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Variable Transmission Line Ratings

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CONTENTS

FIGURES

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VARIABLE TRANSMISSION LINE RATINGS

1. INTRODUCTION

This paper outlines the concept of variable-transmission facility ratings. This topic is of heightened importance following the recent Federal Energy Regulatory Commission (FERC) Order No. 881[a] which requires the implementation of ambient adjusted ratings (AARs) for FERC jurisdictional portions of the transmission system (Figure 1), as opposed to the conventionally used static line ratings (SLR). Additionally, FERC issued an Advanced Notice of Proposed Rulemaking (ANOPR) soliciting comment on future issuance of an order on Dynamic Line Rating (DLR) requirements[b]. The various types of facility-rating methodologies will be discussed with a focus on how they can benefit the stability, capacity, and reliability of the grid.

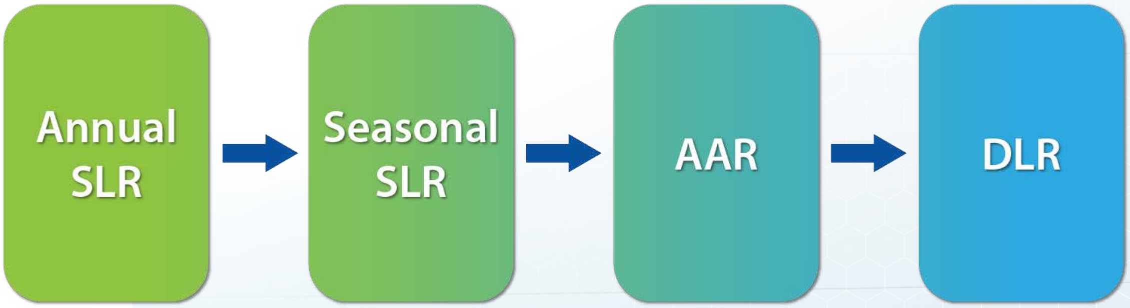

Figure 1. Evolution of line ratings

a FERC Docket No. RM20-16-000; Order No. 881, Managing Transmission Line Ratings, 177 FERC ¶ 61,179, issued December 16, 2021.

b FERC seeks comment on potential DLR framework to improve grid operations & fact sheet. Federal Energy Regulatory Commission. (2024, June 28) https://www.ferc.gov/news-events/news/ferc-seeks-comment-potential-dlr-framework-improve-grid-operations-fact-sheet

2. STATIC LINE RATINGS

The implementation of AARs for transmission-system operations has already taken place in a number of areas across the United States, but many areas have historically only operated under SLRs. SLR means that transmission facilities, like lines and transformers, are assigned a fixed capacity, or static line rating. The SLR was defined as a conservative ampacity or MVA loading limit, defined under the worst-case operating conditions. Within the United States, SLRs for transmission lines are typically calculated per the processes defined in Institute of Electrical and Electronics Engineers (IEEE) Standard 738-2023. SLRs are updated infrequently, on a seasonal basis, and generally use the same conservative weather assumptions applied to all lines across a utility's footprint, regardless of their geographic or climatological variances. Using this approach, the thermal rating of the conductor can be calculated based on the maximum allowable operating temperature of the wire. Deratings are often applied to overhead conductors for conditions as altitude, sag limitations, regional high temperatures, conductor age, or conductor surface weathering. Surface weathering usually occurs with age and can increase solar absorption and conductor heating. Summer and winter seasonal ratings are often calculated at varying time durations where a continuous rating represents the normal rating for the transmission facility when there are no system disturbances present. Emergency ratings are also calculated based on these seasonal dependencies which typically represent short-term (15 to 30 minutes) and long-term (2 to 4 hours) ratings under which increased power flows can be tolerated before the system operator must make adjustments to return power flows in the system to under the normal rating. In many regions the summer rating is typically the more conservative rating which is often used to determine line protective trip parameters[c].

