Lessons from first deployment of Dynamic Line Ratings

42 LineVision Sensors on
5 diverse AES lines

An AES | LineVision case study

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| Keywords

AES, LineVision, Dynamic Line Rating, Grid Enhancing Technology, Grid Modernization, Smart Grid

The U.S. electrical grid needs modernization at a speed and scale that requires adoption of technologies beyond status-quo solutions like new and upgraded lines and substations.

The magnitude and rate of change demands that we use technologies capable of timely and flexible deployment at cost-benefit ratios that ensure value to the end-consumers of energy. By making the most of existing grid assets and new investments, we maximize benefits for customers while managing change and diligently delivering reliability.

Dynamic Line Ratings (DLR), which is a system that uses real-time and forecasted conditions to continually calculate the thermal carrying capacity of lines, is just such a technology that flexibly unlocks grid carrying capacity faster and more affordably than status-quo solutions. Some DLR solutions, like that provided by LineVision, provide situational awareness about grid assets beyond the impact of ambient conditions on carrying capacity. The combined value of this DLR solution – improved ratings methodologies for efficient use of existing line carrying capacity and enhanced situational awareness of grid asset performance – improves the cost-benefit ratio for customers, allows for strategic investments and change, and increases grid reliability.

The Case Study shares AES' experience in selecting DLR and LineVision's solution as well as the planning for and the execution of deployment of 42 LineVision sensors across five AES transmission lines in Indiana and Ohio, each selected for their diverse characteristics and anticipated customer benefit. The Study summarizes initial results from the DLR system and highlights insights from lessons learned and next steps. The purposes of sharing information through this Case Study are to (a) increase market understanding of the beneficial uses of DLR and (b) accelerate future deployment of the technology throughout the U.S. electrical grid.

The grid modernization context

The U.S. electrical grid transmission system is a bottleneck. It is keeping us from connecting and delivering the renewable energy that customers want and need.[1] Unless the U.S. more than doubles regional transmission capacity,[2] the bottleneck and backlog of renewable projects will only increase with growing electricity demand.[3] The goal of a clean electricity system by 2035,[4] defined as part of the effort to address climate change, will be increasingly harder to meet.

Traditional infrastructure investments such as lines and substations fall short in delivering the transmission capacity needed to meet growing demand and achieve decarbonization goals. New lines can take 10 years to construct[5] and are among the most expensive investments made in the grid. New lines and line upgrades should, therefore, be carefully considered and deployed when the line owner lacks a less expensive alternative that meets at least the same objectives and is potentially faster. Utilities should be mindful of the potential economic impact that grid modernization and decarbonization could have on customers and make the effort to understand and incorporate additional technologies into their "toolbox". Among technologies that are particularly useful are those that can deliver grid and customer benefits quickly and affordably, making efficient and smart use of the existing grid.

Grid Enhancing Technologies (GETs) are hardware and software that enable utilities to dynamically expand transmission capacity quickly and cost-effectively on new and existing lines while protecting or improving grid reliability, safety, and efficiency.[6] DLR is a particularly compelling technology in the GETs toolbox because of its relative affordability and speed to deploy, but also because of the valuable data it provides about grid assets in the field and their ability to carry power. For certain DLR technologies, as will be demonstrated in the Case Study, the data extends beyond line carrying capacity to the larger context that the assets are in, such as vegetation, insulator type, and pole condition.

The dynamic and situational visibility into line carrying capacity is a significant improvement over static and ambient adjusted ratings (AAR). Traditionally, static ratings or seasonally adjusted static ratings, which are based on conservative assumptions like hottest time of day, full sun, and low wind speeds, have been used to apply protective approaches to grid reliability.

1. Lawrence Berkeley National Laboratory (LBNL), "Queued Up: 2024 Edition Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2023" (April 2024), accessed on Apr. 13, 2024 at https://emp.lbl.gov/sites/default/files/2024-04/Queued%20Up%202024%20Edition_1.pdf.
2. US Department of Energy (DOE), "National Transmission Needs Study" (October 2023), accessed on Feb. 21, 2024 at https://www.energy.gov/sites/default/files/2023-10/National_Transmission_Needs_Study_2023.pdf.
3. Grid Strategies, "The Era of Flat Power Demand is Over" (December 2023), accessed Feb. 21, 2024 at https://gridstrategiesllc.com/wp-content/uploads/2023/12/National-Load-Growth-Report-2023.pdf.
4. Ibid.
5. See generally, Grid Strategies, LLC, "Ready-to-Go Transmission Projects 2023: Progress and Status since 2021" (Sept. 2023), accessed on Apr. 8, 2024 at https://cleanenergygrid.org/wp-content/uploads/2023/09/ACEG_Transmission-Projects-Ready-To-Go_September-2023.pdf and at page 34.
6. The Brattle Group, "Building a Better Grid: How Grid-Enhancing Technologies Complement Transmission Buildouts" (April 20, 2023), accessed on Feb. 21, 2024 at https://www.brattle.com/wp-content/uploads/2023/04/Building-a-Better-Grid-How-Grid-Enhancing-Technologies-Complement-Transmission-Buildouts.pdf.

In exchange, they leave carrying capacity unused, particularly when the line is not experiencing worst-case conditions. AAR generally track closer to DLR as they take temperature weather modeling into account but lack the precision that DLR brings because AAR do not include insights about the physical context of the line, wind speed, or other factors. And, when DLR reveals ratings below static or AAR, it reveals opportunities to operate assets more safely and reliably. The core benefits of DLR alone are greater capacity and, critically, more accurate ratings that are informed by actual conditions in the field.

These benefits of DLR technology were among the reasons why AES decided to engage in an initial deployment of the technology to better understand what, where, and how much benefit could be extracted from the technology on different types of grid assets and under varied environmental conditions. A unique customer benefit was also identified for each line selected for the deployment so that the hypothesized benefit could be eventually verified and quantified with generated data. The overall objectives and basis for line selection are discussed in the next section of the Case Study.

In selecting the DLR technology provider with whom to partner, AES considered certain key characteristics. First, the experience of LineVision and perceived accuracy and reliability of the line rating solution was of key importance. Second, the safety characteristics of the solution and ability to install and maintain the solution simply without the need to take an outage was important – the LineVision solution is mounted on existing structures requiring basic working at height protections. Third, the method of deploying sensors provided confidence in the flexibility of the solution, specifically that future technologies could be added if desired to provide expanded situational awareness or that the sensors could be moved. Fourth, AES is committed to cybersecurity compliance (e.g., NERC CIP) and appreciated LineVision's approach to ensuring secure and reliable data to protect grid operations. Finally, AES found LineVision to be a committed partner to delivering valuable outcomes important to AES and our customers, which partnership has been demonstrated at each step of the deployment.

Objectives and line selection

AES had several key objectives when defining the deployment project described in this Case Study. As described further below, they related to: (1) learning about the benefits of DLR to AES' unique grid topology to later apply those insights to strategically planning and improving grid capabilities; (2) increasing the number of tools at AES' disposal that enable us to make efficient use of the existing AES grid, unlocking carrying capacity affordably and quickly; (3) ensuring the reliability and safety of the AES grid in a changing electricity system context, and; (4) selecting a variety of asset types and customer use cases to gain well-rounded insights into tool capabilities, opportunities for scaling, and prioritization of future deployments.

