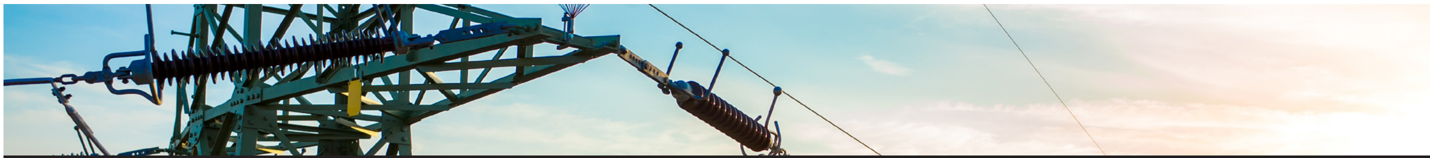
INCREASING TRANSMISSION LINE CAPACITY THROUGH RATINGS

March 2022



Introduction

Potentially low-cost methods to add capacity to overhead transmission lines are more accurate calculation of ratings, use of ambient adjusted or dynamic ratings, and use of conductor coatings.

Traditional overhead lines use static ratings based on assumptions related to worst-case conditions, such as high ambient temperature and low wind speed. When conditions are not the worst case, more current could flow down overhead lines without negative consequences.

This white paper:

- Provides an overview of how static ratings have traditionally been calculated
- Describes different approaches to addressing ratings to increase capacity and the potential increases in capacity
- Lists the considerations and gaps that need to be addressed when implementing these approaches
- Describes ongoing research and field testing presently under way to close these gaps

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Fundamentals of Line Rating

A line's rating is the maximum current that is allowed to flow through it. The maximum allowable current is determined by ensuring that the conductor systems do not exceed their maximum permissible temperatures.

Three factors may limit the maximum allowable temperature of a conductor system:

- Loss of strength due to annealing at higher temperatures. If a conductor loses strength, it may fail during wind or ice events. Often the maximum allowable temperature is 93°C.
- Reduced ground clearances at elevated temperatures. As conductors heat, they expand and consequently sag. Temperature limits ensure conductors do not sag enough to violate safety and legal requirements for physical clearances of other objects, such as vegetation. If clearance limits are exceeded, a line may flash over, which can reduce reliability, create hazards to the public, or contribute to wildfires.
- Increased risk of connector and hardware failure. Connectors, splices, and dead-end connectors, as well as hardware, are rated for specific conductor temperatures (often 93°C). If these temperatures are exceeded, the risk of failure increases.

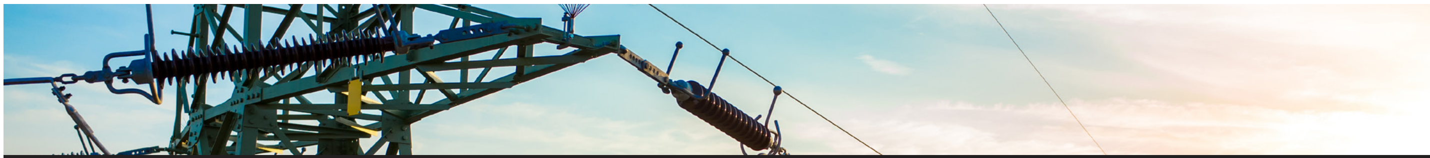
The maximum current that can flow in a conductor system is determined by heat balance equations. In North America, most utilities use the equations found in IEEE Std. 738. The conductor system rating is a function of the factors shown in Table 1.

Table 1. Relationship of line capacity and available capacity

Condition	Rating (Amps)
Air Temperature ↑	↓
Wind Speed ↑	↑↑
Sun Intensity ↑	↓
Conductor Emissivity ↑ (cooling in absence of wind)	↑
Conductor Absorptivity ↑ (rate of heating by the sun)	↓

The traditional approach to determine the static rating of a transmission line is to ensure that maximum allowable conductor temperature is never exceeded, even under worst-case conditions for the parameters shown in Table 1. Since utilities experience different conditions, they may select different worst-case values. Example values used are 40°C, 2 ft/sec wind speed, 96 watts/ft^2 solar radiation, 0.5 emissivity, and 0.5 absorptivity.