Figure 2. Static Line Ratings use Conservative, Worst-Case Seasonal Temperature Assumptions

c N. H. Abas, M. Z., A. Ab Kadir, N. Azis, J. Jasni, N. F. Ab Aziz, and Z. M. Khurshid, "Optimizing Grid With Dynamic Line Rating of Conductors: A Comprehensive Review," in IEEE Access 12 (2024), pp. 9738–9756, doi: 10.1109/ACCESS.2024.3352595.

3. AMBIENT ADJUSTED RATINGS

The next step beyond SLR, whether annual or seasonal, is typically seen in the implementation of Ambient Adjusted Ratings (AAR), which adjusts line rating based on local ambient air temperatures and the presence of solar heating (sun up/sun down). AAR is a limited form of dynamic line ratings (DLR) and has been identified as a method that allows for relatively simple implementation and is generally seen as low cost. Figure 2 shows some of the environmental effects that go into an adjusted calculation, not all of which are required to be taken into account in the calculation of AARs[d].

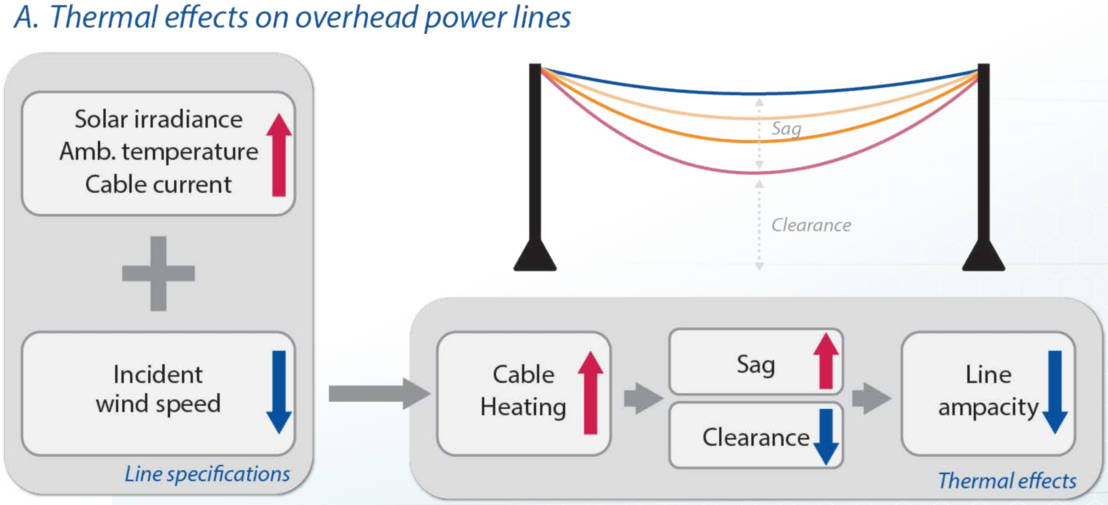

Figure 3. Environmental Effects Affecting Transmission Cables

On December 16, 2021, FERC issued Order No. 881, which required jurisdictional transmission providers to implement AARs that will govern the maximum transfer capability of their transmission network for near-term transmission services. Under FERC's definitions, near-term capacity will be used to determine the ability to meet requests that will be fully completed within a 10-day period. For FERC jurisdictional utilities that are operating within the footprint of a balancing authority (BA), such as an independent system operator (ISO) or regional transmission organization (RTO), rating-reporting requirements are presently being defined. Public utility transmission providers will need to maintain an accessible, password-protected database of the ratings and methodologies of transmission owners. Implementation of AARs will be required by July 2025 for all FERC-jurisdictional entities that own or operate transmission resources and have not been granted a delay.

d Al Estanqueiro et al, "A review of DLR models and their potential for a cost-effective transition to carbon-neutral power systems," in WIREs Wiley Interdisciplinary Reviews

The FERC defined implementation of AAR calls for these continuous and emergency ratings to be calculated for the rolling 10-day period and updated on at least an hourly basis in increments not exceeding 5°F. Beyond this window, it is acceptable to rely on the seasonal SLR for longer-range system-planning efforts, such as available transfer capacity studies and seasonal-congestion revenue-rights calculations. It is recommended that transmission owners revisit other parameters used within the line rating calculation for both AAR and seasonal SLR to ensure these reasonably reflect current industry guidelines due to the FERC Order No. 881 requirement that ratings methodologies must be shared with neighbors.

