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A Non-Contact Sensing Approach for the Measurement of Overhead Conductor Parameters and Dynamic Line Ratings

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SUMMARY

American Electric Power has deployed a non-contact transmission line monitoring system that utilizes an array of electromagnetic field (EMF) sensors to monitor the Cook-Olive 345kV line. The Genscape monitoring system, called LineVision, measures the alternating-current EMF emitted from the conductor. The EMF data is analyzed in a computational model, which determines various conductor properties including loading, clearance, temperature, effective wind speed, and the Dynamic Line Rating (DLR). The line's DLR has shown significant additional capacity above its Static Line Rating, which could be used in power markets to allow for grid flexibility and congestion mitigation. A description of the monitoring system, sensing technique, and data collected are described in this paper.

KEYWORDS

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

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1. Introduction

The landscape of the electricity generation, transmission, and distribution sector is one that is constantly evolving. Generator retirements, new generation coming online, transmission line rebuilds, new transmission lines being energized, and the adoptions of new technologies are some of the factors at play in shaping the short- and long-term operational and planning strategies of utility and market operators. While the timelines associated with these events can be lengthy, the immediate need for flexibility within the existing grid assets persists. Utilities and market operators are constantly looking at technologies and processes to reliably improve the utilization of existing assets. One technology that has shown to have the potential to increase capacity on thermally-limited transmission lines is Dynamic Line Rating (DLR) [1, 2]. In October of 2016, Oak Ridge National Laboratory issued a subcontract to perform a field-based study on the potential impact DLR can have on increasing capacity on existing transmission lines, and that capacity's effect on the efficiency of power market operations. Genscape, Inc., American Electric Power Corporation (AEP), and PJM Interconnection, L.L.C. entered into a research agreement to perform this work. We have provided a description of the methodology used to determine the DLR values.

2. Dynamic Line Ratings

Traditionally, transmission lines are operated, and power markets are cleared, using a line's Static Line Rating (SLR). The SLR is the maximum amount of power flow through a transmission line on a steady-state basis so the conductor will meet (but not exceed) its Maximum Operating Temperature (MOT) – assuming near-worst-case weather conditions [3]. MOT is determined during the line design process – based on two constraining factors: the minimum allowable clearance of the overhead conductors, and the risk of annealing conductors at higher operating temperatures, resulting in a loss of tensile strength. Lines are designed so that regulated minimum clearance limits will not be violated by a (thermally-expanded) conductor at the MOT even after accounting for conductor creep and vegetation growth over time.

With this in mind, the MOT, and (by extension) the SLR are calculated in such a manner, and set to ensure safe and reliable operation of the transmission system. This SLR is often adjusted seasonally, or sometimes daily with Ambient Adjust Ratings. These are based upon the forecasted ambient temperatures for a day in the geographic vicinity of the transmission line.

The governing equation for calculating the MOT is the conductor's heat-balance equation. This contains multiple variables, such as the convective heat loss forced from wind passing over the conductor, natural convection, radiative cooling of the conductor, solar heating from the sun, resistive heating from the electrical current, ambient temperature, humidity, atmospheric pressure, and the presence of precipitation [4, 5]. As these variables will naturally change over time, near-worst-case values for the weather variables are selected when calculating the SLR to be used over long time periods.

As an alternative to utilizing the SLR, transmission lines can by operated dynamically, with a rating that changes based upon the actual weather conditions. This methodology takes advantage of the fact that in the vast majority of the time, prevailing weather conditions will be far more favorable when compared to the assumed near-worst-case condition in the SLR. Installations of field monitoring sensors capturing various weather and/or conductor properties (such as sag or conductor temperature) allow for the calculation of a real-time rating, enabling Dynamic Line Rating (DLR).

It should be noted that not all transmission lines are thermally-limited, as some can be voltage/stability limited (often the case for lines greater than 100 miles).

3. Electromagnetic Field Sensors

The field sensors used to perform the measurements necessary to determine the target line's DLR were Genscape's patented LineVision Electromagnetic Field (EMF) monitors. Using these non-contact, ground-based sensors, EMF values are measured by an array of sensors, then securely and wirelessly transmitted to Genscape's servers – where analytical computations take place.