(1) **Understanding Benefits of DLR:** An existing barrier to scale deployment of DLR is a clear understanding and quantification of the benefits of the technology in both operations and planning. For DLR to be fairly evaluated against other options, its cost-benefit ratio must be as clearly understood as a typical line reconductoring investment. AES believes that visibility into the dynamic headroom, or carrying capacity, of transmission and sub-transmission lines will have efficiency and reliability gains for our customers. We also believe that unlocking grid capacity headroom will allow for more cost-effective delivery of increasingly renewable energy. When insights from operational DLR data are applied to planning forecasts, this should enable connection to the grid of new energy resources at lower cost.[7] We believe that these numerous benefits will make DLR a building-block technology of the future smart transmission grid.

(2) **Efficient Use of the Grid:** The electrical grid is built to deliver energy to end-consumers, our AES customers. We are, therefore, stewards of the resource for the benefit of our customers and are continuously learning about tools that can help us improve service and efficiency. AES believes that DLR is a technology that has great promise for unlocking grid carrying capacity affordably and quickly and provides an alternative approach to traditional lines and substation upgrade approaches that should be considered in strategic planning.

Additionally, the speed at which loads are growing or coming into our grid footprint means that having a solution that can be deployed quickly helps us provide timely improvements to meet the needs of our customers.

(3) **Reliable and Safe Delivery:** While many arguments for the deployment of DLR are made based on the technology's ability to expose additional headroom in lines, AES believes that there is equally important value in understanding when the actual dynamic carrying capacity of lines may fall below currently used static or ambient adjusted ratings. A more precise measure of dynamic ratings allows grid operators to more precisely tailor energy flow across the conductor to prolong the life of grid assets and ensure reliable and safe delivery of energy services. System reliability is also improved when increased thermal capacity allows us to use lines that would be considered constrained under static or ambient adjusted ratings. DLR thus increases operational flexibility for grid operators when the system is in an abnormal state due to a planned or unplanned event.

(4) **Proof Points for a Variety of Assets and Use Cases:** AES understands that grid topology matters as does asset type, condition, and context. Customer needs are similarly numerous. Therefore, a deployment that intentionally selects diverse contexts for technology deployment allows for well-rounded insights to support AES and system learning and future scaling of the technology to benefit all customers.

An additional set of benefits from AES' choice to deploy DLR on a diverse set of lines in both its AES Indiana and AES Ohio footprints is the validation and enhancement of LineVision's technology for various grid contexts. For example, LineVision will complete this deployment with: (i) additional proof points of DLR deployment on higher voltage 345kV transmission lines; (ii) a more precisely trained solution for less commonly monitored sub-transmission lines, such as 69kV; and (iii) approaches for accurate Dynamic Line Ratings on older – but common – assets like single wood poles and post-insulated lines.

7. The AES Corporation, "Smarter Use of the Dynamic Grid: Accessing Transmission Headroom Through GETs Deployment" (April 2024), last accessed on Apr. 12, 2024 at https://www.aes.com/blog/geting-ahead-leveraging-dynamic-grid.

Notable additional benefits from the deployment discussed in the Case Study are that (a) the deployment across multiple lines in a utility service territory provides the opportunity to study any compounding benefit of DLR and (b) by spanning multiple Regional Transmission Operators (RTOs), the deployment will provide insights and opportunities for application into operations and eventually planning for both PJM and MISO.

These objectives guided the AES and LineVision team members as they engaged in a workshop to identify candidate lines for which DLR could provide measurable benefits. Before the workshop, AES generated a list of lines in its utility footprint for which it thought real-time monitoring could deliver customer and operational benefit. Lines at the top of the list were those with: (i) known or expected constraints; (ii) reliability risk; or (iii) planned investment.

During the workshop, AES and LineVision reviewed the list of lines for those that were thermally limited by the conductor – or could be so limited with an inexpensive upgrade of a next-limiting element. Using information like that included below in Table 1, AES and LineVision considered line location, conductor type, and ratings methodology, in addition to customer benefit and the line's contribution to defining a diverse set of lines with different voltage levels and construction practices, in different terrain and regions throughout the AES system.

Table 1. Anonymized Sample List of Candidate Lines, Including Deployed Lines (highlighted)

Anonymized line number	Anticipated customer benefit	Anticipated utility benefit	Confirm conductor as limiting element
69kV-1 (Rural)	Connection of a "step-load"[8] customer	Reduced impact from construction outages	After relay replacement
69kV-2 (Rural)	Connection of a "step-load" customer	Reduced impact from construction outages	Yes, 2 MVA available
69kV-3 (Rural)	Improved reliability	Reduced N-1 reliability risk[9]	Yes, 8 MVA available
138kV-1 (Urban)	Improved reliability, reduced energy costs	Lower startup costs for gas peaker plant	Yes, 81 MVA available
138kV-2 (Urban)	Improved reliability, reduced energy costs	Lower cost congestion reduction	Yes, 78 MVA available
138kV-3 (Urban/Rural)	Improved reliability, reduced energy costs	Lower cost congestion reduction	Yes, 100 MVA available
138kV-4 (Rural)	Reduced energy delivery costs	Lower cost congestion reduction	Yes, 78 MVA available
69vK-4 (Rural)	Reduced energy delivery costs	Reduced grid upgrade costs	Yes, 25 MVA available
69kV-5 (Urban)	Reduced energy delivery costs	Reduced grid upgrade costs	After breaker replacement
345kV-1 (Rural)	Connection of a "step-load" customer, cleaner energy	Reduced impact from construction outages, connect clean energy	Yes, 138 MVA available

8. "Step-load" means the addition of a material amount of load in a single new connection. This commonly occurs with the addition of a data center customer or industrial load.

9. N-1 refers to the state of transmission system after the loss of a single element such as a line or breaker.

To support AES' selection of five lines from the ten short-listed in Table 1, LineVision generated profiling studies for each of the ten lines. To create the DLR profiling studies, which includes summary charts and statistics like those in Chart 1 and Table 2, below, LineVision needed information related to current line rating methodologies, conductor type and limiting element, and utility KMZ files. LineVision's data science team used these inputs, along with several years of historical weather data to run a historical thermal heat balance equation as described in IEEE Standard 738 to predict how much additional capacity could have been available on the lines had DLR been in place.

