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Real-Time Reliability-based Dynamic Line Rating System for Transmission Asset Optimization

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SUMMARY

A new dynamic grid management solution that enables the optimization of transmission path capacity is presented. This methodology brings the technology of real time direct clearance and temperature monitoring together with learning-based dynamic line rating analytics. This methodology can be utilized to maximize existing transmission assets and reduce the potential safety risks inherent in current conventional methodologies. This new solution calibrates IEEE 738-2006 methodology by using known monitored weather and conductor information, thus creating accurate real time dynamic line ratings.

The planning benefits of implementing methodology can also introduce flexibility for the timing of investment in new transmission facilities, and is an example of environmental and business stewardship -- maximizing the value of existing facilities while reducing costs. The ultimate benefit of utilizing real time dynamic line ratings is the ability to provide accurate and reliable 24 hour forecasting. Further, applications and commensurate benefits of the real time direct clearance monitoring technology without the dynamic line rating analysis will also be indicated.

KEYWORDS
Transmission, DLR, Dynamic line rating, Transmission monitor, Forecasting, LiDAR, Clearance, Smart transmission, Smart grid, Power system planning

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1. INTRODUCTION

Transmission Line Rating is the process of determining safe steady state current carrying levels and a related maximum conductor operating temperature. This can include a normal condition rating as well as a sustained period emergency rating and the results can vary significantly between the different seasons of the year. Transmission line systems include infrastructure such as relays, switches, conductors, splices, etc., so the governing operational facility rating is limited and controlled by the lowest individual equipment rating. The maximum operating temperature of the conductor is typically the infrastructure controlling a facilities capacity, depending on the static line rating criteria applied to get the resulting line rating.

2. CHALLENGES FOR THE POWER GRID

One of the well documented challenges for the Power industry is the need for increased transmission line capacity with either existing or new infrastructure. There are many challenges associated with the construction of new transmission lines. A new transmission line typically takes many years to get built from initial planning studies that suggest the need for the facility. Upgrading and uprating existing transmission lines is also a common approach to increasing the ability to transfer more power on existing infrastructure. Understanding the capacity of the existing infrastructure has become increasingly important.

The traditional operational limits established through static transmission line rating methodologies are dependent on several environmental variables identified in IEEE standard 738. The current common practice for transmission line rating is to select conservative values for these environmental variables that equate to a low probability that conductor sag will exceed operational or regulatory limits for a very short duration. This methodology directly acknowledges that operational limits of transmission lines are conservative most of the time, and inherently accepts the operational risk of a relatively low probability of exceeding the established static ratings. The implication of this methodology is often significant transmission grid congestion, resulting in bottlenecks that greatly limit the system operator’s ability to transfer power. These bottlenecks can significantly impact the selection of power generation resources, including renewable resources, the ability to meet the demands of growth and, ultimately, system stability.

3. CONDUCTOR CAPACITY RATINGS

The IEEE 738 [1] standard and CIGRE 207 [2] brochure detail two different but similar approaches in estimating the relationship between the current flowing through, resulting temperature of bare overhead conductors. These calculations have been adopted by most of the industry and are used primarily for planning purposes in determining static operating limits, given a pre-determined conductor rating parameters. The primary intent of these methodologies are to establish a common and best practice for determining static ratings given hypothetical parameters which would have a low probability of occurring. The IEEE 738 document specifically states:

> “This standard includes mathematical methods and indicates sources of the values to be used in the calculation of conductor temperatures and conductor thermal ratings. However, because there is a great diversity of weather conditions and operating circumstances for which conductor temperatures and/or thermal ratings must be calculated, the standard does not undertake to list actual temperature-current relationships for specific conductors or weather conditions. Each user must make their own assessment of which weather data and conductor characteristics best pertain to their area or particular transmission line.”