As real-time ambient temperature measurements, gathered from weather providers such as National Oceanic and Atmospheric Administration (NOAA) weather stations, are the only non-assumed input to AAR ratings, AAR is less accurate than and can be more conservative than DLRs, which are described in the next section. AAR provides up to an average of 15% higher capacity than SLR but still lags Dynamic ratings by up to 16% capacity[e] as can be seen in Figure 4. Hence AAR is the "stepping stone" to the generally higher capacity Dynamic line ratings. However, AAR may come with a significant risk as described below.

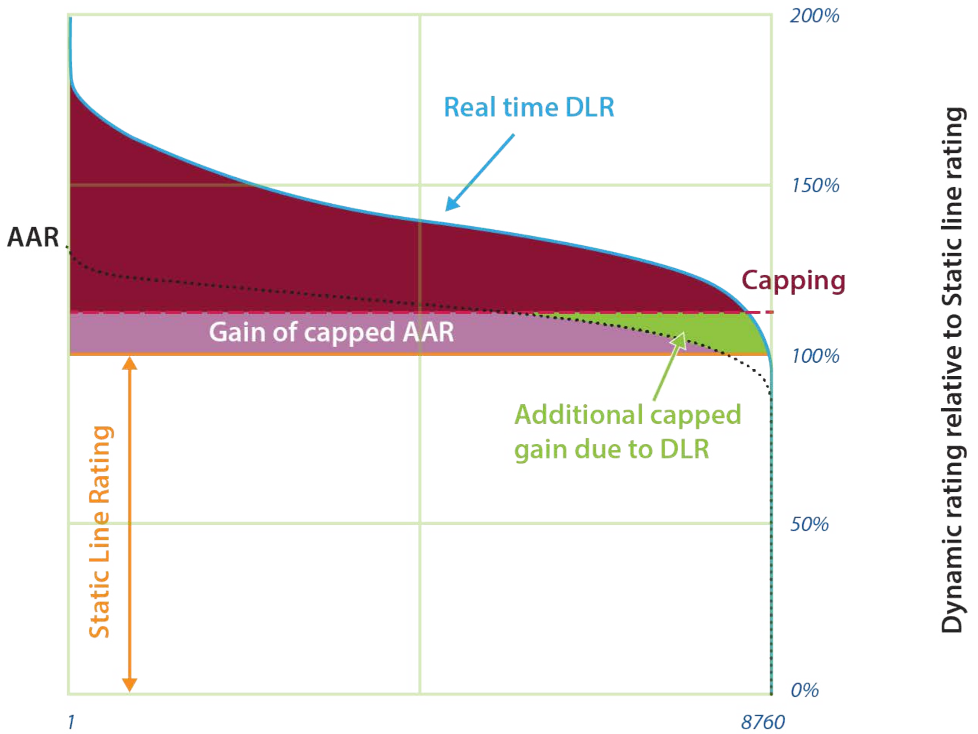

Figure 4. DLR relative to AAR and SLR.

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e K. Engel, J. Marmillo, M. Amini, H. Elyas, B. Enayati, "An Empirical Analysis of the Operational Efficiencies and Risks Associated with Static, Ambient Adjusted, and Dynamic Line Rating Methodologies", CIGRE-US National Committee.

3.1 Risk Associated with Ambient Adjusted Ratings

Caution is encouraged in the use of assumptions for the wind speed and general recommendation is that, unless real-time rating systems are employed, a more conservative effective wind speed should be used than that used to determine the SLR in long-term analysis. In cool ambient temperature conditions with low wind speeds, constant windspeed assumptions inherent to AAR combined with accurate low ambient temperature inputs can result in an overestimate of actual line capacity. This represents risk for applying stress and damage to conductors, plus shock and fire hazards relating to line sag issues triggered by unseen overload due to applied rating methodology.

