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Does Dynamic Line Rating Work without Line Sensor Feedback?

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SUMMARY

Dynamic line rating systems and methods have been proposed which depend only upon weather parameters. The goal of these methods is to eliminate the cost and complexity of purchasing, installing, and communicating with line mounted sensors that provide feedback to dynamic line rating systems (DLR). One reason for proposing such systems is to expand on the use of the ambient adjusted transmission line rating (AAR) method, which uses only ambient temperature in adjusting line ratings. The use of AAR for adjusted line ratings is now mandated in the USA by FERC Order 881.

This paper compares computed DLR values of a traditional sensor-based DLR system with the same system whereby the feedback from conductor monitoring sensors is removed, herein called Sensor-less Rating Estimates, or SREs. This SRE method therefore becomes a weather-only based DLR proxy.

Analysis of the data shows the sensor-less approach proves to be a poor indicator of line rating. SRE ratings varied from the DLR values by more than ±10% for over one-third of all line ratings studied. It is also shown that without the benefit of line-mounted sensors to provide feedback, there is no way of determining whether any SRE rating is based on the actual limiting span along the transmission line. This makes it impossible to determine if any SRE value is within an acceptable DLR rating tolerance.

Risks associated with over-rating and under-rating transmission line capacity are also discussed.

The data set used for the analysis was based on DLR values retrieved from DLR systems installed on three transmission lines. The time period covered 13 months of rating for each line and encompasses over 800,000 data points. To avoid skewed data, the three lines were selected to represent different geographies. The three lines were located in the western USA, the eastern USA, and Europe. The lines traversed open terrain, shielded terrain, and mixed terrain. SRE ratings were calculated for the same lines over the same time span using the same data as available to the DLR system except for the real-time data collected by the DLR sensors. The two lines located in the USA had both the SRE and DLR ratings computed using the IEEE Std 738 methodology, and the line in Europe utilized the CIGRE Guide 601 methodology.

KEYWORDS
Dynamic Line Rating, Static Line Rating, Ambient Adjusted Rating, DLR, AAR, Sensor-less Rating Estimate, IEEE-738, CIGRE-601, FERC Order 881, Risk

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INTRODUCTION

Transmission lines have traditionally been assigned a fixed power carrying capacity based on very conservative weather conditions. This is commonly referred to as the line’s static rating. Seasonal Adjusted Rating (SAR) and Ambient Adjust Rating (AAR) methods adjust these static ratings by recognizing that a line’s capacity is related to ambient temperature. Utilities have used these methods primarily to increase line capacity during times of cooler weather.

To maximize use of a transmission line asset, dynamic line rating, or DLR, is used as it not only considers all weather parameters, but also uses line mounted sensors to provide real-time information about the conductor used in the DLR calculation process. This is recognized by the US Federal Energy Regulatory Commission, FERC, in their statement that all DLR technologies “include remote sensing” [1].

There has been great interest in implementing DLR systems more widely on transmission lines to take advantage of the economic, reliability, operational, and open access benefits DLR can provide. Open access benefits include “reducing the likelihood of ad hoc transmission uprates”, and “helping to ensure equal access to the transmission system via markets on a comparable basis” [1].

Recently, DLR-like rating systems have been proposed which only utilize weather parameters. The goal is to eliminate the cost and complexity of purchasing, installing, and communicating with line mounted sensors that have traditionally provided real-time information about the conductor to DLR systems. One reason for proposing such systems is to extend the use of the weather-only AAR line rating method whose use is now mandated in the USA by FERC Order 881 [2].

This paper compares computed DLR values of a traditional sensor-based system with the same system in which feedback from the line mounted sensing elements is removed. Therefore, the comparison system depends only upon weather data as would be done in a system where sensors are not used. For this paper's purpose, the rating produced by the weather-only method is referred to as a "Sensor-less Rating Estimate (SRE)".

