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Simulating the Economic Impact of a Dynamic Line Rating Project in a Regional Transmission Operator (RTO) Environment

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SUMMARY

In 2017, American Electric Power (AEP), PJM Interconnection, and Genscape, Inc. partnered to perform a dynamic line rating (DLR) pilot project on the Cook-Olive 345 kV transmission line in the AEP Transmission Zone of PJM. DLR technologies report the real-time ampacity capabilities of thermally-limited transmission assets. To determine a line's dynamic limit, measurement equipment is installed in the transmission right-of-way to monitor the real-time conductor temperature, as it changes with weather and loading conditions. This pilot successfully demonstrated the additional capacity and overall variability that DLR ratings can provide on a typical overhead transmission line.

To better understand the overall economic impact of DLR, PJM performed an economic analysis of a hypothetical DLR installation on one of the most congested lines in its footprint, referred to as Target Line. For the study, LineVision generated back-casted hourly DLRs for the Target Line path using historic National Oceanic and Atmospheric Administration weather data. The data were then used as line ratings in a PJM 2018 PROMOD Market Efficiency base case software simulation.

The results of this simulation were compared to a base case simulation using standard summer and winter static line ratings. Comparison results showed an overall reduction in congestion observed on the Target Line, as well as an overall reduction in system congestion payments of more than $4 million during the one-year study. This paper reviews how the economic analysis was performed and summarizes its results.

Note: At the time this project was initiated, LineVision was a business unit within Genscape, Inc. that has subsequently spun off into a standalone company, LineVision Inc.

KEYWORDS

Dynamic Line Ratings, DLR, EMF, Transmission Line Monitoring, Congestion, Market Efficiency

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1. Introduction

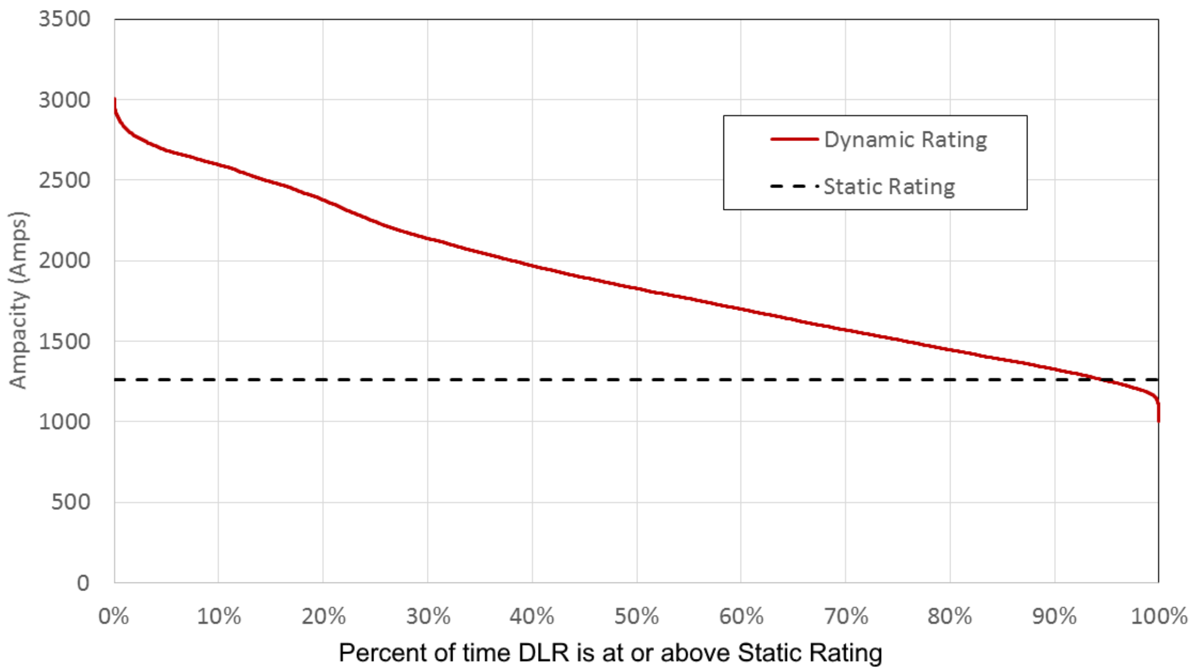
This paper is a continuation of *A Non-Contact Sensing Approach for the Measurement of Overhead Conductor Parameters and Dynamic Line Ratings* [1] published in October 2017. From November 2016 to August 2017, PJM, AEP, and Genscape conducted a DLR pilot project on the Cook-Olive 345 kV transmission line in the AEP Transmission Zone of PJM. The purpose of the project was to demonstrate how the LineVision technology would identify additional transmission capacity on a sample transmission line, and how utilities and regional transmission operators (RTOs) might incorporate such dynamic line ratings (DLR) into real-time operations. LineVision is a non-contact transmission line monitoring and DLR system that measures various electrical and physical parameters of a transmission line in real time. Two of the measured parameters are power flow and conductor position/sag, and along with ambient weather conditions, are used to determine the conductor's temperature and ultimately its DLR.