Air temperature and solar irradiance are the two time-sensitive features considered for the current implementation of AARs. FERC does not require that wind speed or direction be treated as variable for AARs. However, industry guidelines from entities such as International Council on Large Electric Systems (CIGRE) and IEEE have indicated that it is prudent to consider a lower wind speed for lower ambient temperatures during the night when implementing AARs.[e] Higher ambient temperatures induce some wind flow; thus, the wind speeds used for SLRs are not necessarily appropriate for AARs. It is also worth noting that a line's current-carrying capacity is most sensitive to wind speed and direction, with a heightened sensitivity to overhead line's emissivity and absorptivity at higher temperature[f]. For this reason, it is important that transmission owners evaluate this value closely with the change to AARs.

AAR Risk – Capacity Overestimation

AAR is sometimes considered a low-risk and low-cost step between Static and Dynamic line ratings, but can introduce equipment and safety risk not inherent to the other two rating methodologies. Ambient Adjusted Ratings may dip below actual calculated line ratings 22% of the time in the summer and 27% of the time in the winter, falsely conveying excess capacity.

f A. W. Abboud, J. P. Gentle, K. Parikh, and J. Coffey, "Sensitivity Effects of High Temperature Overhead Conductors to Line Rating Variables" . 2020 CIGRE e-Session

4. DYNAMIC LINE RATINGS

A more-accurate assessment of AARs has been seen to positively impact the efficiency of market and system operations. Specifically, Dynamic Line Ratings (DLRs) have the potential to expand practical line capacity, improve line utilization, reduce transmission congestion, and enhance market efficiency. In North America, ISOs and RTOs are counting heavily on mathematical optimization to dispatch generation resources and serve the net demand in their corresponding market footprints.

To take advantage of more accurate wind speed measurements DLRs sensors are typically installed on either the conductor or the transmission tower. These sensors collect and process location-specific wind speed and temperature data to calculate an operationally informed line rating, typically updated on ten-to-fifteen-minute intervals. Implementing large-scale programs and selecting vendors was seen as a burden to utilities, so a staged implementation approach can be seen through the implementation of AARs, which can be determined without the requirement to install new sensor equipment in the field[g]. However, due to increased accuracy of DLR over AAR and the risk of capacity overestimation associated with AAR, DLRs will likely soon be required as demonstrated by the recent DLR Advanced Notice of Proposed Rulemaking (ANOPR). The FERC ANOPR considers two different implementations of DLR: 1) time of day solar tracking to more accurately represent the impact of solar heating for all jurisdictional transmission facilities, 2) time of day and wind monitoring for transmission facilities that meet congestion and wind exposure metrics.

Presently the industry is seeing specific, targeted use of DLRs as pilot projects on facilities that have been identified as frequently triggering system constraints, which have demonstrated effective mitigations[h]. Comparing costs from the winter the year before installation to the winter after installation, Pennsylvania Power & Light (PPL) Electric saw a reduction in congestion costs on the order of $64 million following the installation of DLRs on a targeted transmission line. PPL installed DLRs on three transmission lines, which resulted in an increase of the normal line ratings of approximately 17% relative to equivalent AAR implementation. New York Power Authority (NYPA) identified capacity increases up to 20%, reductions in wind power curtailment requirements, and identified hotspots and limiting line spans using DLR combined with machine learning[i]. This agrees to the generic comparison of DLR with SLR and AAR (Figure 4 on Page 4).

g The FERC ANOPR solicited feedback on the viability of wind monitoring DLR implementations using sensor-less techniques, but the majority of current installations of DLR which incorporate the impact of convective cooling from wind use line or tower mounted sensors.

h E. Howland, "GETs could facilitate 6.6 GW of clean energy in five PJM states, saving $1B a year: RMI," Utility Dive, February 15, 2024, available online: https://www.utilitydive.com/news/gets-grid-enhancing-technology-dlr-pjm-rmi/707612/.

i Windsim Power, RA Rights Analytics, NYPA, "The NYPA Pilot and Results," NYSERDA PON 3770 High Performing Grid.

While Figure 5 illustrates the duration of weather based DLR[j] exceeding beyond or falling below AAR at four locations, each at Georgia, Tennessee, New York and Pennsylvania. The respective transmission lines are presented by their object IDs from the Homeland Infrastructure Foundation-Level Database (HIFLD)[k].