When current is flowing on transmission lines in North America, a 60 Hz AC magnetic field (B-field) is produced. The vector magnetic field is measured in horizontal and vertical directions, in the cross-sectional plane of a typical transmission right-of-way (ROW). This measurement is made using a pair of ferrite-core induction coils (oriented horizontally and vertically), producing a signal that is passed through an active analog bandpass filter before being sampled by a 12-bit Analog-to-Digital Converter (ADC) at 10 kHz. The two magnetic field measurements and the electric field measurement are performed simultaneously, allowing the computation of relative phase angle between the three pairs of 60 Hz sinusoidal signals.

The 60 Hz AC electric field (E-field) created by voltage on energized overhead conductors is measured in the vertical direction – using two aluminum plate electrodes forming a capacitive electrometer. The voltage across the electrometer is filtered and amplified through a high-impedance signal conditioning path, and sampled using a 12-bit ADC at 10 kHz.

The fundamental equation utilized to determine the current flowing on a transmission line and its conductors' positions (and thus sag) is Biot-Savart law, which describes the magnetic field generated by an AC current.

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_C \frac{I d\mathbf{l} \times \mathbf{r}'}{|\mathbf{r}'|^3} \qquad (1)$$

$\mathbf{B}(\mathbf{r})$ = Vector magnetic field at position $\mathbf{r}$
μ_0 = Permittivity of free space
I = Electric current
$\mathbf{r}'$ = Radial distance from conductor
$d\mathbf{l}$ = Conductor element

This unique sensing method allows for the determination of relevant line characteristics, as the amplitude of the magnetic field is proportional to the current on the line, and the vector direction of the magnetic field is related to the position of the line.

A simplified illustration shown below (Figure 1) depicts a single conductor in free space at two different positions (current is flowing in/out of the image). Height H_1 is a cool conductor, and H_2 is a hot conductor – sagging lower. An angular change, $\Delta\Theta$, of the magnetic field, **B**, is produced when the conductor changes positions in height, ΔH, which is a function of the change in the conductor temperature, $f(\Delta Tc)$. The illustration shows the measurements taking place at a single LineVision monitor. When multiple phases exist, as is the case with transmission lines, the electromagnetic fields act as a linear superposition of the single-conductor model, and the signal can be deconstructed by placing multiple LineVision monitors to capture additional variables.

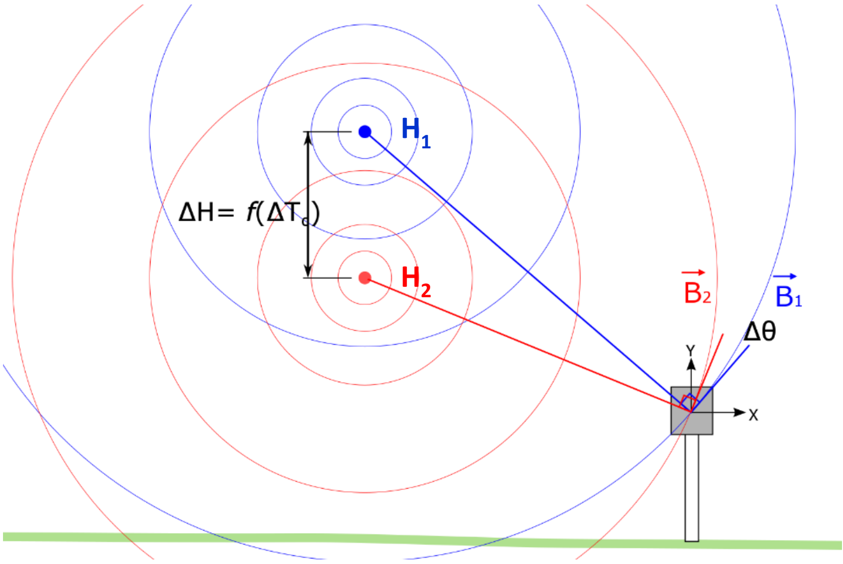

Figure 1 (Left): EMF monitor detecting the angular change of the EMF signal, as a single conductor sags from H_1 to the lower position H_2 when it is heated.