There are several key variables used in these methodologies that involve local environmental weather conditions surrounding the transmission conductors being studied and evaluated. Each operating utility must establish conductor rating criteria that could be used to calculate the conductor’s capacity or rating. For example, using an unlikely weather condition along with an extreme loading event for these criteria will result in a transmission line whose daily capacity is limited by this same combination of unlikely weather event and short duration overload. It should also be noted that developing criteria based on unlikely events involves implicit acceptance of risk if that event were to actually occur. Current safe operation of transmission lines are governed by these planning methodologies and best practices of determining static line ratings, resulting in conservative capacity ratings.

4. DISCREPANCIES IN LINE RATINGS

On October 7, 2010 The North American Electric Reliability Corporation (NERC) released an "alert" recommendation to utilities in the United States and Canada to do the following for all transmission lines [3]:

- Review their current transmission line facility ratings
- Review the methodology used to base those ratings
- Determine if the methodology was producing accurate ratings or if differences between design and as-built field conditions existed.

It is estimated that the NERC alert applied to over 720,000 km (450,000 miles) of transmission lines in the United States and Canada.

Utilities used LiDAR to measure the line's actual "as-built" profile and compared that "moment-in-time" LiDAR measurement data with detailed spatial models developed using transmission line engineering software. The transmission line rating results thus far reported from the NERC Alert reveal a relatively high rate of discrepancies between the in-situ existing conditions and the assumed operational conditions.

NERC reported line rating results for the first year of assessments. The results from that first report represent 16% of the so-called "Phase I" circuits, identified to be the most critical infrastructure. The first report indicated an average of 1.2 discrepancies per circuit. A full 88% of the discrepancies required some form of construction to resolve and the other 12% of lines required de-rating. It is anticipated that the less critical lines will have a higher average occurrence of discrepancies and rate of construction mitigation.

5. UNDERSTANDING THE DISCREPANCIES

There are many reasons that can explain the discrepancies, key ones being:

1. The line rating study itself has a great level of precision at that moment in time when the LiDAR survey was taken, but is only relatively accurate based on the knowledge of the conductor temperature *at that moment in time*.
2. The actual construction of the line may not have been exactly as designed.
3. There may have been an operational event that has caused additional stretch in the conductor such as a heavy ice, wind or high conductor temperature.
4. There may have been something else built since the line was constructed that is now limiting the capacity.

The important things to remember are that lines rating studies are restricted to a moment in time and are performed with conservative static conductor rating criteria.

6. REAL TIME DYNAMIC LINE RATINGS – WHAT IS THE POTENTIAL?

The current methodology for operating the transmission grid is done by monitoring the existing load as compared to the line's static thermal conductor rating. Reliability is incorporated by adding contingency outage events that could cause an increase in load in each particular transmission line and reserving that increase for that worst case scenario.

The concept of real time dynamic line ratings must first be understood as being dependent upon the ability to accurate monitor a transmission line's capacity. The primary author's company has developed a new technology that allows for such monitoring of the critical parameters related to capacity, specifically conductor clearance-to-ground, temperature, current, angular tilt and vibration.

Calculating real-time conductor capacity using the accepted relationship between conductor clearance and conductor temperature along with real time weather must be offset by the potential error of local weather systems and inaccurate local wind angle and speeds. This is the reason for the admonition in the IEEE 738 standard concerning the diversity of weather conditions and operating circumstances. Specifically, true dynamic line rating is only made possible with real-time direct monitoring of conductor behavior in combination with standard, predictive conductor temperature and load relationships.

7. REAL-TIME CONDUCTOR MONITORING

To accomplish the required real-time direct conductor monitoring required for true dynamic line rating, the author's company has developed a novel conductor mounted monitor called the TLM® Conductor Monitor. This device provides a complete picture of conductor behavior including actual conductor clearance-to-ground, conductor temperature, line current, and vibration. Unlike other transmission line monitors that use ancillary measurements to infer sag, not clearance, the TLM monitor provides accurate, actionable, clearance-to-ground distance. See Figure 1.