The minimum wind speed utilized in static ratings applies when the ambient temperature is at its maximum. This wind speed will not necessarily be the minimum at lower temperatures.



Some utilities adjust static ratings seasonally by changing the worst-case ambient air temperature and, at times, the solar radiation values.

Approaches to Increasing Ratings

Ratings are traditionally increased by increasing the size or number of conductors and/or elevating the conductors by re-tensioning or structure modifications.

The following advanced approaches are now being used to increase power flow:

- Reassessing the assumptions used to determine the static ratings through studies and field monitoring
- Implementing ambient adjusted ratings (AAR), which adjusts the forecasted and present ratings based on ambient air temperature
- Using real-time dynamic line ratings (DLR), which adjusts the present rating based on the measured wind speed, solar radiation, and ambient air temperature
- Improving the absorptivity and emissivity factors by coating the conductor

These methods all have advantages and disadvantages, are applicable in different situations, and are at different levels of maturity.

Each of these approaches is intended to send more current (amps) down the transmission line. If more current is sent when conditions are favorable, such as during high wind days, the conductors should remain cool and mitigate some of the consequences. Otherwise, the effects shown in Figure 1 will occur.

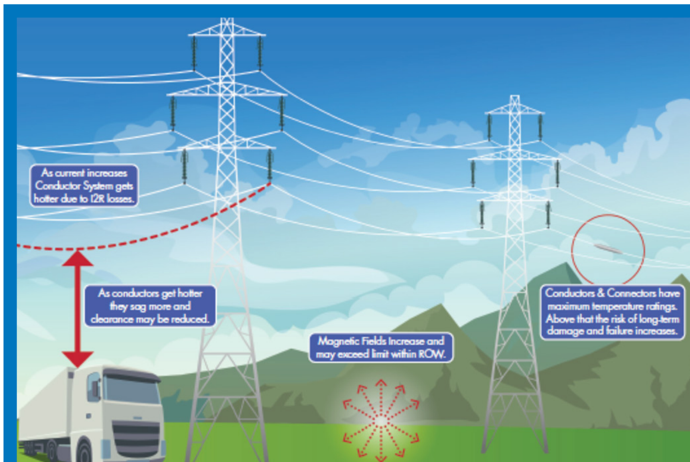


Figure 1. Effects of increasing current in lines

Adjusting Static and Seasonal Ratings with Studies

Ratings studies give utilities better insights into the conditions around their lines. They replace the assumptions about worst-case conditions with values based on statistical assessments of weather and risks.

Ratings studies involve collecting historical weather data in the areas around transmission lines. Statistics are used to identify why conditions are likely or unlikely. A utility will look for conditions that are near the worst-case scenario, such as peak temperatures. Studies can be improved by considering larger data sets, more complex statistics, and climate data that project potential future weather conditions.

The advantages of implementing ratings studies are more accurate ratings and improved understanding of system risks and expected component life. When ratings are accurate, utilities can make informed decisions about the costs and benefits of different line upgrade alternatives and plan future improvements.

The cost of a ratings study is a fraction of the potential savings from increased capacity or reduced component damage. Studies can be completed in less than a year when historical data are used and often in less than two years when right-of-way monitoring is performed. Utilities may opt to use both types of data to obtain the best results.

