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Transmission Line Capacity Forecasting System

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SUMMARY

Dynamic Line Rating (DLR) is not a new concept; however, the ability to use the instantaneous DLR data has not been widely accepted due to the rapidly changing variability of the data. Most utilities recognize the conservative nature of static line ratings and employ seasonally adjusted ratings and/or ambient adjusted ratings, which in some ways are a limited form of forecasting line ratings. What has been needed is a way to combine the advantages of DLR and weather predictions to accurately and reliably forecast a transmission line's capacity in the future.

This paper describes a new system and a methodology used to determine a Forecasted Dynamic Line Rating (FDLR) for a transmission line. The system consists of four key elements which combine to produce the FDLR.

First, real-time conductor data is gathered from specially developed monitors that directly measure key conductor parameters. This differs from previous DLR systems that often use indirect measurements, such as tension, sag, vibration, or inclination, and then cross reference these measurements with lookup tables to arrive at estimates of required clearances. These real-time line monitors are mounted on the energized transmission line and measure line current, conductor temperature, conductor clearance-to-ground, and other environmental factors. The data is transmitted back to the rest of the system using a satellite communication link.

Second, live-weather feeds are 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.

Next, a dynamic line rating is 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 both ensures compliance to clearance limitations and that conductor thermal limits are not exceeded.

Finally, utilizing the most advanced computational weather models from third party services that record and forecast environmental conditions, DLR ratings are then computed for an interval of time in the future. The system compares these future ratings against the actual instantaneous DLR ratings computed at that corresponding actual time in the future. By looking at how well these future DLR forecasts aligned with reality, reliability-based adjustment factors can be created to modify future DLR forecasts to whatever reliability level is required (98% or 99%, etc.).

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From this methodology, system operators can be presented with a forecast DLR, or transmission capacity forecast (TCF), for any desired period of time or specific application, and at any level of reliability. For example, a 1- or 2-hour forecast could be developed for use in emergency line rating. Planners and Transmission Operators (TO) or Independent System Operators (ISO) can look at reliability-based transmission capacity forecasts 24- or 48-hours in the future to optimize economic dispatch while increasing grid flexibility for dynamic response (DR) power transfers.

This system, including line sensors, satellite communications and cloud-based computing, has been installed at several utilities in North America on HV, EHV and UHV transmission lines. The results from some of these installations are presented.

KEYWORDS

Management forecast of a system, Dynamic Line Rating, DLR, Transmission performance rating, Transmission capacity of a link, Transmission system operator

INTRODUCTION

Transmission line rating is dependent on several environmental variables, including heat generated in the line (I^2R losses), heat added to the line (solar radiation), and heat being removed from the line (convective and radiated cooling) due to wind and precipitation. Traditional operational limits of a transmission line are established through "static" transmission line rating methodologies that recognize these variables. These methods, identified in IEEE standard 738 [1] and CIGRE brochure TB 601 [2], while ensuring a very low probability that conductor sag will exceed operational or regulatory limits of even short duration, result in very conservative line ratings.

Seasonally adjusted ratings (SAR) and ambient adjusted ratings (AAR) are commonly used today to increase a line's static rating by acknowledging different environmental conditions exist at different times of the year. [3] [4] Dynamic Line Rating, or DLR, is a transmission line's actual, real-time, power carrying capacity based on the conductor's actual operating temperature using real-time line behavior data and weather conditions. DLR is the natural and logical extension of seasonal and ambient adjusted ratings. DLR techniques have been shown to increase a line's static rating by as much as 100%, though going above 25% may require addressing the next limiting element in the line. [5]

Numerous studies have shown this additional capacity provides opportunities in economic dispatch, trading, operations, and congestion mitigation. Application of DLR is also a powerful tool for improving contingency planning, cost effectively addressing lines with slow load growth, and deferring or eliminating the need for line upgrades or reconductoring. [6] [7]