PJM's interest in this project was to not only test the feasibility of a DLR technology, but also to assess the overall financial impact that the technology might bring to wholesale power markets. PJM staff performed a one-year PROMOD study of a hypothetical DLR installation on one of the most congested lines in PJM, (referred to as Target Line).

In addition to reduced congestion costs, PJM is also interested in how advanced transmission technologies like DLR might improve system resilience. By better monitoring and understanding the real-time capabilities of transmission line assets, grid operators can better ensure that transmission lines are operated below their maximum operating temperature at all times. DLR technologies may also identify areas of additional margin during stressed or emergency system conditions.

2. Dynamic Line Rating (DLR)

DLR is an approach used to determine an overhead conductor's safe allowable current (or apparent power) transfer capacity by utilizing measured or calculated real-time prevailing weather data including ambient temperature, solar irradiation, and wind speed and direction (effective perpendicular wind speed). DLR methods apply to conductors or paths where power transfer capacity is limited by concerns about conductor temperature or thermally induced conductor sag/clearance. Paths limited because of voltage stability concerns are not well suited for typical DLR methods. Traditionally, overhead conductors are rated using a Static Line Rating (SLR) based on unvarying and conservative "worst-case" assumptions about weather conditions in the geographic vicinity of the line corridor. PJM and AEP utilize ambient-adjusted rating sets that vary with local ambient temperature weather conditions. However, this approach still assumes static worst-case wind conditions. [2] Ratings calculated with the DLR method are based on real-time weather that is typically more favorable to conductor cooling, resulting in additional power transfer capacity above the SLR (Graph 1 below).



Graph 1: Histogram of DLR values as determined by a LineVision monitoring system compared the line's SLR. Data from a 138kV line in the Midwestern United States. Data date range from January 2, 2017- August 3, 2017.

Among the various weather conditions affecting conductor temperature, convective cooling has largest and most dynamic influence on the temperature of a bare aluminum overhead conductor. Increasing wind speed by an additional 3 ft/s at a 45° angle to conductor can increase its capacity by 35%, or by 44% when perpendicular to the line [3].

Monitoring systems supply dynamic ratings based on calculations performed to ensure the conductor will not exceed its Maximum Operating Temperature (MOT) and/or its maximum allowable sag [4]. Various monitoring systems are commercially available to perform DLR calculations and employ various measurement approaches. On-conductor systems are capable of performing measurements of sag (clearance), angle-of-inclination, spot temperature, vibrational frequency, and tension, while non-contact methods include placement of weather stations on conductor towers, topographic-specific computational fluid dynamic weather models, and electromagnetic and optical sag sensing systems. With the variables measured by the systems and additional inputs from utility Supervisory Control And Data Acquisition (SCADA) systems, such as line current (if not already measured by the monitoring system), the formulae for steady-state and transient heat balance equations for overhead conductors found in CIGRE TB 601 [5] and IEEE 738-2012 [6] can be performed to determine the DLR. When a DLR monitoring system is installed for a particular line and the communications are established between the system and the utility / RTO system operations control room, DLR can be integrated into system monitoring and dispatch.

The overall adoption rate of DLR is lower in the United States than in other nations with developed power markets. Canada, Belgium, France, England, Ireland, Austria, Slovenia, Bangladesh, Australia and many other countries with performance-based incentive regulations have already adopted DLR [7,8,9,10,11,12,13].

3. Market Analysis

As mentioned above, PJM's interest in DLR lies not only in recognizing additional transfer capability on existing equipment but is also focused on the overall savings DLR could provide by reducing system congestion. ABB market simulation software PROMOD [14] is a fundamental electric market simulation solution that incorporates extensive details in generating unit operating characteristics, transmission grid topology and constraints, and market system operations to support economic transmission planning. PROMOD models the hourly security-constrained commitment and dispatch of generation over a future annual period and provides nodal Locational Marginal Price (LMP) forecasting and congestion analysis. PROMOD is widely used in the electric utility industry to perform future-based economic analyses of a power system.