While it may be assumed obvious that an instrumented DLR system would provide more accurate ratings than a weather-only system, an objective comparison is deserved. The goal of the study was to determine how DLR and SRE values compare, and what – if any – risks can be identified by using a method that produces SRE values instead of DLR values.

METHODOLOGY

DLR values were obtained from installed DLR systems. The SRE values were developed based on the same weather data and conductor properties used in the DLR systems, excluding sensor feedback. Only real-time ratings were computed in both cases. No forecast ratings were developed.

DLR METHOD

Data was collected from installed DLR systems for multiple locations spread across three (3) geographical regions: the western USA, eastern USA, and Europe, representing approximately 90 miles (145 km) of transmission line. Data was collected from each of the installed DLR systems over a thirteen (13) month period. Over 800,000 data points were collected during all seasons and weather conditions.

The three lines were installed in a combination of arid/semi-arid desert, humid continental, and maritime climates, each of which experienced four distinct seasons. The lines included shielded terrain, non-shielded terrain, and mixed shielding conditions.

Calculations for the US locations were done using the IEEE-738 [3] method and the European locations were done using the CIGRE Guide 601 method [4].

For the DLR system real-time conductor data was gathered from specially developed monitors that directly measure key conductor parameters. These real-time line monitors were mounted on the energized transmission line and measured line current, conductor temperature, conductor clearance-to-ground, inclination, and other environmental factors. The data was transmitted back using a satellite communication link.

Live-weather feeds were time synchronized to the conductor data and passed through a learning-based system to develop a dynamic conductor temperature-clearance model that characterizes the conductor behavior based on the experienced real-time weather and loading conditions.

The dynamic line rating (DLR) was then determined based on real-time weather and line conditions using the developed conductor temperature-clearance model. The result is a clearance based dynamic line rating that ensures compliance with clearance limitations and conductor thermal limits. This method is fully described in the paper titled "Reliability Based Transmission Capacity Forecasting" as presented and published in conjunction with CIGRE Paris Session 2018. [5].

The overall line rating is determined by the lowest DLR calculated from the monitored spans. This is the Limiting Span. The limiting monitored span is the span which would result in the minimum required clearance-to-ground or the conductor having reached its maximum operating temperature if the line was loaded to the DLR value. This dictates the highest load that can be applied to the line.

SRE METHOD

Sensor-less Rating Estimates (SRE) were computed using the same computation method as was used in the DLR calculations, utilizing the same real-time ambient temperature, perpendicular wind speed[1], conductor maximum operating temperature (MOT), absorption, emissivity, location, elevation, etc. The difference between SRE and DLR is that SRE does not use any in-situ conductor measurements to produce adjustments based on feedback from sensors on the line. SRE's only use weather data and the line configuration for normal operation, i.e., the configuration used to determine the static rating of the line.

The limiting span for the SRE method was determined to be that with the lowest calculated SRE value. This is the span at which the lowest SRE value does not exceed the conductor thermal limits (as defined by the MOT) based on the aforementioned real-time weather conditions. The assumption was made that the MOT is determined to be a safe thermal limit, and that achieving the conductor thermal limit will not exceed the clearance limit. Because the modeled lines were fully instrumented, the data did show this was the case. However, for situations where SRE methods would be applied without such benefit, this simplifying assumption may introduce additional errors in the SRE method. For the sake of this analysis, any possible such errors were not considered. Note that the same weather data was used for the DLR and SRE methods. The same spans on which the sensors were installed for the DLR method were used for the SRE calculations. This makes the comparison of the two methods equivalent.

ANALYSIS: MIS-INDENTIFICATION OF THE LIMITING SPAN

The SRE method selected a non-limiting span to form the basis of the line rating for 27% of all cases (i.e., the correct span was chosen in only 73% of cases). See Table 1 and Table 4. That is, the lowest rated span on a line in the SRE method was not the actual limiting span based on the feedback provided by the DLR system's conductor monitors. Recall that for instrumented spans, the lowest

[1] Wind speed and wind direction are provided by the weather service. The perpendicular wind speed is derived from these parameters by computing the equivalent wind speed component that is perpendicular to the conductor along each monitored span.

rated span will always be the limiting span as the rating is based not only on weather conditions, but parameters such as sag, clearance-to-ground, conductor temperature, accumulated creep[2], and so forth.