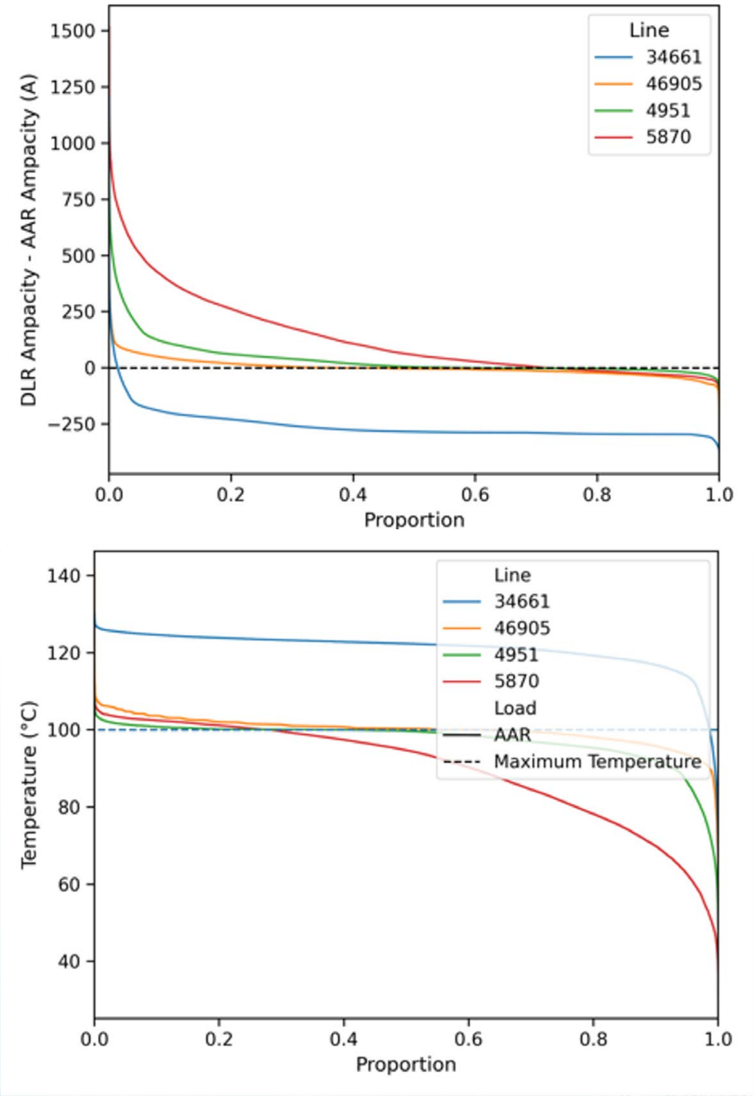

Figure 5: DLR - AAR Duration Curves for selected overhead transmission lines in four locations (top). Transmission lines are identified by their respective Object IDs. Ampacity of the Transmission line in Georgia (Object ID 34661) has been being overestimated by AAR and not accounting for temperature (bottom).

j B. P. Bhattarai et al., "Improvement of Transmission Line Ampacity Utilization by Weather-Based Dynamic Line Rating," in IEEE Transactions on Power Delivery, vol. 33, no. 4, pp. 1853-1863, Aug. 2018, doi: 10.1109/TPWRD.2018.2798411..