Chart 1. Anonymized Hourly Heat Map from LineVision DLR Profiling Study for Line "138kV-3"

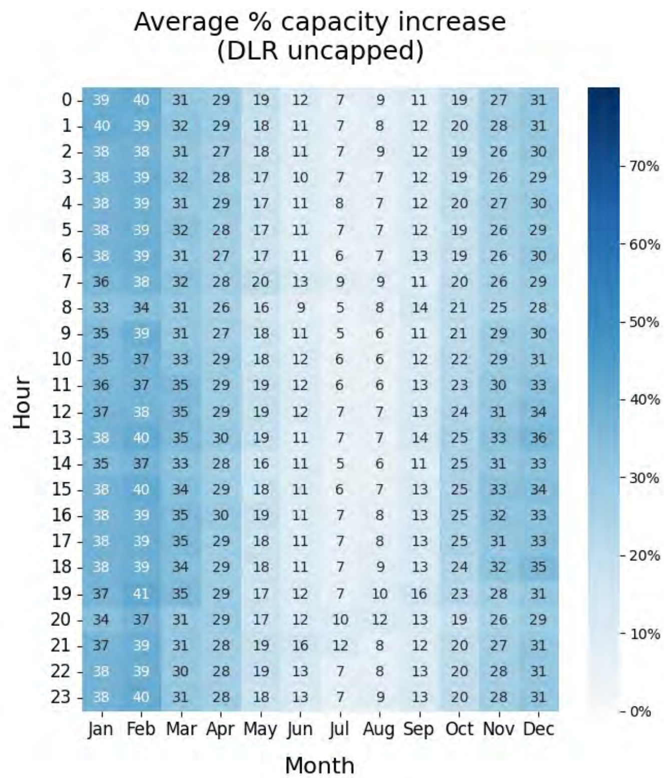


Table 2. Anonymized Estimation of Percentage Carrying Capacity Increase and Time that DLR Would Exceed Static Line Rating by Seasonal Variation Used in Static Ratings[10]

Anonymized line number	Summer average % capacity increase	Winter average % capacity increase	Summer % of time DLR > Static	Winter % of time DLR > Static
345kV-1	27%	81%	94%	100%
138kV-2	19%	55%	93%	100%
138kV-3	9%	35%	76%	99%
69kV-2	23%	9%	90%	72%
69kV-4	21%	7%	90%	70%

10. AES uses both all-season and seasonally-adjusted static ratings depending on the line location.

Image 1. Image of LineVision's LUX sensor

Using the data insights generated for the DLR profiling studies, AES and LineVision prioritized the five lines highlighted in Table 1, above. For the selected lines, AES provided more detailed line information including PLS-CADD reports and engineering design and construction documents. LineVision used this information to inform the number and location for placement of LineVision LUX sensors, which use LiDAR sensor technology mounted to transmission structures to measure conductor position to determine information such as the sag, blowout, average conductor temperature for the stringing section, and DLR.

There were several important asset characteristics that had direct impact in determining the number and placement of LineVision sensors. Critical considerations for deployment included changes in: (a) heading; (b) building or tree density; (c) topology; and (d) conductor construction (e.g., ACSR Drake vs. ACSR Penguin). Each of these characteristics are impacted by local weather conditions, wind speeds, and (ultimately) the maximum amperage capacity of the asset. Capacity limitations also exist for each stringing section, so dead end structures must be taken into account. LineVision models wind speeds and directions based on several of these inputs to ensure that the most limiting stringing sections are monitored by sensors across a variety of weather conditions. This enables an accurate calculation of capacity for the asset while guaranteeing the most efficient placement of sensors along a monitored line.

With lines identified and requirements for 42 sensors parameterized, AES and LineVision teams could move on to prepare for installation. From the initial agreement to pursue a deployment project through scoping of potential lines to delivery of the profiling studies and recommended installation location scope, the teams spent just under 8 weeks. AES and LineVision were energized to keep the momentum going.

Installation experience

Installation of the 42 LineVision sensors on AES' 5 lines in Indiana and Ohio occurred safely, efficiently, and quickly. Total installation time took less than two weeks with an average sensor installation time of approximately 30 minutes, excluding travel time. The installation process can be summarized in four steps:

(1) **Installation Plan and Pre-Briefing:** LineVision developed an installation plan for sensor deployment on AES' Indiana and Ohio grids. They conducted a comprehensive pre-installation briefing with AES operations and line crew personnel. At this meeting, the teams reviewed site access requirements, line clearance, and other safety considerations. LineVision also provided an overview of the hardware to be installed and the method for installation. LineVision made pre-installation site visits to each sensor location to identify any unique conditions and develop an installation plan. LineVision provided all necessary hardware, including mounting brackets and bands to secure sensors to existing structures. AES line crews contributed hand tools and ladders, embracing collaborative work.

(2) **Safe and Efficient Installation:** A LineVision engineer conducted on-site training for the AES line crew to support safe and efficient installation. The training familiarized AES' line crew with the DLR technology and its deployment. LineVision's engineer remained on-site during installation, supervising the process to ensure accuracy and adherence to safety protocols. The installation process was extremely straightforward and the AES line crew expressed excitement to learn about the actual, dynamic capacity of the lines. The sensors are installed approximately 15-20 feet above grade on the structure, well outside the minimum approach distances for live conductors. No outages were required and there was no disruption to grid operations. With basic training, two 30-foot ladders, and standard hand tools, the AES crew seamlessly deployed the DLR sensors. Remarkably, only one of the 42 sensors needed relocation to the other side of the same tower – an installation oversight promptly corrected due to the proximity of the work to the ground. All the other 41 sensors were installed correctly on the first effort and immediately started generating data about line conditions.

Scan here to view aerial video from the installation process

Image 2. Collection of still images from installation of LineVision sensor in AES Indiana

(3) **Data Collection and Model Enhancement:** On installation the LineVision sensors began collecting data immediately. Indeed, while AES people were in the field they could already see data plots populating. LiDAR readings from the sensors were securely transmitted to LineVision's ratings platform. LineVision collaborated with a local engineering firm to conduct LiDAR-enabled drone flights over each monitored span, establishing a baseline model. One location experienced a two-week delay in completing overhead drone flights due to airport approval requirements for access to airspace. AES localized LineVision's base model by providing historical line loading data from its SCADA[11] system through a batch data process.

(4) **Delivery of Line Ratings:** Once a localized model was built for each of the five AES lines, LineVision further trained the base model with three months of AES loading data. To create the model, three steps are performed. First, Computational Fluid Dynamics are run for the transmission corridor to understand how the wind is expected to move across terrain and includes the hyper-local physical features that regional wind data does not show. Topography and vegetation data are used to model the wind speeds and directions of every span on the transmission line. This allows precision wind calculations in very localized terrain where hills, valleys, trees, bushes, and buildings greatly impact the cooling available from wind for many spans.

Second, Blowout, the horizontal displacement of the conductor is analyzed. Blowout measurements can be used to, in effect, turn the transmission conductor into a hyper-local anemometer and directly calculate the perpendicular wind speed from this movement. While the horizontal position of the conductor is known from the LiDAR measurements, the perpendicular force necessary for the conductor to be physically located at that position, and thus the wind speed, can be calculated. This calculated wind speed is representative of the net effective wind speed along the entire span, a far more accurate measure than a single-point wind speed from a weather station. Third, and finally, loading data and local weather data are paired with LiDAR observations of the conductor's position to build a sag-to-temperature curve. Conductor sag can be used to determine the average temperature of the entire stringing section, which includes many spans. CIGRE TB 498 makes recommendations on how to define and build the sag-to-temperature curve for a conductor as a means to understand transmission line capacity with the maximum operating temperature as the limiting factor.