Table 1: Percent of Cases where the Limiting Span is Correctly Identified by SRE Method

Region	Percent of SRE Values Correctly Based on the Limiting Span	Percent of SRE Values NOT Based on the Limiting Span
US (East)	76.9%	23.1 %
US (West)	64.2%	35.8 %
Europe	77.9%	22.1 %
AVERAGE	73.0%	27.0%

ANALYSIS: SIGNIFICANT RATING DISCREPANCIES

For those cases where the SRE method correctly identified the limiting span, Table 2 summarizes how the SRE method overestimated or underestimated its line rating value compared to the computed DLR value. When making rating comparison, any SRE value less than 10 % above or below the DLR rating was considered acceptable. Using this tolerance band as the basis, 34.5 % of all SRE line ratings fell outside the +/- 10% DLR value. This results in significant over-rating or under-rating of lines for over one-third of all cases.

Some rating errors were quite substantial. Table 3 shows the maximum discrepancy range for each of the three lines.

Table 2: Magnitude of Discrepancy between SRE and DLR Values

	Magnitude of Discrepancy	Percent of cases with related magnitudes of discrepancy (+/-)		
		Under	Over	Total
Discrepancy Between SRE and DLR Values for All Cases	10-15%	7.0%	5.3%	12.3%
	15-20%	2.6%	4.1%	6.7%
	20-25%	2.1%	2.1%	4.2%
	>25%	10.0%	1.3%	11.3%
	Total	21.7%	12.8%	34.5%

*Note: SRE discrepancy magnitudes of <+/-10% of DLR are not included.

Table 3: Worst-Case Minimum and Maximum Rating Differences between SRE and DLR Methods

Line Region	Greatest Under Rating by SRE compared to DLR	Greatest Over Rating by SRE compared to DLR
US (East)	22.3 %	18.8 %
US (West)	47.0 %	51.2 %
Europe	28.7 %	33.5 %

It is interesting to note that during the analysis, the median discrepancy of the SRE value would increase or decrease with an apparent seasonality, with under-rating of lines being more common

[2] Comparing the designed and as-installed sag and clearance parameters to measured sag and clearance values within the same clearance-vs-temperature range allows for the computation of accumulated creep.

during spring and summer, and over-rating of lines more common in the fall and winter. The distribution of SRE value discrepancies compared to that of the computed DLR values is visualized in Figure 1, where this shift can be seen. While this suggests that some form of SRE value compensation might be possible, no such cyclicality was seen over the course of 24-hour periods, where discrepancies appeared to be random, making possible compensation difficult if not impractical. However, this also underscores the underlying variability seen in SRE values compared to DLR.