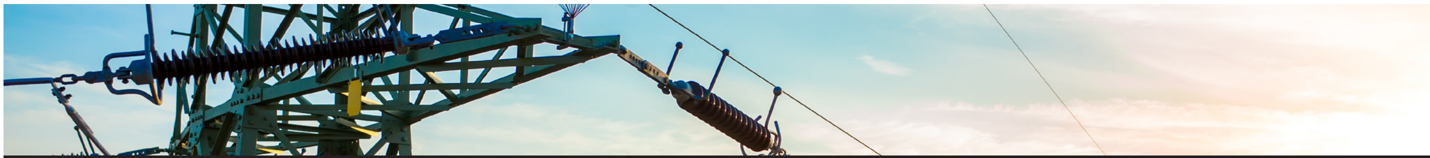
Validating the accuracy of historical weather data poses a significant challenge. In many locations, data from nearby airports are used. Research has indicated these data do not usually result in accurate ratings. Utilities using weather models must pick from a wide array of commercial and public models without knowing what is most appropriate for their lines.

Although this outcome is unlikely, a ratings study may show that the assumptions used for years are not conservative, and that the utility has been exposed to a higher than acceptable risk.

Ambient Adjusted Ratings

For AAR, all conditions in Table 1 are assumed to be static except air temperature. Therefore, the ratings will increase on cooler days and decrease on hot days.

Since ambient air temperatures can be reasonably accurately predicted, it may be possible to use them to predict the future rating of a line, accounting for inaccuracies in the forecast.



To implement AAR, a utility must either measure air temperatures at many locations in its service area or have very accurate weather models for air temperatures. These air temperatures can be transmitted to an operations center, where they are used to calculate ratings "on the fly."

AAR are relatively cost-effective since air temperature does not change dramatically over time or distance. Therefore, the models or sensors used to collect data can be less expensive than those for DLR.

A potential downside is that AAR can increase risks to utilities. A utility may increase a rating on a cool day. However, if the wind speed is below the assumed minimum value (e.g., 2 ft/sec), a line can easily operate >30°C hotter than was assumed. This can accelerate damage due to annealing and cause clearances to be violated.

The industry needs guidance on how to manage risks to systems when AAR are implemented. There is also a need for guidance on selecting appropriate weather models used to obtain air temperatures.

Dynamic Line Ratings

The concept of DLR is similar to that of AAR, but the amount of sun (solar heating) and the wind speed and direction are also considered. Having an accurate DLR is the closest a utility can come to knowing the true capacity of a line and maximizing its potential for power flow.

As with AAR, to implement DLR a utility must know the weather along the line. Presently, utilities can deploy weather stations for direct measurement of weather parameters or utilize sensors that measure conductor temperature or sag and calculate the weather parameters from these. Complex models that accurately determine wind speed/direction and solar radiation in real time are in the research phase.

Wind speeds change rapidly over time and distance, so DLR requires more weather stations than AAR.

DLR has three major advantages:

- It is the most accurate method to identify a line's rating.
- It does not increase risks based on weather conditions (unlike AAR).
- It can be combined with other uprating approaches to maximize capacity gains, as shown in Figure 2.

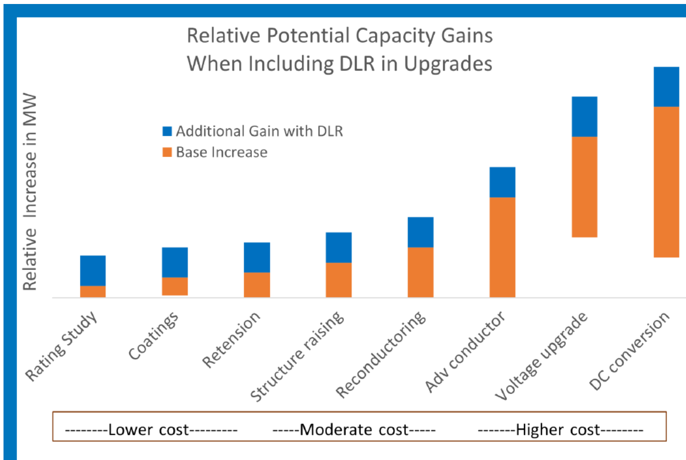


Figure 2. Potential capacity gains of DLR and other technologies

DLR does not add tension to conductors or mechanical stress to structures and foundations, as other uprating methods can. DLR also requires less capital cost and outage time.