k HIFLD. (n.d.-a). https://hifld-geoplatform.hub.arcgis.com/

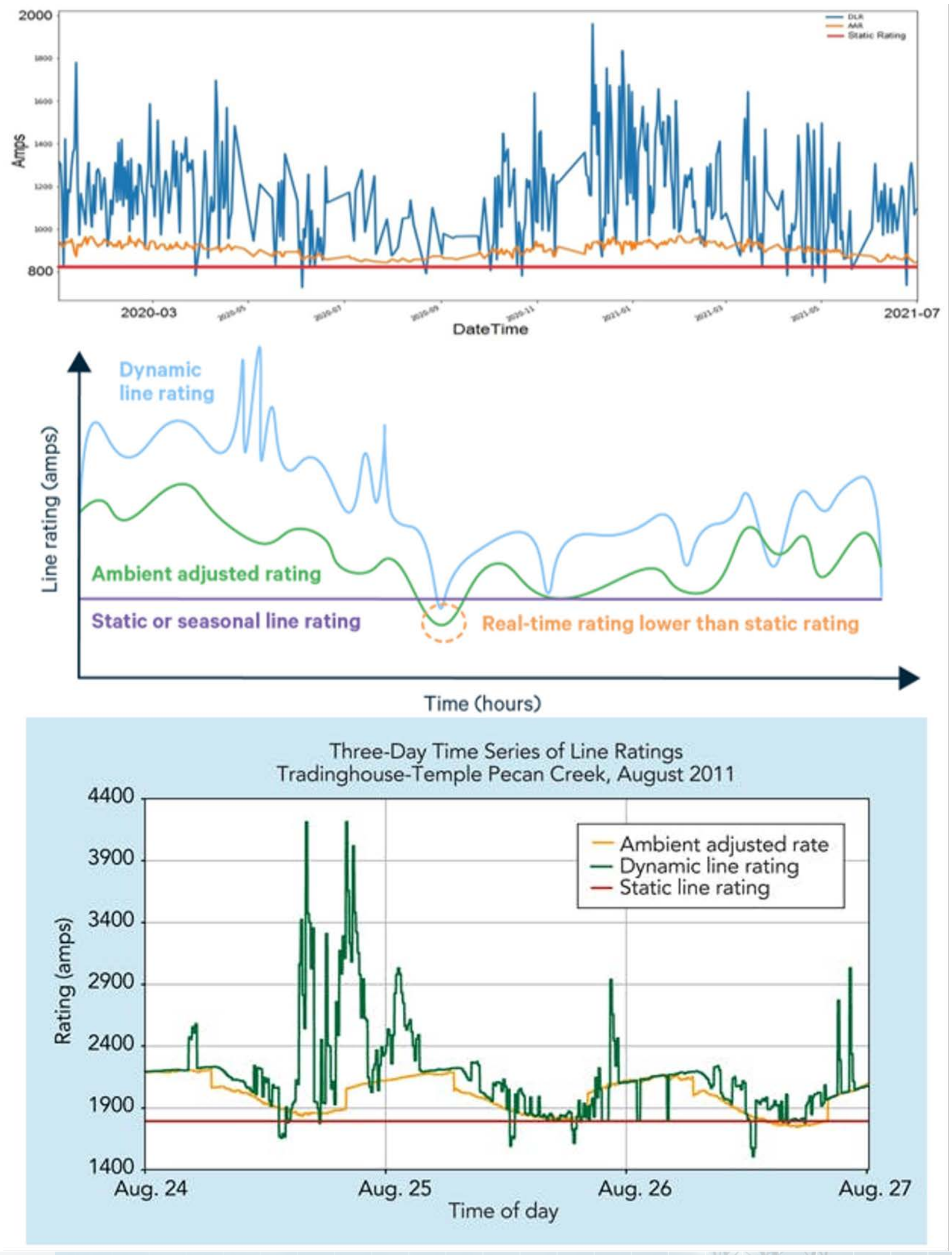

Figure 6. Comparison of static, ambient, and dynamic ratings for a particular line over a 3-day period.[1]

As seen in Figure 6, on average, AARs and DLRs exceed SLRs; however, there are notable instances where the DLRs fall below either AARs or SLRs. Something similar can be said for

1 Goodwin, T., "Oncor Portends a Dynamic Future," T&DWorld, March 4, 2014, Oncor Portends a Dynamic Future | T&D World (tdworld.com).

the early hours of August 26th when the AAR rating fell below the SLR. In these instances, this presents as operational risk—i.e., instances where the line is potentially being operated above rated capacity using the SLR or AAR values. Only DLRs can provide this level of granularity with the facility's true rating. Under other such scenarios, this could translate into risks such as decreases in conductor-rated breaker strength, sag violations, or premature aging of the resource. Figure 7 provides an assessment of periods when the DLR rating was below both the AAR and SLR for a specific 345 kV in the Midwest that had line-monitoring sensors installed.