PJM uses PROMOD in its Market Efficiency process [2], where a proposed transmission project is entered into a planning model case to estimate the overall economic impact it might bring to the bulk power system. If a project is able to bring more transfer capability to a congested area of the system, this will reduce the congestion component of the Localized Marginal Price (LMP) observed in the area. Proposed transmission projects are simulated in PROMOD and then compared with a base case run that does not include the project. Projects are measured using two Tariff/Operating Agreement criteria. First, the project must address congestion as simulated in the Market Efficiency analysis. Second, the project benefits must exceed the costs by at least 25 percent. Project benefits are measured by comparing the benefits in the form of net load payments and/or production costs with and without the proposed project for a 15-year study period.

To study how a Dynamic Line Ratings installation project would perform in this analysis, several assumptions needed to be made. First, a DLR technology will only bring benefit when the transmission conductor is the most thermally limited element in the line. Often times long transmission lines with high nominal voltage within PJM are limited by their impact to post-contingency system stability. Other equipment limitations could include a non-conductor line device like insulators, wave trap communication devices, switching elements, and connective sections of conductor line station drops or tower jumpers. A proposed DLR project must focus on a line that is limited only by the conductor, or the project must also include upgrades to non-conductor limiting elements. Second, we assume in this analysis that DLR installations should be prioritized on the most heavily congested areas of a power system. The Cook- Olive line in AEP was selected to demonstrate a DLR technology not because it is frequently congested in operations, but because it is a short, 22 mile long line with a straight right of way ideal for installation. The line was an excellent candidate to demonstrate the overall installation process of Genscape's LineVision EMF monitor technology, and to demonstrate the variable behavior of real-time DLR data. To study DLR economic benefits, it was assumed that the heavily-congested 500 kV Target Line would see a similar ampacity benefit from a DLR installation. This line was used in this market analysis as it often exhibits congestion in PJM market operations.

Because this analysis was based on a hypothetical DLR installation on the Target Line, DLRs used were based on historically-observed weather conditions. Dynamic thermal conductor ratings are calculated based on observed weather conditions that govern the rate at which heat generated by joule/resistive heating is dissipated from an overhead conductor into the surrounding air. The key weather variables include air temperature, wind speed and direction, and sunlight/radiation. The IEEE 738-2012 standard provides the necessary formulas and constants required to calculate DLR from a set of weather observations, coupled with additional details about the (static) material properties of the conductor, including conductor material type, stranding, surface emissivity, etc. [6].

In this study, hypothetical back-casted hourly DLRs were computed for the Target Line transmission path using historic weather data from six (6) meteorological observation stations surrounding the Target Line path. This data was obtained from the National Oceanic and Atmospheric Administration (NOAA), which makes historical weather observation data from urban-center and airport-based meteorological stations available on its website (https://gis.ncdc.noaa.gov/maps/ncei/).

For the purpose of applying the weather observation data to the calculation of back-casted DLRs, several pre-conditioning steps were taken. Ambient air temperatures were computed as a simple average of the six stations. Wind speed and direction, being the most highly influential variables in the calculation of DLR, were treated more conservatively by adopting the lowest observed wind speed at each hour (with the accompanying direction) as the wind speed and direction used in the calculation of DLR for the Target Line pathway. Solar irradiance was also calculated using a conservative approximation that assumed zero cloud coverage and was calculated for each hour of the day based the sun's position in the sky above the Target Line path.

The Target Line path is roughly 18 miles in length. For the purposes of the computation of DLRs, the line was divided into three segments distinguished by different average section headings. Because DLR is strongly dependent on the incidence angle of wind against the overhead conductor, sections with different line headings can have significantly different ratings based on the same assumed wind speed and direction. The overall rating of the Target Line pathway was determined as the lowest calculated rating among the three sections for each hour of the study period. This approach reflects the nature of line path ratings, in which the line segment with the lowest rating (caused by low local wind speeds) sets the effective rating for the entire path.