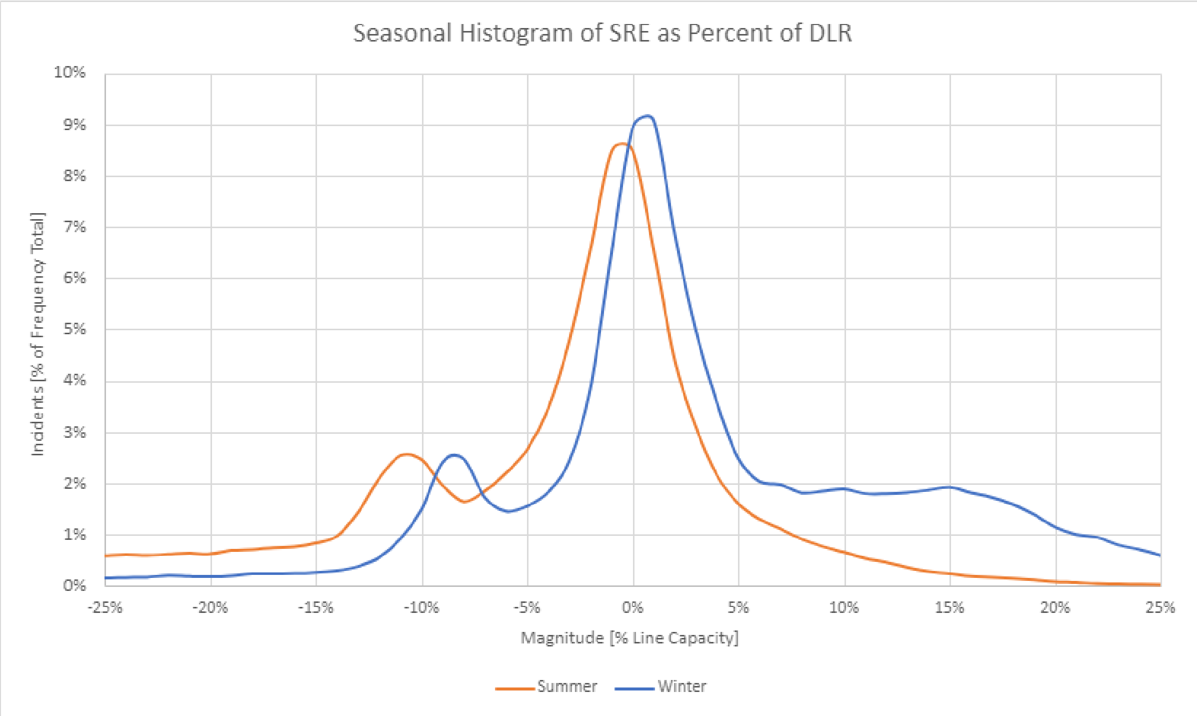

Figure 1: Seasonal Histogram of All SRE Values as a Percentage of DLR Values

ANALYSIS: INABILITY TO BASE RATING ON THE LIMITING SPAN

The basic risk associated with using the SRE method can be clearly seen from the first two tables.

- For example, from Table 1 we see that the SRE method correctly identifies the limiting span for the European line (the best case) for 77.9% of the data samples.
- Table 2 shows that for this same line, 21.7% of those ratings will be low by 10% or more, and 12.8% will be high by 10% or more. Therefore only 51% [77.9%*(1-34.5%)] of the ratings will be within +/-10% of the computed DLR value when both methods correctly identify the limiting span. Table 4 summarizes this calculation for all three lines.
- The second data column in Table 1 shows a significant percentage of SRE ratings for all lines are based on the incorrect span. It must be noted that some SRE values will be based on use of the wrong limiting span and still be within the stated acceptable +/- 10% discrepancy range.

Table 4: Summary of Convergence of SRE and DLR Ratings When Both Methods Select the Same Limiting Span

Line Region	Percent of SRE Values within +/-10% of Computed DLR Value
US (East)	50.4%
US (West)	42.0%
Europe	51.0 %
AVERAGE	47.8%

This is a key failing of the SRE method; without the benefit of a sensor, there is no way of determining whether any rating is based on the limiting span. Therefore, determining if any SRE value is within an acceptable rating tolerance compared to DLR is not possible; it is simply not possible to know if the rating is based on the limiting span.

To improve the selection of the limiting span by the SRE method, it was theorized that the span with the lowest perpendicular wind speed would make an excellent indicator. This assumes the limiting span would correlate highly to the lowest perpendicular wind speed as this parameter typically has the greatest impact on conductor cooling. However, upon examination, this proved to be a poor assumption. On average, for all three regions, the limiting span was not the same as the span with the lowest perpendicular wind speed for 13.5% of all instances. In retrospect, this makes sense. It was previously noted that for instrumented DLR spans, the lowest rated span can be based not only on weather conditions, but also on other parameters such as sag, clearance-to-ground, conductor temperature, accumulated creep, etc. See Table 5 for detail.