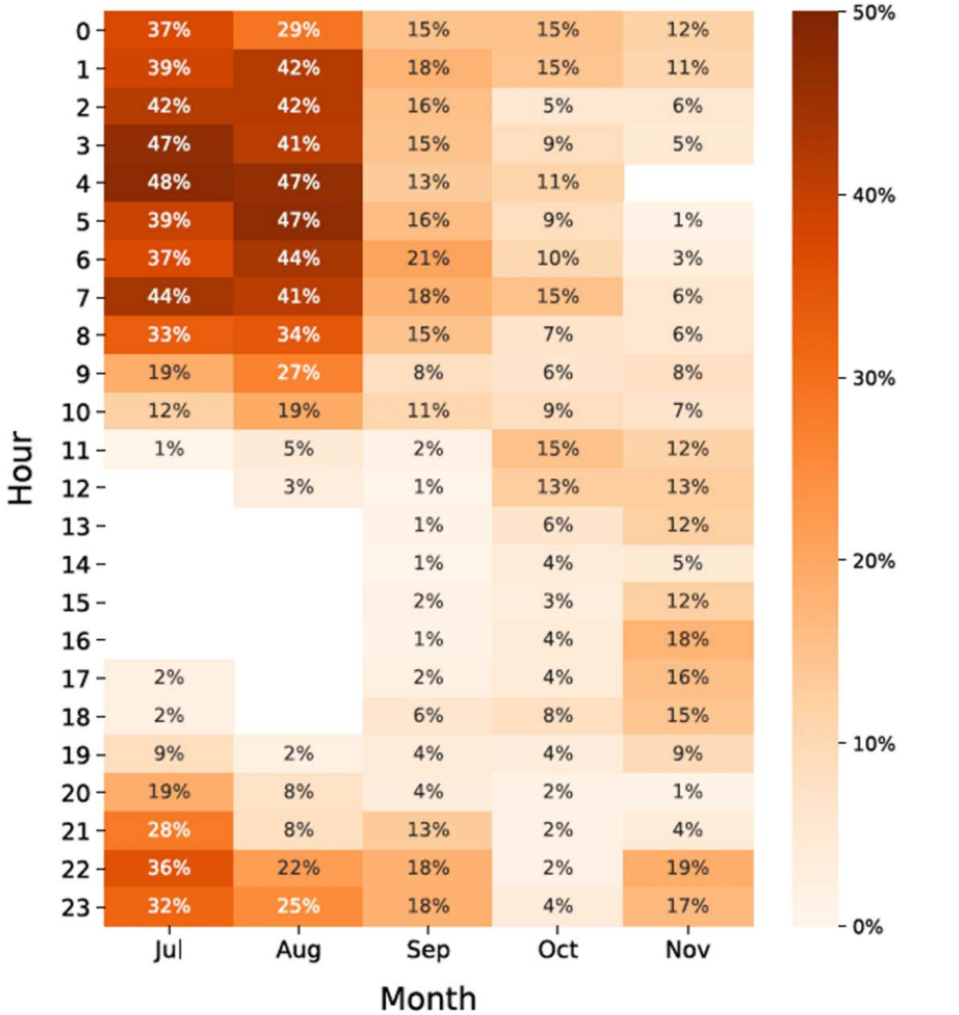

Figure 7. Percentage of timeline during which DLR was below AAR[m]

The equipment needed to implement AAR and DLR can have a wide range of requirements for locally installed or remote equipment. For AAR, implementation can be done by using the

m Caspary, J. "It's Time to Use Accurate Line Ratings," Watt-Transmission, https://watt-transmission.org/its-time-to-use-accurate-line-ratings/.

transmission line location, altitude, and ambient weather conditions. Weather conditions can be gathered from resources such as the National Oceanic and Atmospheric Administration (NOAA), AccuWeather, staff meteorologists, private vendors, and other sources. The 10-day projection requirement means that one of the sources used for determining AARs would require a 10-day-ahead forecast, provided on an hourly basis. To avoid spurious inputs, incorporating multiple sources into the determination method might be considered. AARs do not require line-mounted or even locally placed equipment to develop the variable ratings; however, DLRs typically utilize direct monitoring of the lines and the ambient weather conditions to which they are exposed.