The disadvantage of DLR is the additional complexity. DLR can change significantly over short periods. The need for more of weather stations or monitors also carries additional capital and O&M costs. Weather data can be collected in a right-of-way without an outage; however, installation of conductor monitors may require an outage or live work.

In some cases, vendors have deployed monitors that are not suitably accurate and can increase risks and liabilities for utilities. There is a need within the industry to develop and apply consistent evaluation criteria for commercial solutions. Ratings monitors can only measure present conditions, so they are not effective in forecasting future ratings.

Operators need processes, practices, and training on how to fully utilize DLR. These have not been well developed.

Conductor Coatings

The costs and benefits of AAR and DLR can be compared against those of alternatives, such as advanced coatings on conductors. Conductors get warmed by the sun and cool themselves by emitting infrared light. With many conductors, this process is not efficient. Coatings can be applied to make it harder for the sun to heat the conductor and easier for the conductor to emit its own heat.

To realize capacity gains, a utility can specify a coated conductor when designing a new line or reconductoring a line. Use of improved heating and cooling factors in line rating and clearance calculations can often increase ratings by 5–15%.

The main advantage of conductor coatings is the relative simplicity of the capacity gains. The coated conductor is installed and operated much like any traditional conductor, though some care is needed in preparing connections. A second advantage is consistency. AAR will decrease during a heat wave when increased power flow is critical; a coating will continue to provide capacity gains regardless of the weather conditions.

The disadvantages are mainly due to lack of industry experience with and independent testing of these products. Testing has suggested that in some cases, the capacity gains may be slightly lower than predicted. The longevity of these coatings is also unclear.

Summary of Advanced Approaches

Advanced line rating approaches may require conductor and weather monitoring equipment, as well as integration of accurate weather forecast models. When developing an advanced rating approach, cost, capacity, and risk all need to be accounted for, striking a balance between achieving efficiency and obtaining more accurate information.

Figure 3 compares the potential increased capacity from each of the advanced rating methods compared to a traditional year-round static rating (100%). When evaluating advanced methods, a utility must compare them to more traditional approaches with known risks, such as conductor re-tensioning, addition of more conductors, or structure modification.

When considering deploying the instrumentation needed for AAR or DLR, utilities need to consider:

- Field data and analysis needed either to determine the location and number of weather stations or to use data from other sources
- The selection and proper installation of weather stations and sensors to ensure accurate measurements
- The costs and benefits of implementing advanced ratings; these are not always well known
- O&M costs to maintain the instrumentation and ensure high-quality, reliable data
- Tools to visualize the data in operations and send new ratings to the energy management system (EMS)