Figure 1: Lindsey TLM Conductor Monitor

Figure 2: Location of LiDAR measurement taken from installed conductor monitor

The distance of the nearest object to the conductor is measured using an on-board LiDAR sensor providing a highly accurate (+/-0.3% at 40m) line clearance measurement regardless of tower or insulator motion, varying span lengths, or other line conditions [4]. See Figure 2. Accurate (+/-1%) line current is measured simultaneously with conductor clearance. Local conductor current measurement is especially important in lines with multiple taps where the nearest substation-based current measurements may not be accurate representations of the local line current.

Conductor temperature is measured, critical for use in dynamic line rating computations, and also necessary to keep track of excessive temperatures that lead to conductor annealing. To facilitate simple field installation, the TLM monitor self-powered by line current as low as 100A, and may be installed on live lines using hot stick or bare hand practices up through 765kV.

8. THE VALUE OF DYNAMIC LINE RATING

The values associated with dynamic line rating are many and include [5]:

- Increased transmission capacity at minimal investment
- Deferment of large capital investments
- Enhanced performance of reliability of aging assets
- Efficient integration of renewables such as wind and solar energy
- Potential savings with generation dispatch
- Increased situational awareness for operators
- Real time monitoring of thermal state of conductors
- Increased reliability during system emergencies
- Improved forecasting

Further, dynamic line rating based on real time monitoring of direct clearance measurements provides immediate and accurate knowledge of clearance regulatory compliance.

9. WHAT ARE REAL TIME DYNAMIC LINE RATINGS?

Real time dynamic line ratings is a grid management solution that utilizes direct temperature and LiDAR clearance monitoring from transmission line monitors attached directly to the conductor, together with real time data analytics. The data from these devices is used to calculate real time dynamic line ratings to maximize existing transmission assets and eliminate the potential safety risks inherent in current conventional methodologies. The solution provides a suite of valuable data and real time data analytics that can be used in a variety of line condition monitoring and transmission system asset management tools.

By directly monitoring a measured conductor temperature and clearance to ground over time, accurate operational real time dynamic line ratings can be determined by calibrating the empirical formulas defined within the IEEE 738 or CIGRE 207 standard. These solutions can also compliment aerial LiDAR line rating studies by calibrating the conductor temperature-to-sag relationship, for improved finite element models and ultimately lower cost. This solution lowers risk of safe operation by bringing transmission line clearance intelligence to operations, and avoiding the relatively low probability of exceeding static ratings.

10. CALCULATION METHODOLOGY

The relationship between conductor temperature and the electrical line load has been observed for many years and the calculation methodology for IEEE and CIGRE are presented in IEEE 738 and CIGRE Brochure 207 respectfully. The challenge of incorporating real time monitored conductor and weather information and thus creating a dynamic line rating can be done by calibrating either of these methodologies with live monitored conductor information. The most important information that could be monitored is clearance and conductor temperature; it is what controlled the design of the line and it is what physically governs the operations of each line. Dynamic Line Ratings depend on understanding conductor clearance and conductor temperature with respect to the load at any one moment in time.

In Figure 3, the IEEE 738 relationship has been calculated with real time data from one moment in time using the actual weather conditions.