With three months of training, LineVision was able to develop dynamic ratings for the two of the five transmission lines that were similar to lines on which DLR is more commonly deployed. The other three lines would need more training to be ready (see the Insights section, below for more details). Certain AES people were provided credentials to access the LineVision cloud platform to view data and line rating results. Historical ratings and 240-hour ratings forecast for each line were provided through an interactive dashboard.

In sum, the installation of the LineVision sensors was a safe, simple, and efficient process. Generation of Dynamic Line Ratings for lines fitting a common DLR transmission profile (e.g., 345kV-1 with steel structures, wide rights of way, and few changes of heading), were similarly straightforward. For the less common line types, more refining of data and models was and will be needed. Both types of learnings are shared in the Insights section, below.

11. Supervisory Control and Data Acquisition

Insights into early rating results and extension of models

Top level learnings from first deployment of Dynamic Line Ratings on a diverse set of lines in AES' Indiana and Ohio footprints are three:

(i) There are "common" transmission lines for which DLR models are currently experienced and ready "out-of-the-box". These are extra high voltage lines on steel structures with suspension-type insulators.

(ii) There are high voltage and sub-transmission lines that may benefit from DLR that have not been modeled typically and may require additional model training to return verified ratings. These lines include lines that may be older in construction and supported by wood poles with post-type insulators. These characteristics can cause movement in poles resulting in greater variations in line sag, which arguably provides additional safety and reliability arguments for dynamic awareness of actual line carrying capacity measurements.

(iii) DLR has provided improved situational awareness and an opportunity for informed decision-making in all five deployments, which will inform next steps for each line.

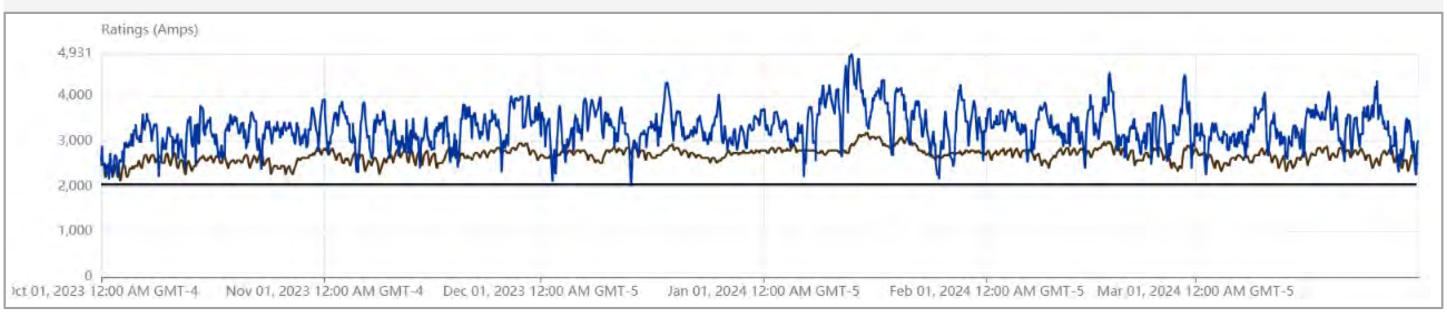
The rest of this section starts with early results from winter months (October 2023 through March 2024) for a 345kV line in the AES Indiana footprint (anonymized to "345kV-1") and a 69kV line in the AES Ohio footprint (anonymized to "69kV-4"). The section then highlights the material differences present in the three other deployed lines (anonymized lines "69kV-2", "138kV-2", and "138kV-3") that require additional data and model training to extend reliable insights from dynamic line rating models to those lines.

A. 345kV-1 (October 1, 2023 through March 31, 2024)

The first of the five demonstration lines (anonymized as "345kV-1"), was selected because AES is aware of significant anticipated economic development in the area served by the line, which could result in two incremental additions of step-change load. While the first step-change addition might result in loading still under the line's existing static rating, a second step-change addition would potentially create overloads. Even without the second step-change load addition, AES anticipates that line outages will be needed during related construction and will cause increased load across line 345kV-1, for which visibility into total line headroom can enable uninterrupted operation for all grid customers. In addition to the growing load, several solar generation projects are in various stages of development in the area and AES anticipates that additional carrying capacity will be required to support delivery of the generated energy.

Line 345kV-1 currently uses an all-season static line value of 2043 Amps. The first six months of DLR data for line 345kV-1, which represent typically cooler periods of the year, evidenced a high DLR rating of 4931 Amps, or 141% increase over the static value. The DLR values represent the most likely (50th percentile) rating for the line for each hour based on uncertainties of each input variable. The lowest DLR rating was 2003 Amps, or a 2% decrease from the static value.

Chart 2. Time Series of Line 345kV-1 line ratings, including DLR, AAR, and static ratings



DLR is in blue, AAR is in brown, and static ratings are in black.

The data show that the headroom gain on the line with DLR is relatively consistent and significant. The mean, or average, DLR value during the six-month period was 3294 Amps (61% increase over static). The median (or middle) DLR value was 3279 Amps (60% increase over static), close to the average value. The mode, or most frequently occurring DLR value, was 3038 Amps (49% increase over static). The standard deviation is 13% from the mean.

In comparison, AAR values show only a 5% standard deviation from the mean and were calculated based on historical weather information and AES-provided AAR lookup tables. AES Indiana's AAR assumptions include 2 mph wind at a 67.5-degree angle and maximum solar gain. The mean AAR value during the six-month period was 2687 Amps (32% increase over static). The median AAR value was 2685 Amps (31% increase over static). The mode was 2792 Amps (37% increase over static).

Table 3. Summary percent increases for line 345kV-1 over static ratings and AAR

Measure	Static rating	AAR
Average % Capacity Increase of DLR over Rating	61%	23%
% of Time DLR > Rating	100%	95%
% of Time DLR > Rating+5%	100%	89%
% of Time DLR > Rating+10%	100%	82%

DLR is consistently higher than the year-round static line rating and the AAR, indicating that the effective cooling wind speed is regularly higher than the fixed wind speed and wind angle assumptions used in the static and AAR methodologies.

The frequency that the DLR rating for line 345kV-1 exceeded the static rating or AAR for that line can be represented on an 8760 hourly basis in the heat maps on the following page, which helps visualize how ratings change over the course of the day and year, in this instance limited to six months due to the available data.