DLRs can be determined using local measurement devices, such as weather stations, line-mounted or tower-mounted sag sensors, tension sensors, vibration sensors, conductor temperature sensors, current flow sensors, and also fiber-optic cables with data-processing equipment. Remote sensors that could support this implementation would include a wide area weather model that is used by the entity to evaluate ambient weather conditions. For DLRs, three-dimensional modeling of the surrounding line terrain could be used in conjunction with computational fluid dynamics to evaluate site-specific wind conditions measured from local weather stations and wide area weather models to determine wind conditions at every span of a transmission line without needing line sensors at every span. This approach is sometimes used as a supplemental step to help equipment vendors identify the critical spans where line sensors should be mounted, particularly in areas with complex terrain.

It should be noted that AARs and DLRs only pertain to lines that have a sensitivity to ambient conditions, which means that underground lines would generally be exempted. Lines with underground segments may have these segments act as the limiting element, depending on design and the segment's rating.

5. RISKS ASSOCIATED WITH ADJUSTABLE RATINGS

The risks listed below apply to both AAR and DLR, and in many cases to all grid additions requiring communications and data processing. Best practices for mitigating these risks exist and should be considered in any AAR or DLR project.

5.1 Operational risks.

The implementation of AARs and DLRs on a system means that the system could be operated closer to its design limits, which can magnify the effect of outages when lower system margin is available to absorb these outages. AARs and/or DLRs should not be used to offset or obscure progress on longer-term transmission-system solutions that might be needed because AARs and DLRs may not dependably mitigate reliability violations, although they can defer longer term transmission upgrades and new builds. A thorough understanding of the transmission constraint is required to determine the necessary mitigation to address it. AARs and/or DLRs can be used to support lower-cost economic dispatches, make better use of the true available capacity of the transmission system, and alleviate false transmission constraints.

Some transmission lines have other pre-existing constraints, such as sag, voltage, or angular limits, that would not be superseded by higher capacity limits. At the same time, the facility rating would be equal to the most-limiting applicable equipment rating of the individual series-connected equipment that comprises a transmission facility per North American Energy Reliability Corporation (NERC) FAC 008, such as breakers, cables, switches, current transformers, jumpers, or wave traps. These other pieces of equipment can also have ambient-temperature dependencies that can be incorporated into the variable rating. Special mention will be provided here for taking additional care if power transformers are considered for AAR implementation. Coordination with the transformer manufacturer should be pursued to ensure that the transformer could be operated beyond the nameplate rating. The intent is both to make the best use of the existing transmission facilities and to maintain a practice of safe operation of these facilities.

Additionally, automatic relaying equipment protecting transmission lines would need to be reviewed and possibly adjusted to take into account higher and varying line ratings. This may necessitate upgrades to hardware and networks to securely protect against conductor and equipment damage while allowing for capacity increases.

5.2 Cybersecurity risks.

Additional equipment feeding into an energy management system will increase cybersecurity risk to some degree, but the risk is generally seen as low and one that can be mitigated. This can provide a potential point of entry for malicious actors—for example, digitally or physically manipulating sensor parameters such that ambient temperature reads lower than reality, potentially leading to overloading a transmission facility. However, sufficient system architecture using a defense-in- depth strategy can remedy much of this risk.

5.3 Failure of Measurement Equipment.

In the event that a component measurement system fails or an AAR/DLR component or weather-collection system is compromised, measurement gathering can be inaccurate. This can force reversion to the applicable seasonal SLR, causing sudden capacity re-routing requirements, curtailment, or redispatch. This reinforces the need for proper data-quality checks to address the risk of either cyberattack or component failure. Another specific risk has been observed in adjacent fields; namely, if a vendor is selected to provide equipment used to implement AARs or DLRs, this can lead towards functional obsolescence issues as equipment ages. Similar concerns are present for vendors that may go out of business.