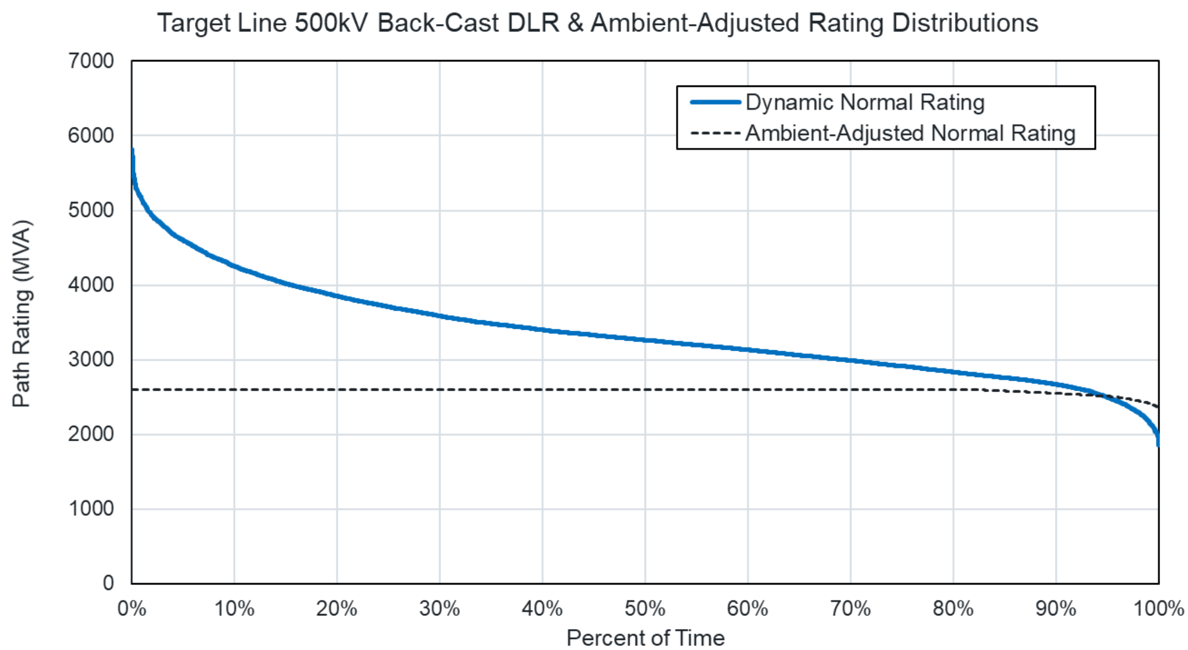


Figure 2: Distribution of the back-casted DLRs for the Target Line 500kV path and the distribution of the Ambient Adjusted Ratings

The economic analysis included near-term simulations to identify the collective and constraint-specific transmission system impacts of the DLR project. PJM conducted market simulations for study year 2018 under the following assumptions:

- PROMOD version 11.1 was used in this analysis
- The PJM Market Efficiency 2018 AS-IS Base Case was used: 2018 Summer Peak MMWG transmission system topology; 2018 PJM Load Forecast; PJM queue generation as of October 2017

An issue was identified regarding the limiting element for Target Line 500 kV facility being the station equipment. To address this issue, it was assumed that an already approved reliability upgrade was accelerated.

With the back-casted ratings formulated, the next step was to load the data into PROMOD. Two PROMOD simulations were employed: a Base simulation using planning ratings 2800 MVA normal and 3500 MVA emergency for the 500 kV Target Line; a PROMOD DLR simulation using dynamic hourly ratings. The economic savings generated by the DLR project can be determined by comparing results of the simulations above that had the same fundamental supply and demand operating constraints, but differing transmission ratings. This basic technique allowed PJM to evaluate congestion benefits of the specific DLR project.

A PROMOD nomogram was used to represent this hourly line limit. The nomogram was constructed as the difference between Target Line loading and the hourly dynamic limit.

$$N_{PBC} = DLR_{PBC} - MW_{PBC} > 0$$

This nomogram is treated as an additional constraint in the economic simulation to ensure that the transmission line will not be loaded above the dynamic limit. For each hour of our study year, the generation dispatch was optimized to meet system load while respecting all constraints at the lowest possible operating cost. This analysis was run and congestion costs were analyzed for each congested transmission line over the one-year period.

PJM congestion costs from market simulations for study year 2018 are shown in Table 1. Results show annual congestion cost reductions of more than $4 Million. The reduction in congestion can be attributed to the DLR project. The following table summarizes the results observed.

Total Annual Congestion			
Circuit	**Base Case**	**DLR Case**	**Congestion Savings**
Target Line 500 kV	$ (11,118,805)		$ 11,118,805
Target Line Terminus Substation Transformer 500/230 kV	$ (10,011,856)	$ (9,780,911)	$ 30,945
Downstream Line #1 230 kV	$ (20,386,483)	$ (22,773,039)	$ (2,386,555)
Downstream Line #2 to Downstream Reactor 230 kV	$ (13,491,444)	$ (16,180,653)	$ (2,689,209)
Downstream Reactor - Target Line Terminus 230 kV	$ (1,145,829)	$ (2,492,945)	$ (1,347,115)
Downstream Line #3 - Target Line Origin 230 kV	$ (2,867,503)	$ (3,336,319)	$ (468,816)
Downstream Line #4 230 kV	$ (19,570,723)	$ (19,824,341)	$ (253,619)
			$ 4,204,436