Chart 3. "8760" Heat Map for line 345kV-1, DLR > Static, limited to six months of available data

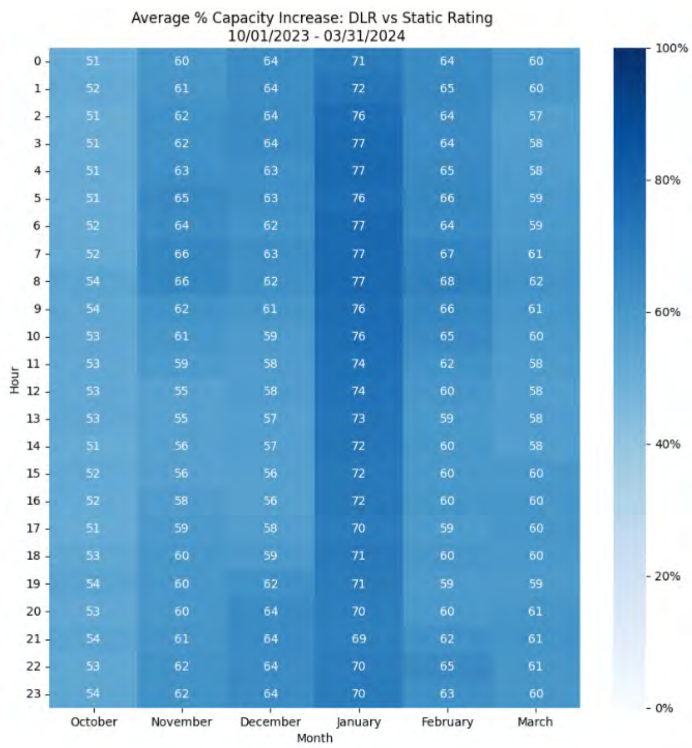
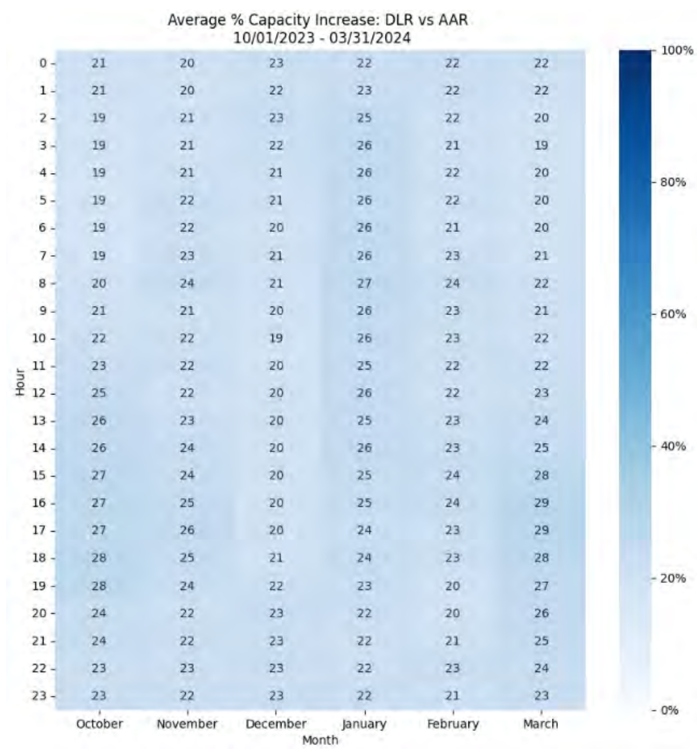


Chart 4. "8760" Heat Map for line 345kV-1, DLR > AAR, limited to six months of available data



LineVision DLR insights in Charts 5 and 6 below also show that certain segments of a line can create the overall line constraint, providing utilities an opportunity to strategically consider maintenance or investment strategies targeting specific constraints, such as asset upgrades, vegetation management, or additional data collection.

Chart 5. 345kV-1, Segment 1 (March 1 through March 15, 2024)

DLR is in blue, AAR is in brown, and static ratings are in black.

Chart 6. 345kV-1, Segment 3 (March 1 through March 15, 2024)

DLR is in blue, AAR is in brown, and static ratings are in black.

Line 345kV-1 characterizes a category of technologically "no-regrets" upgrades for which DLR provides consistently higher-than-static values and frequently higher-than-AAR values. Higher voltage lines on steel tower or pole construction are often located in wider rights of way and have a higher conductor height above ground, resulting in better cooling and less vegetation obstruction. These structures also generally experience less movement and use suspension-type insulators that allow the line tension to equalize between attachment points. Higher voltage lines are also generally designed to have fewer changes in headings than lower voltage lines (i.e., they run straighter) because of the higher costs associated with angle towers. These construction characteristics have the added benefit of generally requiring fewer sensors to monitor the line, reducing the overall cost of the deployment. Finally, higher voltage lines typically have better monitoring and construction records (e.g., PLS-CADD models), which help deliver a highly accurate computational fluid dynamics model and related DLR value.

If a load growth, reliability, congestion, or similarly beneficial narrative supports the comparatively modest investment in DLR technology, these types of lines present a use case for rapid scaling for the U.S. electrical grid. Indeed, when compared to traditional solutions to increasing carrying capacity, DLR is a powerful option.

Table 4. Comparison of cost and time for a 20-year DLR project versus reconductored asset

Measure	DLR	Reconductoring
Average Capacity Delivered	>50%	50%
Cost	$45K per mile[12]	$590K per mile[13]
Time to Operational	9 months	2 years
Outage required	None	1 week per mile[14]

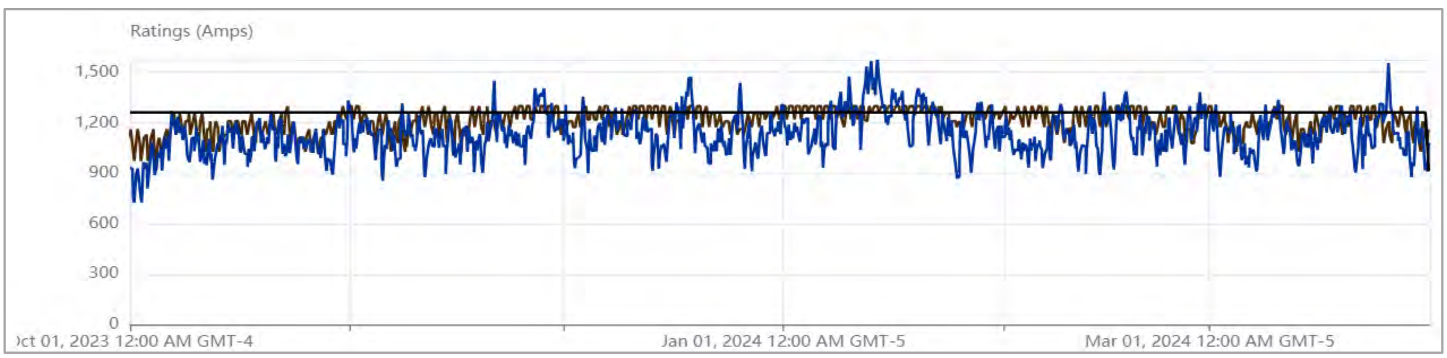
12. Includes 20 years of software costs.
13. MISO Transmission Cost Estimation Guide, last accessed Apr. 8, 2024 at https://cdn.misoenergy.org/MISO%20Transmission%20Cost%20Estimation%20Guide%20for%20MTEP23337433.pdf
14. MISO Transmission Planning Business Practices Manual BPM-020-r30, last accessed Apr. 8, 2024 at https://www.misoenergy.org/legal/rules-manuals-and-agreements/business-practice-manuals/

B. 69kV-4 (October 1, 2023 through March 31, 2024)

The second of the five demonstration lines (anonymized as "69kV-4"), was selected because AES identified regular thermal overload from energy generation sources at one end of the line. Mitigation of the overloads through DLR is expected to be a lower-cost option than traditional upgrade methods for the line and, not unlike with line 345kV-1, DLR should help manage power flow changes in the electrically related system anticipated from construction outages that support planned transmission upgrades. Finally, DLR on line 69kV-4 provides general grid reliability reinforcement for the area as a heavily used line.