With the conductor position known, a sag-temperature curve is constructed and refined, based upon the thermo-mechanical properties of the conductor's known materials. With this information, all the variables in the governing Steady State Heat Balance Equation (2) [4] are now known – with the exception of the effective wind speed that is cooling the conductor, S_{wind}, which can now be solved.

$$I^2R + Q_{solar}(\varepsilon) = Q_{rad.}(\varepsilon, T_c, T_a) + Q_{conv.}(T_c, T_a, S_{wind}) \qquad (2)$$

I^2 = Current flowing on the line
R = Resistivity
ε = Conductor emissivity
T_c = Conductor temperature
T_a = Ambient Temperature
S_{wind} = Effective wind speed

With the effective wind speed known, Equation (2) can be used to solve for I_{max} by making I_{max} the unknown in place of I, while using the known effective wind speed previously calculated, and substituting the maximum conductor operating temperature, T_{max}, in the place of T_c. This is shown in Equation (3).

$$I_{max}{}^2R + Q_{solar}(\varepsilon) = Q_{rad.}(\varepsilon, T_{max}, T_a) + Q_{conv.}(T_{max}, T_a, S_{wind}) \qquad (3)$$

I_{max}, is the DLR, or the current at which the conductor will meet, but not exceed, the MOT – based upon the present ambient weather conditions. This DLR is continually recalculated as weather condition incidents on the conductor change, causing changes in conductor temperature and sag, as reported by the LineVision monitoring system.

4. Selection of the Target Transmission Line and Monitoring Sites

Engineers from AEP, PJM, and Genscape worked together to identify a transmission line for this DLR study and took various criteria into consideration. These included ease of access to potential installation sites, simplicity in design (i.e. relatively few variations in topography and line heading), and the presence of synchrophasors at the line origin and at terminus substations. After considering multiple options, the Cook-Olive 345kV line was selected. This line originates in southwest Michigan, runs east for approximately 5 miles, takes a 90-degree turn south, and continues for approximately 18 miles, where it terminates in northwest Indiana.

Figure 2 (right): Path of the Cook-Olive 345kV line with monitoring site installations identified. Image source: Google Earth Pro

Significant variations in solar irradiance/cloud cover, wind speed, and wind direction can occur along a transmission line path. DLRs calculated using the measured physical properties of the conductor (sag, temperature) aggregate the effects of local variations in wind speed into a single average conductor temperature at a shared horizontal tension [6]. Separate monitors must be used on neighboring line segments separated by dead-end structures or by significant geographic obstacles (e.g. valley or ridge crossing), to accurately capture the representatively lowest DLR of a total line path at any given moment and ensure safe and reliable operation. AEP engineers were able to identify two critical clearance limited spans on the north-south heading. These were the sites selected as installation locations for the LineVision monitoring systems. One site was also selected on the portion of the line that runs east-west, to capture variations in localized weather.

5. Installation of the EMF Line Monitoring Equipment

Prior to installation of the LineVision monitors, AEP engineers compiled documentation on various known aspects of the Cook-Olive line such as design tension/sag, the in-service date, phase order information, conductor type, bundle configuration, insulator design, Maximum Operating Temperature, seasonal Static Line Ratings, historical seasonal maximum loadings, next limiting element information, and critical clearance-limited spans.

Installations were performed by Genscape and AEP field engineers after daily safety briefings and scope of work reviews were completed. LineVision EMF monitors were installed by securing the weatherproof sensor enclosure onto a steel mounting post (secured on a concrete foundation approximately 24" deep). For each monitored circuit, an array of three EMF monitors is specified. Because the sensor does not contact the line or structure, no outage coordination, lineman crews, or bucket trucks were required to complete the work performed.

Figure 3: Field engineer configuring a monitor.

Figure 4: An array of installed monitors.

After the installation of monitoring units at each site was completed, the field engineers used laser measurement tools to perform a comprehensive site survey. They recorded the critical distances from a point of reference to various components that are necessary for the configuration of the computational geometrical model. Components included sensor locations, conductor height and spacing, insulator height and spacing, and span distance. A simplified version of this model is shown below.