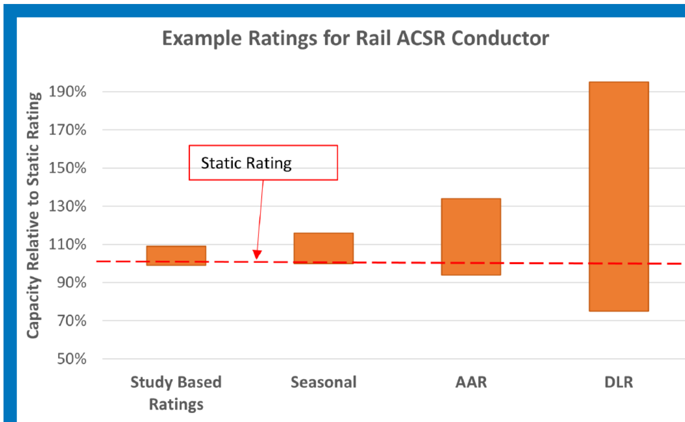


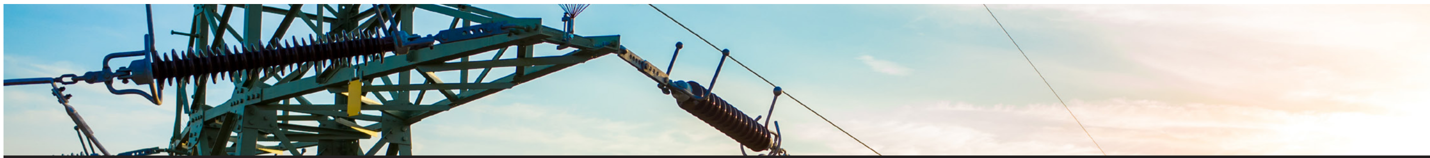
Figure 3. Example of advanced vs. static ratings (100% is a year-round static rating)

Present Industry Practices

In North America, static and seasonal line ratings are most commonly used. Some U.S. utilities have integrated AAR into control room operations, U.S. adoption of AAR will increase in the coming years due to FERC Order 881. In Europe, the DLR approach has been used and is gaining favor. In the United States, most DLR equipment deployed has been for ratings studies, rather than integration into control room operations.

Numerous utilities are reassessing the basis for their static and seasonal ratings. They are deploying instrumentation to measure local weather and line parameters for an extended period (>1 year) and determining the most appropriate values to use for static (seasonal) ratings. The expectation is that the traditionally assumed worst-case conditions almost never occur, and therefore the line will never be operated beyond its design limit. Having more data would enable utilities to adjust the worst-case values and thus assume more well-defined risk. In practice, field monitoring and research have shown in some cases that utilities using traditional static ratings already exceed true line capacity more than 10% of the time and may therefore should consider more conservative assumptions. Studies by the Electric Power Research Institute (EPRI) at multiple utilities are showing that in general, traditional seasonal ratings are too conservative in the summer but not conservative in the winter.

Static ratings may leave a significant amount of capacity unutilized. For example, studies are showing that the DLR may be above the static rating 90% of the time. The capacity can be as high as double the static rating during periods of prolonged high winds, as demonstrated in Figure 3. However, this implies that for 10% of the time the DLR is equal to or lower than the static rating.



In practice, lower capacity gains are realized as measures are implemented to reduce the frequency of rating changes in the control room. Typical capacity gains are closer to 3–7% for AAR and 20–40% for DLR.

Utilities using AAR often use look-up tables, with ratings for different ranges of air temperatures (for example, 70–80°F) on tables provided to both operations and market monitors. This is beneficial for operations teams as the rating will not change by the minute or hour. For example, the line rating only changes when the temperature goes below 70°F or above 80°F.

DLR improves the ability to understand the real-time conditions to optimize power flow, relieve congestion, and minimize curtailments. DLR does not allow forecasted ratings since the prediction of wind speed is uncertain. AAR has a greater potential to aid in forecasted ratings since ambient temperature prediction is more reliable. Seasonal ratings cannot be entirely replaced by AAR or DLR as they are needed for long-term planning and line design.

Implementation of AAR and DLR can be complex. The up-front cost of weather stations is small compared to the costs of field crew time for installation and engineering for integration, as well as ongoing maintenance. Once the initial data integration challenges are overcome, repeating this process on additional lines becomes routine, reducing cost and time to implementation.

Utilities should be aware that, as with any type of increased-capacity project, attention needs to be paid to relay settings, transient recovery voltages, circuit hardware, and EMS settings that may be affected by sending more power down the lines.