Table 1: Comparison of Congestion Payments between Base Case and DLR

There are many observations to be noted in the results in Table 1. First, we see that all congestion observed on our Target Line in the base case was eliminated in the DLR case. This results in $11.1 Million of savings on that particular line. We also see that many parallel and downstream circuits saw an increase in congestion when compared to the original base case. This makes intuitive sense, as the additional capacity found on the Target Line caused more MWs to be imported across the line. This increase in MW transfers will increase until a nearby (parallel or downstream) circuit becomes overloaded. However, because we are relaxing a single constraint in an optimization, we will expect that the reduction in congestion on the target line will outweigh additional congestion seen on nearby elements. This could encourage DLR projects to propose device installation on several transmission circuits in a congested area. This DLR case market simulation resulted in overall system congestion savings of $4,204,436.

It is important to note that this economic analysis has assumed perfect alignment between real time and day ahead energy markets. Day-ahead unit commitment utilizes forecasted demand and transmission outage information to predict impeding congestion and commit generation to meet system load while mitigating line overloads and other equipment violations. When real-time conditions deviate from the day-ahead case, costs are incurred to adjust the system generation profile to meet current violations. In order for grid operators to most effectively utilize the additional transfer capacity observed by DLR, these dynamic ratings must be forecasted and provided as input data to the day-ahead market. Further, when real-time DLR values deviate from their forecasted values, balancing congestion costs may occur. The provider of DLR forecasts must be certain that the values provided are realistic and accurate.

4. Future Research

AEP anticipates the potential for these types of advanced transmission line monitoring technologies to be utilized in a variety of manners to add value into utility practices. Future work on additional projects could be considered to investigate the existence of co-convection, wind generator output occurring at the same time as increased capacity on nearby transmission lines from Dynamic Line Ratings.

Additionally, AEP could explore utilizing advanced analytics on these new types of datasets that had not previously been available to the utility industry. AEP's Asset Health Center are new metrics and algorithms that focus on galloping and icing detection, as well as anomalous conductor motion indicative of equipment damage, or extreme weather events. Trending the measured conductor data over long periods of time may be able to provide indicators on conductor health (i.e. a mechanical property of the conductor has changed, perhaps as a result of annealing which is indicated by a change in tensile strength). Analyzing change in conductor strength as a function of sag as compared to historical time-series measured values could identify signatures and patterns of conductor degradation and reveal shortened lifespans triggering preventative maintenance or rebuild events prior to catastrophic failure occurs.

5. Conclusion

Having determined that significant additional capacity could be provided via the implementation of a LineVision DLR system on the Cook-Olive line, a congested line within the PJM footprint (Target Line) was selected for further study, and a DLR economic impact analysis was performed. The congested 500kV Target Line did not have a DLR system available to determine the line ratings, so an alternative method using NOAA historical weather data was utilized to create back-casted ratings. A PROMOD analysis incorporating these computed DLRs was then performed and the resulting economic impact showed that the additional capacity provided in the DLR case led to a net congestion saving of over $4 Million in the one-year study period. It is also important to note that an installation and implementation of a commercially available DLR system on the Target Line would roughly cost around $500,000 which would result in a rapid payback period of approximately two months of operational use.

These results show great potential for DLR systems to be used as a congestion management tool for utilities and RTOs. Such systems allow for increased asset utilization and have been shown to be a cost-effective advanced transmission technology. As DLR systems can be retrofitted to existing transmission lines, these systems could be rapidly installed to provide needed capacity during the time between proposal of a Regional Transmission Expansion Plan (RTEP) enhancement and it being put into service. It is important to engage conductor asset owners like AEP when considering the use of DLR as it relates to Transmission Owner engineering and design requirements of physical equipment. Because DLR technologies exist only to enhance the capabilities of existing transmission assets, the participation of these asset owners is critical to ensure proper use and protection of all transmission conductors. Asset owners must provide detailed operating temperature specifications of transmission assets, including maximum operating temperatures, safety clearance limits, and required margins of capacity utilization.

In addition to the economic benefits these systems can provide, incorporating these types of advanced transmission technologies provides greater visibility into the real-time situational awareness of the grid increasing system resiliency. Eliminating the use of ambient weather assumptions, as per static line ratings, and switching to operations utilizing DLR, based on measured line parameters, alleviates reliability and safety risks associated with the select times when a line’s static rating may not be conservative enough. Further applications of DLR to improve system resilience could focus on contingent lines associated with planned outages, or as means to increase capacity in emergencies or critical operating conditions.

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