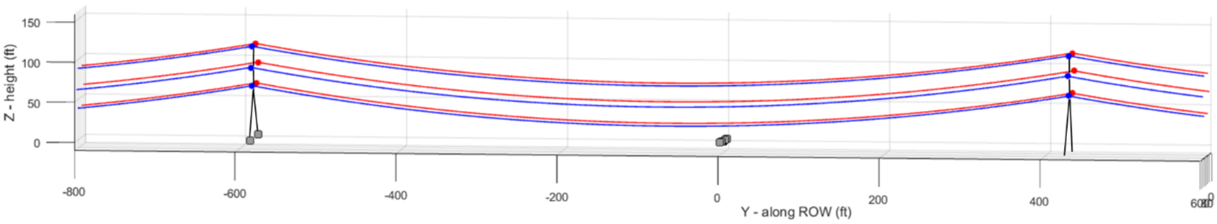

Figure 5: View along the Right-of-Way. Gray boxes represent EMF monitors.

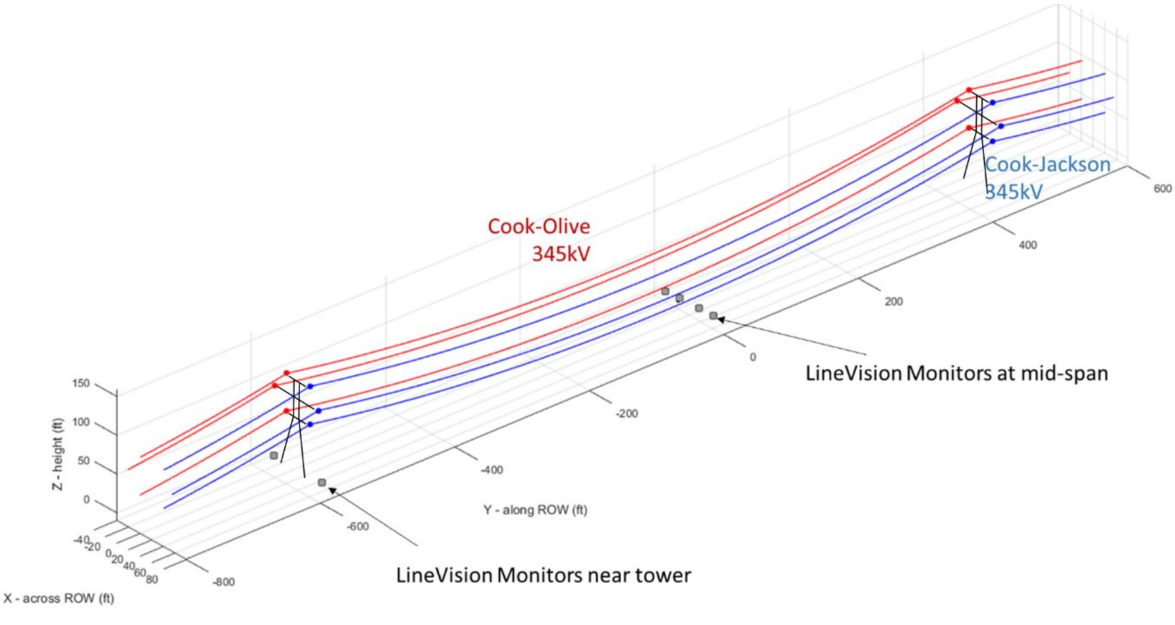

Figure 6: Orthographic Projection View. Gray boxes represent EMF monitors.