Line 69kV-4 currently uses a winter-seasonal static line value of 1262 Amps.[15] The first six full months of DLR data for line 69kV-4 evidenced a high DLR rating of 1578 Amps, or 25% increase over the static value. The lowest DLR rating was 711 Amps, or a 44% decrease from the static value.

Chart 7. Time Series of Line 69kV-4 line ratings, including DLR, AAR, and static ratings



DLR is in blue, AAR is in brown, and static ratings are in black.

The data initially showed that (as compared to winter-seasonal ratings), DLR was variably above and below the seasonal static rating, as was AAR. The mean, or average, DLR value during the six-month period was 1135 Amps (10% decrease from static). The median (or middle) DLR value was 1131 Amps (10% decrease from static), close to the average value. The mode, or most frequently occurring DLR value, was 1125 Amps (11% decrease from static). The standard deviation is 10% from the mean.

In comparison, AAR values show only a 6% standard deviation from the mean and were calculated based on historical weather information and AES-provided assumptions of 2 mph perpendicular wind and maximum solar gain. The mean AAR value during the six-month period was 1214 Amps (4% decrease from static). The median AAR value was 1220 Amps (4% decrease from static). The mode was 1300 Amps (3% increase over static). The proximity of seasonal-static ratings and AAR is not surprising as both are derived from an awareness of weather patterns. However, they both lack the precision of DLR, which considers actual readings of both physical and ambient conditions.

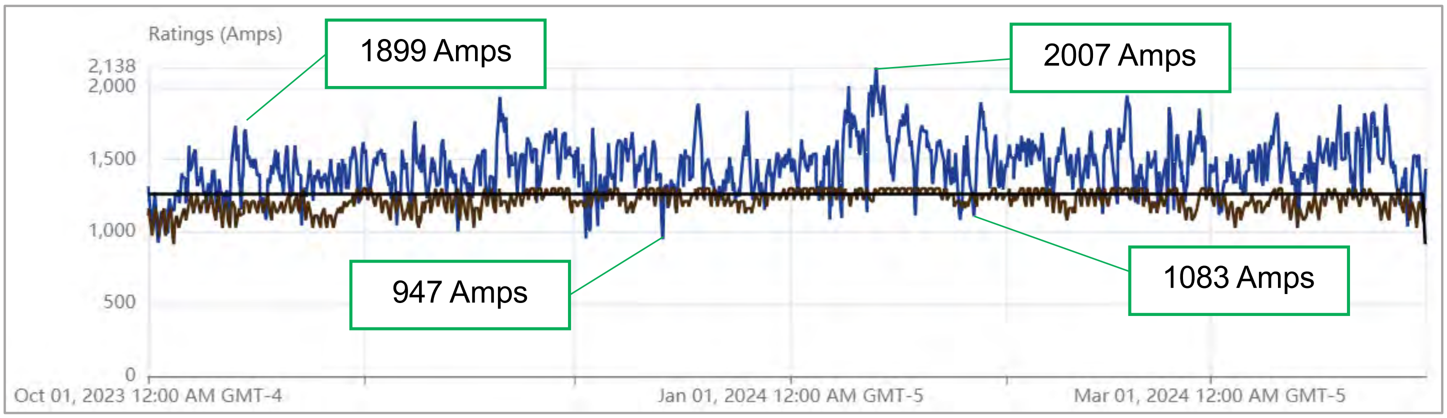
15. Summer-seasonal ratings come into effect in April and last through September and are 913 Amps on line 69kV-4.

Table 5. Summary percent increases for line 69kV-4 over static ratings and AAR

Measure	Static rating	AAR
Average % Capacity Increase of DLR over Rating	-10%	-7%
% of Time DLR > Rating	13%	23%
% of Time DLR > Rating+5%	6%	10%
% of Time DLR > Rating+10%	2%	4%

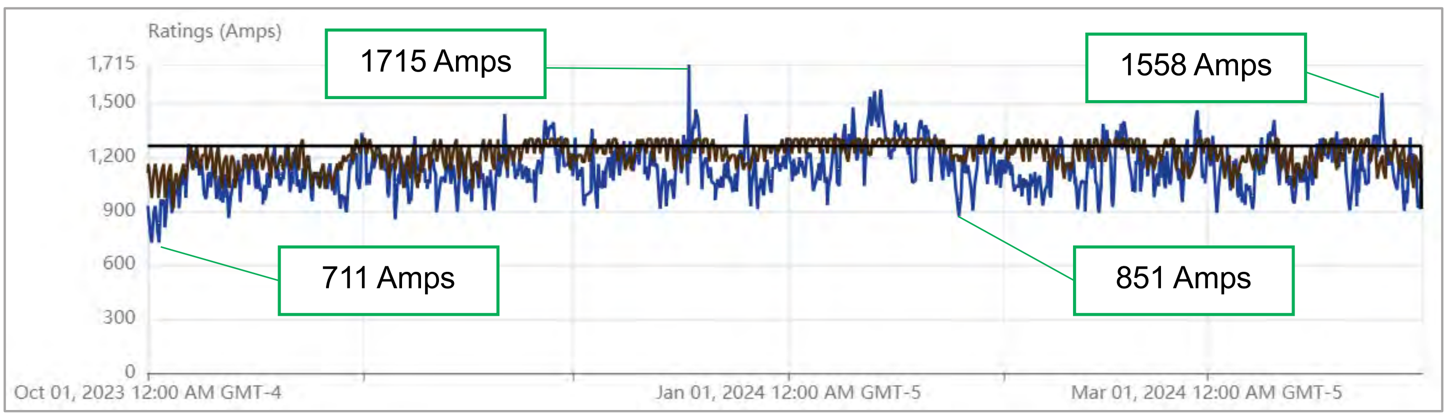
Because DLR can account for physical conditions along the line, LineVision and AES dug into the segments of line 69kV-4 to determine if a specific line segment may be disproportionately impacting the overall line's rating. The team noted meaningful differences between rating measurements in different segments of the line, as illustrated in Charts 8, 9, 10, below.