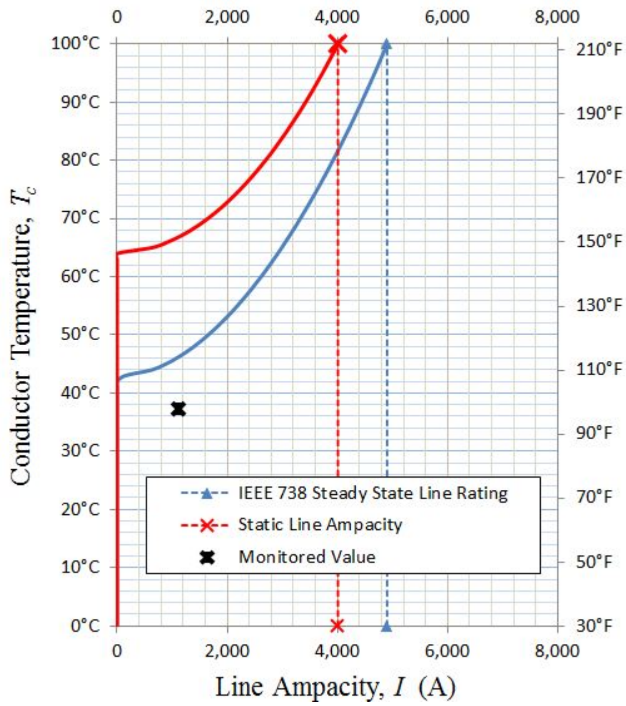

Figure 3: IEEE Standard 738 Conductor Temperature - Line Current Relationship [6]

It can be observed that the real time weather data typically results in much greater capacity than the static conductor rating, although, this is expected due to the typical conservative conductor rating criteria. The heat balance equations are very sensitive and general weather data is not always consistent with location specific conditions. Dynamic Ratings are calculated by calibrating real time location specific conductor temperature and clearance with the relationship defined by IEEE 738 or CIGRE Brochure 207 with real time weather, ideally with location specific weather for best results. In the example in Figure 3, the monitored conductor temperature is observed to be less than the IEEE relationship, thus calibrating would shift the relationship curve down to intersect the monitored, resulting in a higher ultimate conductor rating, see Figure 4. The resulting conductor capacity would also be decreased when the monitored data is above the relationship curve, thus resulting is less capacity. It is also important to realize that real time monitoring and dynamic line rating analysis can validate actual in-situ conductor conditions continuously, not just a moment in time.

The final calculation involves correlating the conductor rating with the direct clearance measurement. This is done by first monitoring the conductor behavior between conductor clearance and conductor temperature and developing a predictive model for the conductor's behavior. See Figure 5. Once this relationship is established, the direct monitored clearance can be used to determine an effective conductor temperature and using the same method of calibrating with the IEEE 738 or CIGRE 207, results in a dynamic conductor rating that is directly determined from clearance monitoring. The advantage of a dynamic conductor rating based on directly monitored clearances – as compared to other methods - is a more consistent, less sporadic resultant rating. This is because the rating is determined through monitoring the real governing factor in conductor ratings.

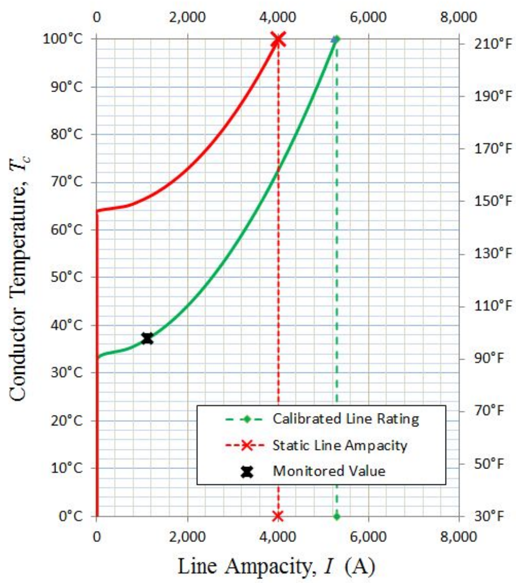

Figure 4: Calibrated Conductor Temperature to - Load Relationship

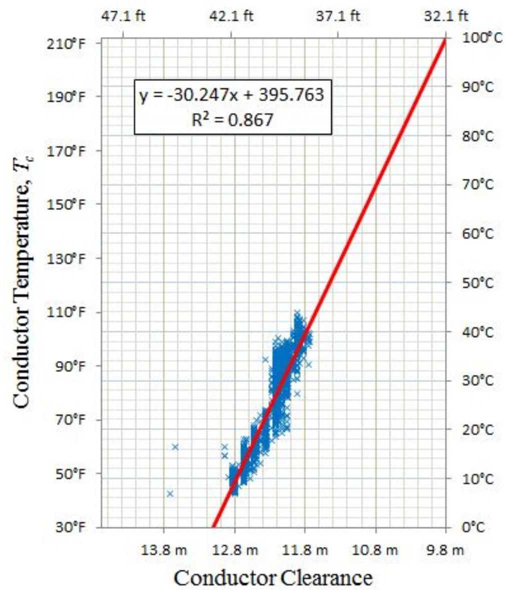

Figure 5: Predictable average span temperature obtained from clearance measurements