DLR AND FORECASTED DLR

With all the identified economic advantages, DLR is still sparsely deployed. One reason is that first generation DLR systems presented numerous issues to early adopters, discouraging wider deployment. A DLR system consists of line sensors to determine the conductor status, a communication channel for these sensors, and software to compute the dynamic rating. Issues encountered by early adopters included use of sensors that took indirect measurements and therefore depended on the use of lookup tables, complexity of installation or operation, communications reliability, complexities involved in obtaining local power, and general device reliability. [3] [8]

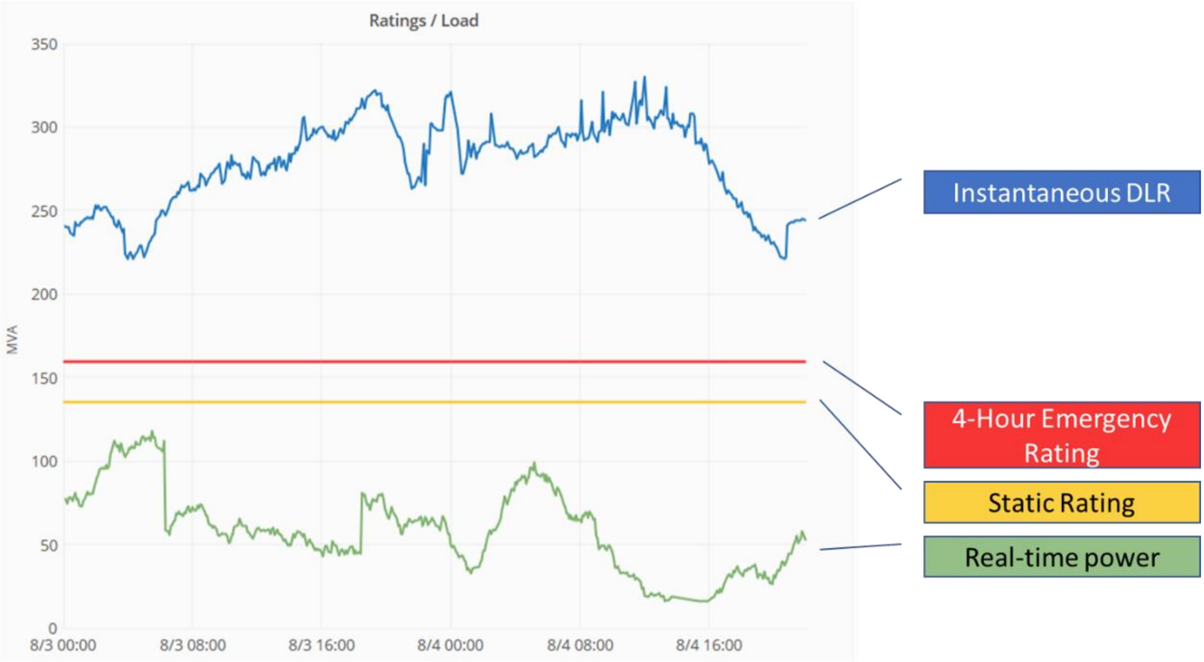

Figure 1: Dynamic line chart. Upper line is instantaneous DLR which varies rapidly (2-day period shown)

Another key reason was operational in nature. The fluctuating nature of grid behaviour made incorporation of similarly variable real time dynamic line ratings into grid operations difficult. One study showed how the determination of certain benefits could only be accomplished by running simulations of the day ahead market with and without DLR. [6] This makes intuitive sense as examination of a line's DLR rating shows that the dynamic rating fluctuates rapidly and continuously as a result of shifts in the various environmental factors that affect the line's thermal capacity. See Figure 1. One way of interpreting this result is that real-time DLR is not fast enough; the real operational need is for forecasted DLR.

