, and yet, unleveraged, self-damping characteristics.

Figure 9. Temporary support of energized phase conductors using insulated crane mounted lift [6]

How Can EPRI Support?

Over the last several years, EPRI has performed a significant amount of work to determine the impact of high temperature operation of overhead transmission lines on the conductors and associated hardware components.

The EPRI Conductor Aging Test Frame (Figure 10) allows simultaneous application of installed tension and thermal cycling, simulating 40 years of operation.

Performance of different HTLS conductors and fittings (Figure 11) has been validated by resistance, infra-red, direct temperature measurements, and x-rays.

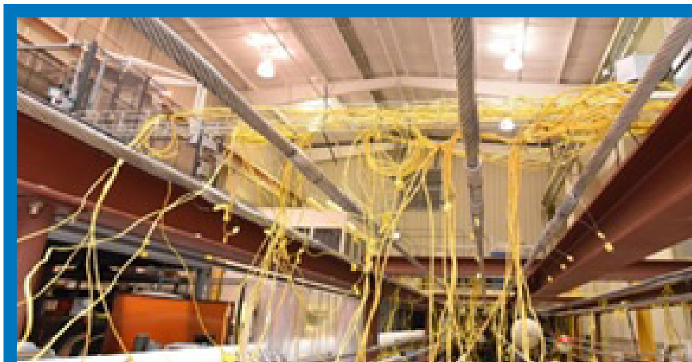


Figure 10. EPRI Conductor Aging Test Frame

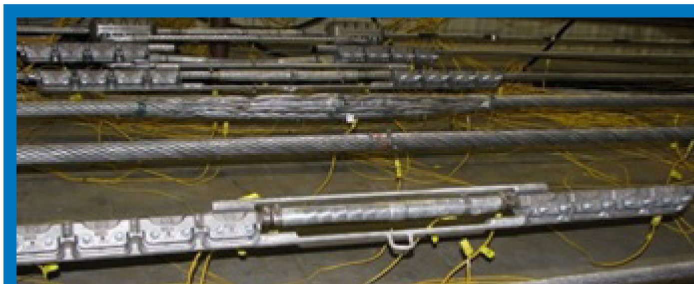


Figure 11. Shunt Device Testing

This work has revealed the vulnerability of compression connectors to high temperature excursions [7], failures of HTLS conductors, and has shaped industry standards, such as the IEEE 1283 Guide for High Temperature Operation.

HTLS specific software developed by EPRI includes the HTC Matrix (Figure 12), which highlights sensitive installation aspects, contains calculators to determine the effects of annealing and creep on conductors, AC and DC conductor resistance at elevated temperatures and conductor temperatures and time constants under different operating and weather conditions [8].

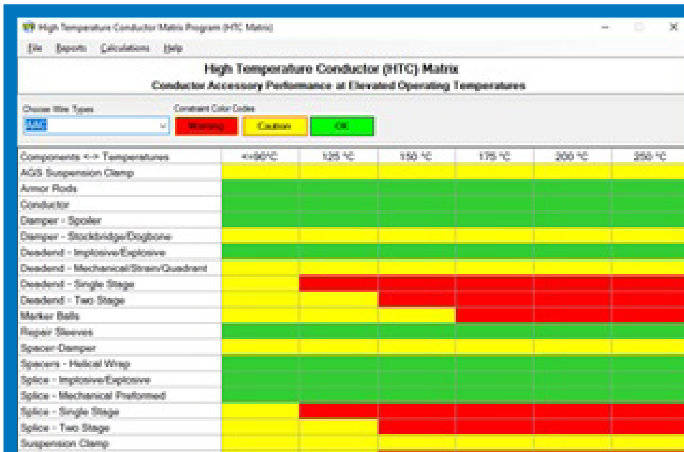


Figure 12. HTC Matrix Software [8]

EPRI has also developed a shorter-term qualification testing procedure for carbon fiber core conductors for utilities to include in their specifications. This test determines the thermal and mechanical performance of carbon core conductors and connectors in a relatively short period of time. Up to the end of 2020, only 40% of the conductors evaluated have passed the test, using specific criteria developed [9].