Key Questions from Utilities

Utilities are often concerned with how new methods and technologies will perform in the field. In many cases, vendors have claimed capabilities that have yet to be validated with independent, non-biased testing. Common utility questions involve:

- Durability, performance, and special design considerations for coated conductors
- Accuracy and reliability of field-deployed weather stations and line sensors for DLR
- Number of weather stations and line monitors required
- Locations for weather stations or line monitors
- Specification requirements and best practices for installing weather stations and line monitors
- Selection and performance of weather forecasting models
- Risk presently assumed with traditional static ratings and level of risk acceptable using more advanced methods

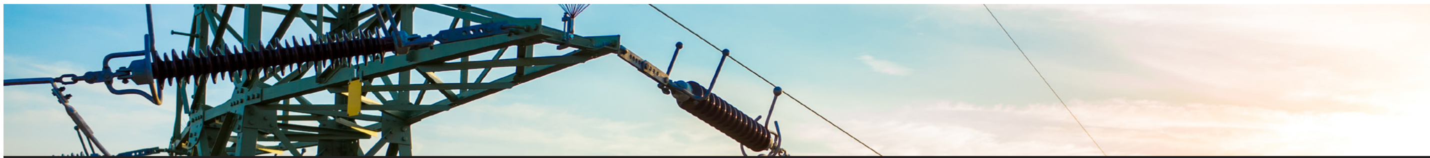
EPRI's Previous Contributions

EPRI has been increasingly active in ratings research since developing some of the earliest dynamic ratings software in the 1980s (DynAmp and Dynamic Thermal Circuit Rating [DTCR]). Research is ongoing to keep pace with advancements in technology and evolving utility industry requirements. EPRI has published guidance in the following areas to help utilities identify and apply accurate transmission ratings:

- Conductor emissivity is a variable in line ratings. Most ratings standards include assumed values; however, EPRI has unique test capabilities and can provide utilities with measurement results. Applying these findings improves rating accuracy and reduces risks [1].
- Accurate data collection is key to successful implementation of AAR or DLR. EPRI has published guidance on location and number of weather stations, as well as on implementation and management of risks related to solar heating and wind cooling of transmission lines [2, 3].
- Public and commercial weather models are being surveyed to identify what makes a model suitable for forecasted and real-time line ratings. Validations are under way in utility field trials [4].
- An assessment of increased-utilization projects completed by utilities was published in 2020. It compares DLR performance and other upgrade options, illustrating what utilities are doing for their capacity needs [5].
- EPRI has published and is continually enhancing guidance for operating conductors and line components at elevated currents, and consequently higher operating temperatures (see Figure 4) [6].
- EPRI's comprehensive *Increased Power Flow Guidebook* covers not only line ratings, but also substations, transformers, and underground cables [7].

Ongoing EPRI Initiatives

Although much work has been done in the field of ratings, significant research is still required to help the industry move forward. New utility goals to increase both environmental and economic efficiency require new ways of thinking as well as advanced technology solutions. To address these industry needs, research has been developed with several objectives, as shown in Figure 5.



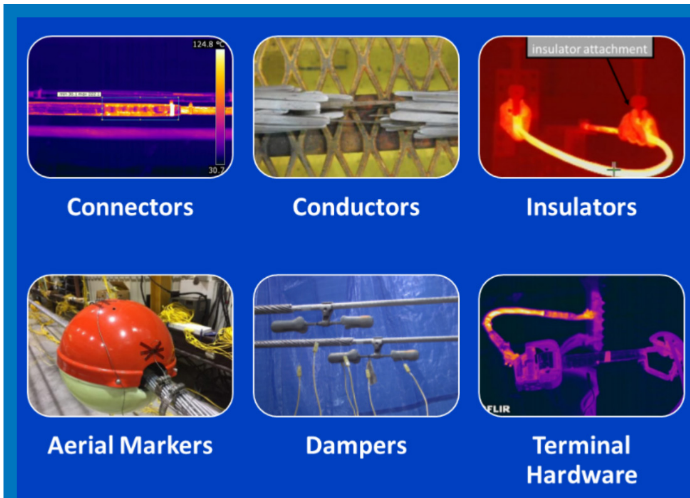


Figure 4. Components with thermal limits addressed in EPRI's high-temperature operation research