Chart 8. Ratings for line 69kV-4 from October 1, 2023 through March 31, 2024, Segment 34



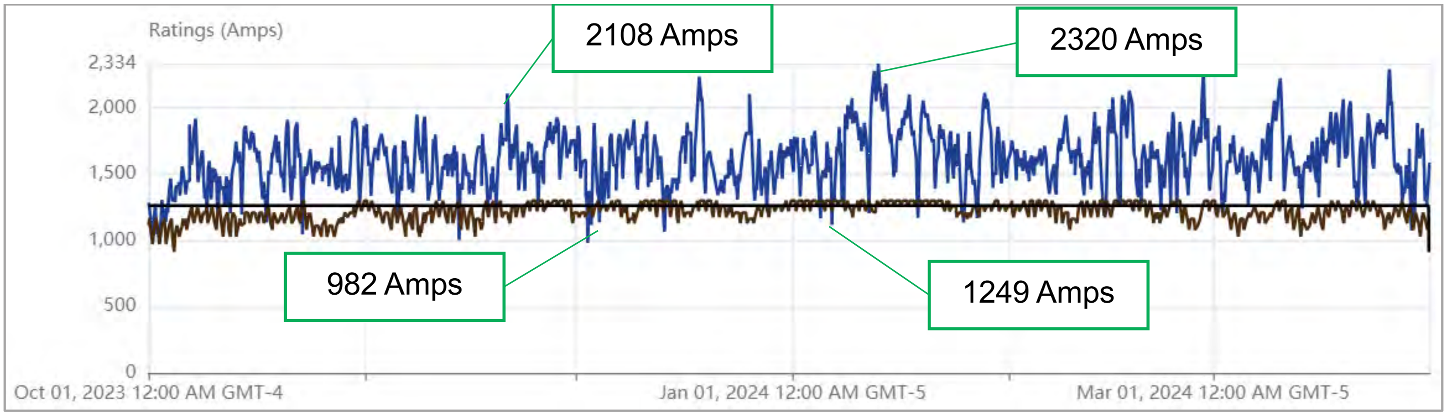
DLR is in blue, AAR is in brown, and static ratings are in black.

Chart 9. Ratings for line 69kV-4 from October 1, 2023 through March 31, 2024, Segment 37



DLR is in blue, AAR is in brown, and static ratings are in black.

Chart 10. Ratings for line 69kV-4 from October 1, 2023 through March 31, 2024, Segment 40



DLR is in blue, AAR is in brown, and static ratings are in black.

Segment 37 stood out as an area experiencing significant constraints, so LineVision reviewed LiDAR data produced by its sensors and confirmed through field visits that an approximately half mile stretch of 69kV-4 is in a narrow, low-wind and high vegetation corridor. As the hyper-localized wind speed values in this corridor impact the carrying capacity of the entire line, the team installed two anemometers on adjacent towers for further validation of wind information. The anemometer-collected data was compared to wind speeds provided by third party weather data and the DLR model was further tested through computational fluid dynamics and data from the LiDAR sensors.

Anemometer data corroborated the low wind speeds in the limited corridor as identified by the DLR model. The situational awareness and higher fidelity and dynamic line ratings provided by LineVision's sensors and calculations are a valuable safety and reliability use case for DLR. Without awareness of low wind speeds and vegetation and their combined impact on line carrying capacity, there could be a risk of higher conductor sag in that segment if static line ratings were adhered to. The assumptions in AES' seasonal ratings methodology resulted in a static rating frequently higher than the more detailed DLR thermal rating. As more DLR and anemometer data is collected, the AES operations team is closely monitoring the loading on 69kV-4 to ensure it is maintained within safe limits.

The situational awareness provided by the DLR solution also provides opportunities for strategic planning of assets or management of the grid. For example, AES can explore mitigation methods such as vegetation management or reconductoring of the limiting half mile.

If reconductoring is completed on the most limiting segment, it is anticipated that the line would experience an average increase in measured carrying capacity of 10% above winter-seasonal static and 14% above AAR. The combination of DLR, situational awareness, and targeted asset upgrade represents a relatively capital efficient approach to optimizing a transmission corridor where certain limiting spans exist. AES estimates a saving of approximately $1.24M by applying DLR and limited reconductoring as compared to reconductoring of the full length of the line to meet the reliability and load growth needs on line 69kV-4.

Table 6. Cost for DLR plus targeted reconductoring versus full reconductoring for line 69kV-4

Measure	DLR + Targeted reconductor	Full reconductoring
Average Capacity Delivered	>10%	10%
Cost	$0.39M[16,17]	$1.63M
Time to Operational	1 year	2 years
Outage required	3 to 4 days[18]	5 weeks

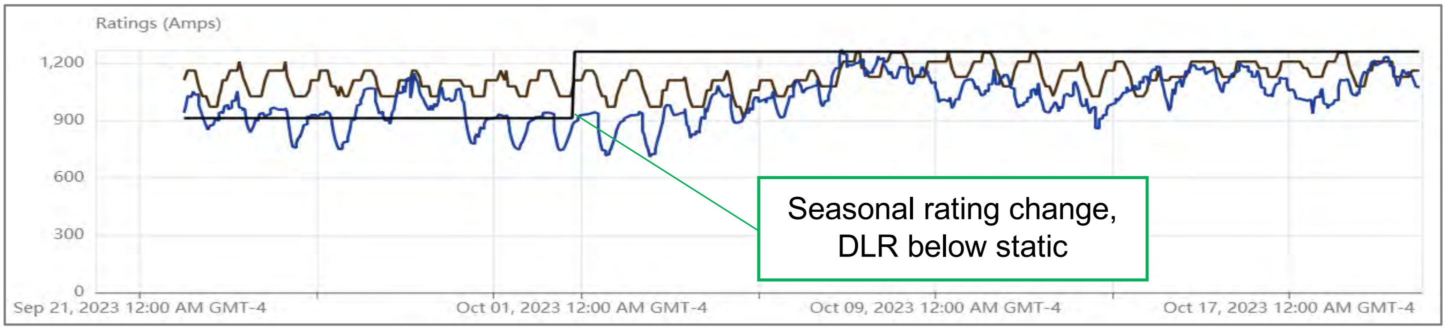
Line 69kV-4 also provides a concrete example of the arguably imprecise impact of static line ratings. Charts 11 and 12, below, compare data for line 69kV-4 around the inflection point at which seasonal static ratings change (October and April for AES Ohio), one can observe that DLR and AAR remain consistent within a band of values while the static ratings make leaps from 913 Amps carrying capacity to 1262 Amps, and vice versa. Suddenly, overnight, the more dynamic measures of carrying capacity shift from above or close to static ratings to firmly below. This data put into question the capability of static ratings to enable efficient use of grid assets and ensure consistently reliable loading of lines. The former question (efficiency) may not be surprising as line ratings were originally developed in the 1930s as a reliability measure, not as a measure of true line thermal carrying capacity. The later question (consistent reliability) may offer greater concern as it illuminates that the static line ratings (seasonal or otherwise) lack situational awareness that has measurable impact on true line thermal carrying capacity.

16. Cost calculations in this table are specific to this line, 69kV-4, and include 20 years of software costs for the DLR product. The calculations for the DLR plus targeted reconductoring are: DLR ($45k per mile) $230K + $160K for 0.5 miles reconductor ($320k per mile) = $0.39M for 5.1 miles. The calculations for the full reconductoring are: 5.1 miles at $320K per mile = $1.63M.