6. Data Analysis

With the field monitors now collecting and transmitting data, the LineVision system was able to run the computational models (using the methods previously described) to determine the conductor's loading, clearance, temperature, and normal dynamic line rating (steady state). A sample set of three days of data (beginning on January 8, 2017 and ending on January 10), is displayed below. At certain times, clearance and conductor temperature values are shown as horizontal grey lines. During these periods, loading on Cook-Olive was low in comparison to the Cook-Jackson line that runs on the eastern side of the vertical-parallel structures. In this situation, the EMFs emitted from the Cook-Jackson conductors superimpose and overwhelm the EMF signals available from the Cook-Olive line to the extent that EMF measurement uncertainty makes it difficult to discern the clearance of the Cook-Olive conductors with satisfactory accuracy. During these times, DLR is, instead, calculated based on wind speed and direction data acquired from a weather data model. This model provides latitude-, longitude-, and elevation-specific weather variables parameterized by NOAA meteorological station inputs and forecasts. Because considerable uncertainty exists in this weather model approach, a 50% reduction was applied to modeled wind speeds before calculating DLRs, resulting in more conservative ratings that reflect likely microclimate conditions along the ROW – in which actual wind speeds are lower.

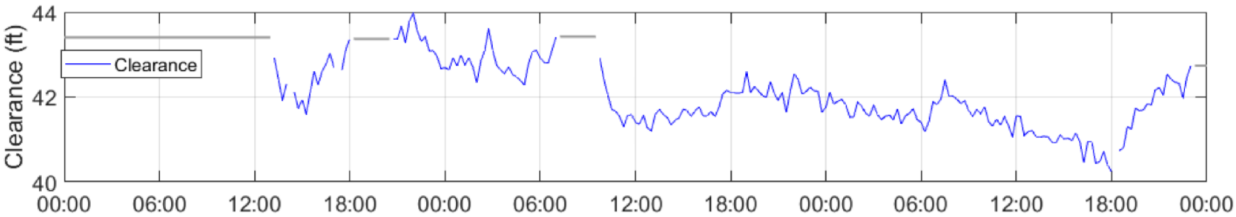

Figure 7: Conductor clearance in feet over a 3 day period.

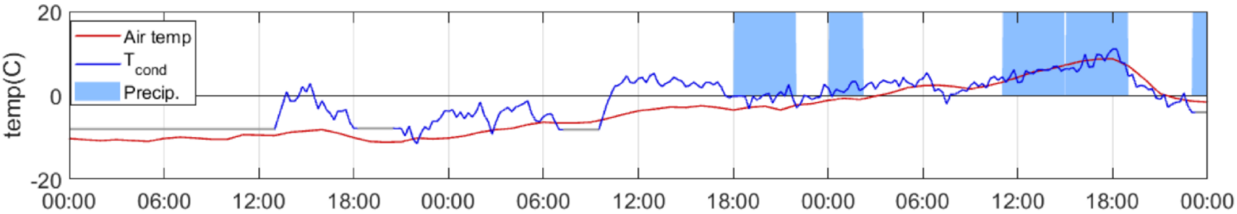

Figure 8: Conductor temperature and ambient temperature in Deg C over a 3 day period.

In Figure 8, a trend can be seen between the conductor's temperature and the ambient temperature. As the conductor is relatively lightly loaded, the resistive heating component is low, and conductor temperature correlates strongly with the ambient temperature.

When comparing Figure 7 and Figure 8, another trend can be seen as the graph line of the conductor temperature moves inversely to that of the conductor clearance. This indicates that when the conductor is warmer, it sags closer to the ground, as expected.