Table 5: How often the span with the lowest perpendicular wind speed is not the limiting span

Line Region	Percent of DLR Values where the Limiting Span does not have the Lowest Perpendicular Wind Speed
US (East)	3.4%
US (West)	20.6%
Europe	16.4%
For all Lines	13.5%

RISKS

From the above analysis it is seen that the SRE values from a system relying upon weather data and without feedback from a line mounted sensor will produce line ratings that are frequently, and often substantially, above or below the computed DLR values which use real-time line conductor information. It was also observed that without the benefit of a sensor, there is no way of determining whether any SRE value corresponds to the limiting span, lending additional uncertainty to the values. It is important to understand what these risks are in evaluating any decision to use SRE values in place of DLR values.

RISKS ASSOCIATED WITH OVER-RATING A LINE’S CAPACITY

The primary risk in over-rating a transmission line is violation of any mandated clearance-to-ground limit. In the USA, this limit is imposed by the National Electric Safety Code (NESC) and represents the minimum distance to ground which must always be maintained. If a line is operated above a rating such that it exceeds its maximum operating temperature, then the resulting sag will cause it to exceed its allowed clearance to ground as well.

There are several secondary risks associated with exceeding transmission line clearances:

- The line can flash over to underlying foliage resulting in a line to ground fault and subsequent circuit breaker operation.
- A flash-over can ignite a fire in underlying foliage. Wildfires initiated by transmission lines can result in the loss of property and/or lives. Note that wind driven power line related wildfires become on average 10 times larger than wildfires ignited by other causes [6], and may result in extreme liabilities [7].
- If a line is operated above its maximum operating temperature repeatedly, it will shorten the life of the conductor and hardware through the process of annealing. This may result in a premature requirement to replace the damaged conductor.

RISKS ASSOCIATED WITH UNDER-RATING A LINE’S CAPACITY

- Financial: Operating the line at load levels below that which it is capable of handling is a lost opportunity risk. If a line, or lines, limit the transfer of power from cheaper generation

sources, forcing the use of more expensive generation sources, the resulting difference becomes a congestion cost. These costs are borne by the rate payer.
- Legal: It is possible that using a method that may knowingly under-rate a transmission line could possibly be construed as artificially manipulating electricity prices. In the past, electricity price manipulation has resulted in legal actions. [8]
- Operational: In extreme conditions, excessive congestion in a network will result in generators denying the delivery of power to loads. This can lead to the use of rolling blackouts to minimize the loads needing to be served via the congested network.

CONCLUSIONS

Systems have been proposed to reduce the cost and complexity of implementing DLR on a transmission line by eliminating the use of the line mounted sensors used as part of a DLR system. The paper studied the ratings produced by such a method, herein called Sensor-less Rating Estimates, or SREs, with the DLR values produced on three transmission lines over the course of 13 months, representing over 800,000 data points. The geography of the lines covered the western USA, the eastern USA, and Europe. The lines traversed open terrain, shielded terrain, and mixed terrain. The two lines located in the USA had both the SRE and DLR ratings computed using the IEEE Std 738 methodology, and the line in Europe utilized the CIGRE Guide 601 methodology.

Analysis of this data set has shown:
- On average, 27 % of the time the SRE method mis-identifies which span of a transmission line is the limiting span.
- For the data set, 12.3% of all SRE method values resulted in over-rating a transmission line by 10% or more compared to the computed DLR values.
- For the data set, 29.8% of all SRE method values resulted in under-rating a transmission line by 10% or more compared to the computed DLR values.
- Without the benefit of a sensor, there is no way of determining whether any SRE rating is based on the limiting span. This makes it impossible to determine if any SRE value is within an acceptable DLR rating tolerance as it is not known if the value is based on the limiting span.

In general, the SRE method of attempting to compute DLR values without the benefit of feedback from line mounted sensors proved to be a poor indicator of line rating.

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