17. ACSR reconductor assuming existing towers are sufficient. MISO Transmission Cost Estimation Guide, last accessed Apr. 8, 2024 at https://cdn.misoenergy.org/MISO%20Transmission%20Cost%20Estimation%20Guide%20for%20MTEP23337433.pdf

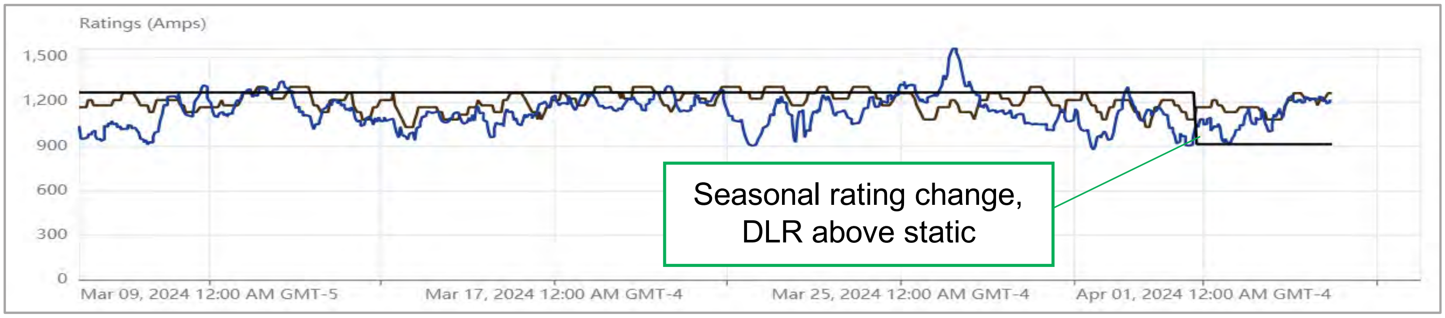
18. MISO Transmission Planning Business Practices Manual BPM-020-r30, last accessed Apr. 8, 2024 at https://www.misoenergy.org/legal/rules-manuals-and-agreements/business-practice-manuals/

Chart 11. Ratings for line 69kV-4 from September 20, 2023 through October 19, 2023



DLR is in blue, AAR is in brown, and static ratings are in black.

Chart 12. Ratings for line 69kV-4 from March 6, 2024 through April 5, 2024



DLR is in blue, AAR is in brown, and static ratings are in black.

C. 138kV-2, 138kV-3, and 69kV-2

The three remaining selected demonstration lines were chosen in connection with two use cases.

→ Lines 138kV-2 and 138kV-3 are a pair of electrically related lines that are outgoing from a critical generation source at risk of curtailment if any one of five lines go out of service. The two selected lines are those at greater risk of loss and are also candidates for DLR as the conductors are the limiting element. Deployment of DLR, therefore, provides a mitigation strategy for renewable energy curtailment within a system.

→ Line 69kV-2 is one of three lines serving an area of step-change load growth, similar to line 345kV-1 but at lower voltage. Improving the carrying capacity of this line could mitigate potential congestion to other parts of the grid while construction occurs and the system upgraded to support the addition of step-change load.

The value of increased carrying capacity on these lines remains clear and worthwhile. Extending the efficacy of DLR models to the specific challenges presented by the lower voltage, older construction wood poles will provide the added benefit of creating a DLR solution that is capable of scaling more fully across the use cases for which dynamic ratings and situational awareness is needed in the electrical grid.

Two characteristics of the older construction wood poles were found to materially impact the ease of developing DLR values with confidence. First, the poles are more prone to pole movement from environmental and line conditions when compared to steel tower type assets with more robust foundations.[19] Second, because the conductor is clipped into each pole's post insulator, the differential line tension can contribute to pole movement. This pole movement complicates the measurement of the sag of the conductor by the LiDAR sensor. It is difficult to differentiate between sag caused by pole movement and sag related to conductor temperature.

19. Line 69kV-4 also uses wood pole construction but it does not experience pole movement impacting DLR modeling. This is likely because it uses a larger class of poles.

AES and LineVision are currently collecting additional anemometer and LiDAR data in connection with these lines to confirm or refine DLR model outputs. The additional sensors required are low cost and fast to deploy and have not impacted the cost-benefit analysis of the deployment. The additional work required for these three lines will enhance the team's access to data, knowledge of how the environmental and physical context of grid assets impacts performance, and – ultimately – the scalability of the DLR solution. In the team's opinion, this is also "no-regrets".

D. Additional General Learnings

This Case Study memorializes a list of additional, broad learnings with the goal of helping others gain confidence in the broad deployment of DLR solutions and structure projects for greatest success. The insights are grouped based on AES' experience in connection with (a) planning, (b) installation, (c) data.

(a) Planning

→ The line selection process can help a utility better evaluate the most limiting elements of a circuit which may include a single piece of equipment in the substation such as a breaker, relay, or switch.

→ The improved understanding of most limiting element can help a utility prioritize asset upgrades first through equipment replacement to make the line the limiting element, and then with the addition of DLR.

→ Transmission lines that also support distribution circuits on the same structure can make sensor placement more complicated. This is more common on 69kV and 138kV lines.

→ A best practice is to conduct pre-installation site visits in addition to the desktop line profile study to confirm each sensor location.

→ Sub-transmission lines do not always have the same level of quality PLS-CADD or other asset design data as higher voltage lines. Thus, building the DLR model may require collecting additional field information and making conservative assumptions.

(b) Installation

→ Installation was remarkably easy, but one of the 42 sensors was installed on the wrong side of the pole at first. The risk of this error can be mitigated in the future by including pictures with cardinal directions for each site in the detailed project construction documents.

(c) Data

→ There is value in the early creation of a data pipeline to support sharing of line loading data from SCADA to the DLR model.

→ Historical SCADA data may be incomplete and require calculations to establish the amps flowing through each line section, especially for lines with multiple taps and limited relay data.

→ Some lines may be owned by one utility and operated by another, requiring a separate process of data sharing to be established. This highlights that no utility is an island.

Conclusion and next steps

This Case Study is an initial report of the insights AES and LineVision have developed from the team's deployment of 42 sensors on 5 diverse lines in AES' Ohio and Indiana utilities. The data provided on line 345kV-1 and 69kV-4 represent only six months of insights, limited to the cooler months of the year. As more data is collected for all five lines, the team will be able to refine insights about the lines and advance the deployment initiative by (a) completing a full year of DLR values; (b) moving from "observation" to deployment of DLR in operations; and (c) demonstrating with specific line data how dynamic operational information can be used to derive planning inputs.

Moreover, AES anticipates synergies between operationalizing DLR and implementation of AAR as required by FERC Order 881. The change management required to upgrade operations systems such as the Energy Management System (EMS), train operators, and update ratings methodologies will be similar for both AAR and DLR.

AES will also use the situational awareness provided by the LineVision solution to evaluate the potential value of reconductoring a portion of line 69kV-4 (or changing vegetation management in the area), and if there are improvements that can be made to aging wood pole assets or future transmission structure design and placement to ensure improved carrying capacity and line efficiency.

AES and LineVision look forward to their continued collaboration and additional publication of insights that will pave the way for scale deployment of DLR solutions in the U.S.