FORECASTED DLR METHODLOGY

Over the past 7 years, a complete forecast DLR system was developed which comprises three primary system components, see Figure 2. The components are:

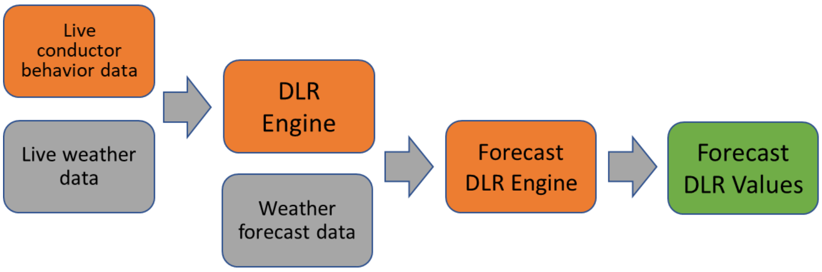

Figure 2: Forecast DLR System Process Flow

- A data collection system comprised of conductor monitors which collect real-time data, and location interpolated real-time weather data for the GPS location of the sensors. These provide input to;
- A reliability-based DLR computation engine. The output of this, combined with GPS location based weather forecasts, provides input to;
- The reliability-based DLR forecasting engine.

LINE SENSORS

A self-contained line sensor was developed over the past eight years that both directly measures key conductor parameters and which addresses observed issues with earlier systems. The monitor is:

- Self-powered requiring no battery or external power source, eliminating a major cause of maintenance. The unit shown harvests power from the magnetic field of the conductor, eliminating the need for external connections.
- Sensors providing direct measurement of conductor current, conductor spot temperature, ground temperature, conductor vibration, and most critically, the actual conductor-to-ground distance measurement via built-in LiDAR. The latter eliminates the need for sag estimations and avoids issues associated with differences between plan profile drawings and actual as-built conditions.
- Built-in satellite radio, providing the ability to communicate the monitored data from any transmission span, regardless of location. This eliminates the need for additional or nearby communication infrastructure or equipment. The satellite radio also provides unique cyber-security as the radio is built-in to the sensor and transmits only non-operational, measured data directly to the DLR software. The sensor's mid-span physical location also effectively eliminates physical access as an attack vector.
- To address installation complexity concerns, the device can be installed in a few minutes on either energized or de-energized lines and requires no modification of the line or line structures. The device has been tested corona free through 765kV.

While various versions of the sensor were developed and deployed over the past 8 years, the current version, has been successfully deployed over the past 3 years in conditions ranging from desert to subarctic climatic zones, and at voltages from 138kV to 735kV.

For DLR applications, a conservative analysis of the line is performed to identify each span that could become critical, by either exceeding minimum clearance requirement or exceeding the conductor's thermal rating. Line sensors are recommended to be installed on each identified span.

RELIABILITY-BASED DLR ENGINE

With the monitors providing the necessary real-time conductor information, the next step is to develop the reliability-based DLR. Instead of depending upon published conductor temperature-sag relationship curves and look up tables, the system instead learns the actual conductor behavior. This is accomplished by using the measured conductor temperature from the conductor monitor and the actual conductor to ground clearance. These data point pairs are collected continuously over time, and a curve is fit to the collected data. [9] [10] Figure 3 shows the example of a simple linear regression fit to a collection of such data. The curve equation can be interpreted as the effective conductor temperature for any given measured clearance to ground. This learned model is continuously updated and refined as additional data is gathered.

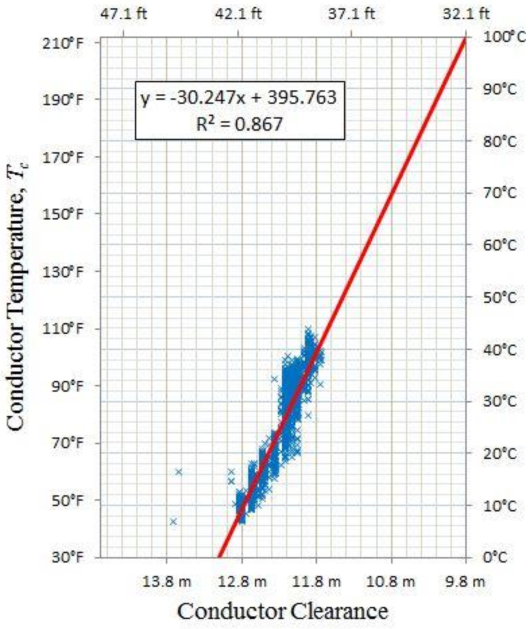

Figure 3: Example of learned average span temperature based on conductor behavior