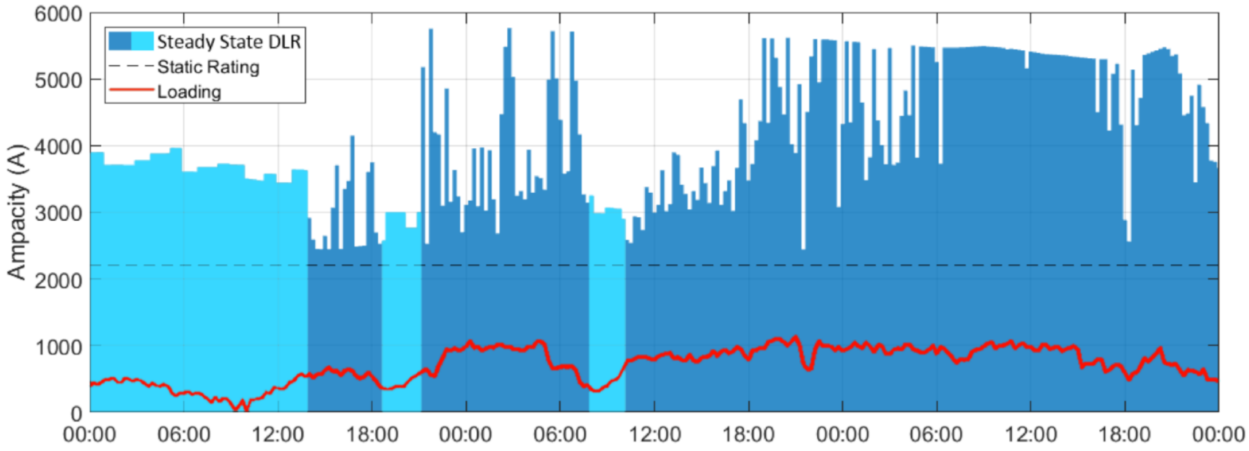

Figure 9: Circuit loading, Steady-State DLR, and Static Line Rating (SLR) shown over a 3 day period. The lighter shade of blue (teal) indicates times when the system utilized the external weather data source as opposed to the sag as determined from the LineVision EMF monitors.

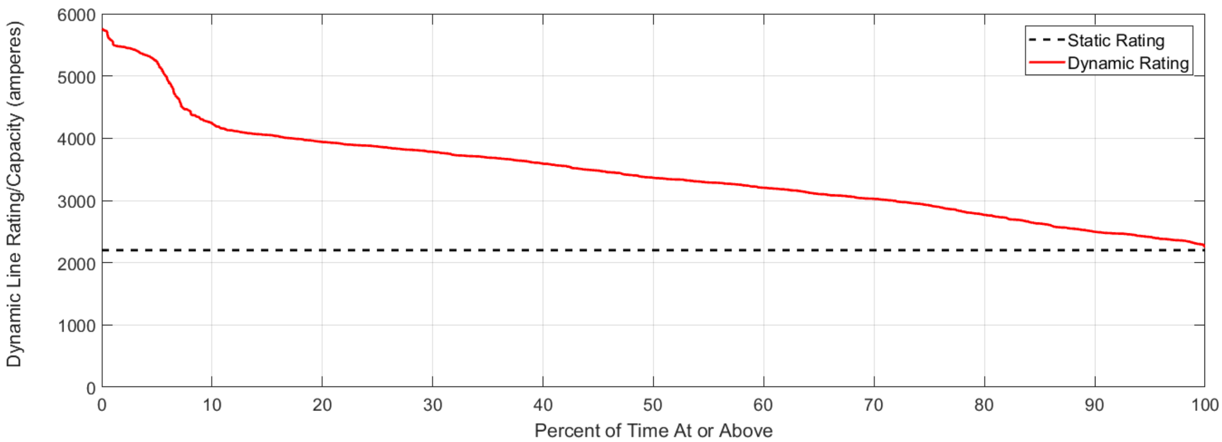

Figure 10: Histogram for the month of January 2017,
showing the amount of time the line's capacity was at, or above, its Static Line Rating.

As seen over the 3 day period in
Figure 9 and the month long histogram shown in Figure 10, the DLR (as determined by the LineVision system) provided additional capacity, when compared to the SLR.

7. Conclusion

A non-contact monitoring system utilizing an array of EMF sensors was deployed under AEP's Cook-Olive 345kV transmission line. The sensors collected EMF data which was then fed into an analytical model that determined various conductor properties including loading, clearance, temperature, effective wind speed, and DLR. The line's DLR was shown to provide significant additional capacity, as compared to its static line rating, during the sample period of January 2017. The additional capacity provided by DLR is an example of how an advanced transmission technology can provide flexibility to grid operators, while reducing congestion in power markets and improving their efficiency, increasing situational awareness and aiding grid resiliency. In future work, PJM will incorporate the DLR values that are being recorded over a longer period of time into a market simulation tool to determine the potential financial impact that the DLR values could have if they were used in market operations.

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