The calculations are then computed and compiled for all critical points on a line (i.e., from monitoring all critical, ruling, spans) in real time as shown in Figure 6. This allows for an intelligent understanding of a transmission line's capacity and the ability to maximize its utilization. The capacity of a line can also be forecasted using a statistical analysis of historical, actual monitored data combined with a selectable confidence factor as shown in Figure 7. Initially the historical data set would involve a recent duration of time, such as the previous two to four weeks. Over time, as the data set is expanded, the system would learn from similar historical measurements compared with forecasted events.

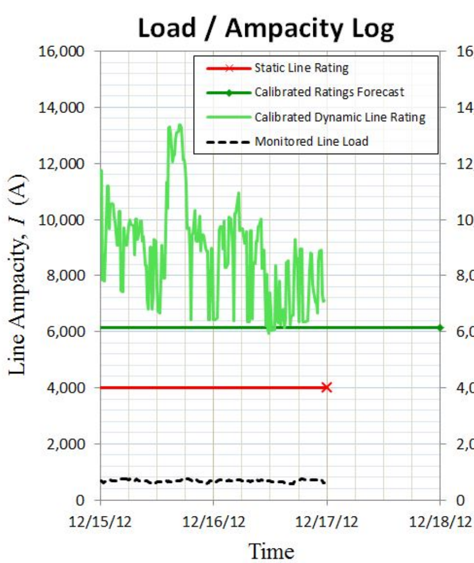

Figure 6: Dynamic Line Rating

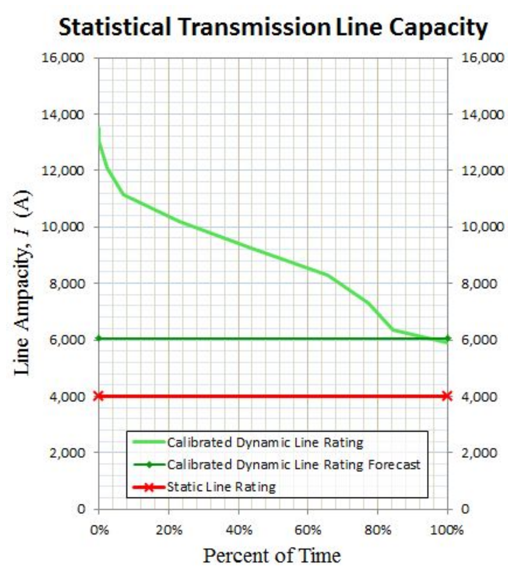

Figure 7: Dynamic line capacity versus confidence factor

11. OTHER APPLICATIONS

The real-time distance-to-ground measurement capabilities of the conductor monitor can prove useful for other, non-dynamic line rating related applications. One application in particular is for use in monitor the clearance between crossing lines. Here, a monitor mounted on each line provides the distance to ground measurement for each. Subtraction of these two values provides the line-to-line clearance.

12. CONCLUSIONS

The application of real time measurement of line parameters and real time calculation of dynamic capacity offers a paradigm shift in the operation of the power grid that has the potential of significant savings in cost and increases in revenue, while increasing the safety in operating transmission lines. Realizing the full capacity of the existing infrastructure and maximizing future infrastructure facilitates is an optimal placement of a utilities capital expenditures, while minimizing operational and maintenance expenses. This methodology can also create timing flexibility on the investment of new facilities, thus freeing up capital expenditures for the most needed locations. Finally, this methodology offers potential relief to grid congestion and creates opportunities for greater diversities in generation portfolios, including renewables.

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