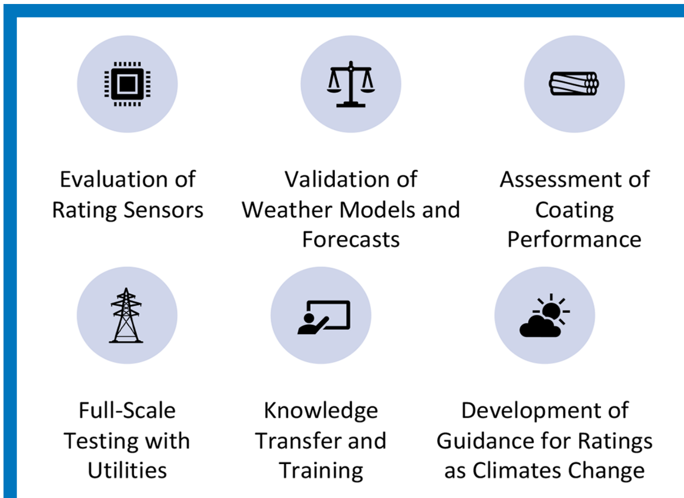


Figure 5. Activities under way to address ratings knowledge gaps

Full-scale field trials looking at weather models, weather forecasts, and commercial ratings sensors are all under way to provide utilities with a technical basis for decision making. Participants obtain comparative measurements to assess not only the accuracy of new technologies, but the risks they can pose to the system if they are not accurate.

The weather conditions that drive line ratings are not the same across a utility service area and are also changing over time. Guidance is being developed for installing weather stations in the most effective locations to minimize the number needed to rate an entire utility. Methods are being developed to handle how ratings are expected to change over time with increased extreme weather events.

EPRI also maintains a database of failed transmission line components, including conductors, connectors, and other hardware. As utilities seek to push lines to their full limits, failure rates may increase. Data related to such failures are collected and analyzed to provide improved inspection, operation, and maintenance guidance.

New methods to identify and compare ratings risk are being developed. These guide more effective implementation of advanced ratings methods. When a utility is looking at the relative costs and capacity gains of options, such as seasonal ratings vs. DLR vs. coatings, it can also assess the risks to its system.

Emissivity testing (which has predominantly been performed on aluminum conductor steel-reinforced [ACSR] conductors) is now being performed on advanced conductors and coated conductors to guide the accurate selection of ratings. New tests are also being developed and performed to determine the life cycle of the coating and identify any special maintenance or handling considerations.

These ongoing research efforts are open to additional utility participation.

References

1. *Conductor Emissivity and Absorptivity Database: Update of Test Results 2006–2020.* EPRI, Palo Alto, CA: 2020. 3002019088.
2. *Selection of Overhead Transmission Line Rating Criteria: For Radiative Heat Transfer.* EPRI, Palo Alto, CA: 2017. 3002010152.
3. *Selection of Rating Criteria for Convection (Wind) Considerations: New Recommendations for Treatment of Wind in Overhead Line Rating.* EPRI, Palo Alto, CA: 2018. 3002012667.
4. *Summary of Weather Data Measurements and Modeling: Use in Real-time and Forecasted Line Rating.* EPRI, Palo Alto, CA: 2020. 3002019087.
5. *Summary of Recent Increased Transmission Line Utilization Projects: 115 kV and Above.* EPRI, Palo Alto, CA: 2020. 3002020158.
6. *Guide for Operating Overhead Lines at High Temperatures: Effects of Increased Capacity by Increased Current Load.* EPRI, Palo Alto, CA: 2019. 3002015646.
7. *EPRI Increased Power Flow Guidebook—2020: Increasing Power Flow in Lines, Cables, and Substations (Platinum Book).* EPRI, Palo Alto, CA: 2020. 3002019086.

About EPRI

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Overhead Transmission

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