Other testing conducted has included determining the effects of rain on the performance of compression connectors, understanding the impact of improper connector installation, high temperature effects on marker balls and fired wedge connectors.

Two real-time monitored field trials of advanced conductors have been undertaken by EPRI. The first field trial evaluated 5 different conductors at 4 different utility locations [10].

Presently end of life inspection technologies for carbon/ceramic cored conductors are being investigated as well as guides for installation.

EPRI has developed a comprehensive guide [11] on the selection and application of HTLS conductors which is regularly updated with the latest information. This guide contains information on the different types of HTLS conductors currently available as well as several case studies of how utilities have applied these conductors in their transmission systems.

Conclusion

Reconductoring, re-tensioning, and advanced conductor technologies are one of the techniques to obtain a moderate increase in capacity. The approaches are well known and regularly used for small to moderate gains in capacity. When considering against other options a comprehensive evaluation which includes a) considers all practical options, and b) includes a life-cycle cost-based approach which quantifies the operational cost of running different solutions is required.

Significant advances have been made in the field of new HTLS conductors. HTLS conductors have the highest potential rating increases for existing lines, but also exhibit some sensitivity during installation and there is some unknown in terms of life expectancy and inspection techniques.

Improved care during installation is important to leverage the full capacity of these new generation HTLS options.

The large range of uprating options open to utility engineers lends itself to creative hybrid options where aspects of other increased transfer capacity solutions, such as combining uprating with forecast-based re-rating or real-time rating, may be combined to allow even greater increases.

References

1. Increasing the Capacity of Transmission Lines and Rights-of-Way. EPRI White Paper, Palo Alto, CA: 2021. 3002023004.
2. Dynamic and Ambient Adjusted Ratings. EPRI White Paper. Palo Alto, CA: 2021. 3002023333.
3. Voltage Upgrading Transmission Lines to Increase Power Flow. EPRI White Paper, Palo Alto, CA: 2021. 3002023334.
4. AC to DC Line Conversion. EPRI White Paper, Palo Alto, CA: 2021. 3002023332.
5. EPRI Increased Power Flow Guidebook–2020: Increasing Power Flow in Lines, Cables, and Substations (Platinum Book). EPRI, Palo Alto, CA: 2020. 3002019086.
6. Advanced Overhead Line Design–Interim Report 2: Advanced Solutions for Producing High Value Overhead Lines. EPRI, Palo Alto, CA: 2021. 3002022070.
7. Performance of Compression Fittings at Elevated Temperatures: Final Report. EPRI, Palo Alto, CA: 2009. 1018782.
8. High Temperature Conductor Matrix (HTC Matrix) v10.0: Resistance Calculator. EPRI, Palo Alto, CA:2020. 3002019092.
9. Carbon Fiber Core Conductor Qualification Testing: 2017 Test Results. EPRI, Palo Alto, CA: 2017. 3002010173.
10. High-Temperature Low-Sag Conductor Field Trial: Summary of Results. EPRI, Palo Alto, CA: 2018. 3002012674.
11. Guide for Selection and Application of High-Temperature Conductors. EPRI, Palo Alto, CA: 2020. 3002019096.

Glossary of Conductor Terms

- AAAC – All Aluminum Alloy Conductor
- ACAR – Aluminum Conductor Alloy Reinforced
- ACCC – Aluminum Conductor Composite Core HTLS conductor with fully annealed Al alloy
- ACSR – Aluminum Conductor Steel Reinforced conductor
- ACSS – Aluminum Conductor Steel Supported HTLS conductor with fully annealed Al alloy
- GZTACSR – Gap-type conductor utilizing ZTAl alloy
- HTLS - High Temperature, Low Sag (conductor)
- MACT - Maximum Allowable Conductor Temperature (often defined over a period, e.g., 1 hour)
- Continuous operating temperature: the temperature that a conductor can operate at continuously.

EPRI RESOURCES

Jean-Pierre Marais, *Technical Executive*
704.595.2495, Jmarais@epri.com

Program 35: 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.

3002023335 April 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