A third-party service is used to provide real-time weather information to the DLR engine for the GPS location at which each conductor monitor is installed. Weather information used by the DLR engine includes wind speed, wind bearing, ambient temperature, solar radiation, cloud cover, and humidity. The DLR engine then solves the thermal balance equations from IEEE Standard 738 and CIGRE brochure TB 601 methodologies for the line rating. This is the instantaneous DLR for that span or line section, as appropriate. For inputs to the thermal balance equations, the system uses the real-time weather data, the effective conductor temperature from the learned characteristic, conductor current as measured by the monitor, and the actual conductor to ground clearance.

The use of remote, rather than local, weather monitoring offers certain advantages and some limitations. Eliminating the need to install local weather stations across the line's geography and communications links to those stations greatly increases the economy of system implementation. Systematic errors in the remote weather data becomes adapted by the learned conductor behavior. Using GPS-specific forecast weather on the same basis as the GPS-specific real-time weather also allows for correlation of the forecast error. In comparison, the use of local weather stations, in particular for wind speed and bearing, would provide more precise data for the monitored location. This is because the heat balance equation is very sensitive to wind particularly at low speeds. While the system could be enhanced by use of local data, it would add system complexity and cost. Note too that local stations would not preclude the need for obtaining a weather forecast, which will be based on the weather stations used by the weather forecasting entity, not the local weather stations.

Another possible concern are errors to DLR forecasts under low current conditions. This system effectively eliminates these through use of the learned conductor behavior characteristic. The shape of a conductor characteristic is known in that it is generally a straight line. The curve fitting and statistical techniques used result in a forecast rating equally accurate whether an individual real-time DLR point is computed from a low current instantaneous reading or a high current reading.

The use of actual conductor to ground clearance measurements eliminates variables inherent in other methods. Compared to direct clearance measurements, other systems have used various techniques to develop an indication of conductor sag. These include measurement of conductor tension or vibration frequency, measurement of conductor inclination, or use of optical targets. While these methods may be effective in determining the degree of sag, they all involve one or more computations or static lookup tables to estimate the clearance resulting from such sag. [8] Accuracy of those computations typically depend on the accuracy of the line’s plan and profile drawings, and assumptions regarding the condition of the conductor (creepage, previous or future annealing, etc.). Such techniques also cannot consider the possibility of ground terrain change due to underbrush growth or construction. Additionally, the use of direct clearance measurement provides the ability to monitor the clearances between crossing lines. [11]

Because the rating is determined through monitoring the real governing factor in conductor ratings – clearance – the result are more consistent ratings. Moreover, if conditions mandate full use of a forecasted rating, knowledge of actual measured clearance to ground becomes paramount as maintaining line clearance is critical for safe operation of a line.

Calculations are made for all monitored spans in real time with a separate DLR computed for each span. The line DLR for any moment in time is the lowest computed DLR of any span. This allows for an intelligent understanding of the transmission line’s capacity and the ability to maximize its utilization.

RELIABILITY-BASED FORECAST DLR ENGINE

To develop the forecast DLR, the system starts by developing future DLR ratings for the desired forecast time period based on forecasted weather data. Call this DLR_i'. The system then computes the actual instantaneous DLR once the actual moment in time has arrived; DLR_i. The difference of $DLR_i - DLR_i'$ is the error between the two. This data is collected over time until a statistically significant number of data pairs (errors) have been collected which allows the system to calibrate the forecast DLR values to this data set. The forecast DLR value is set to ensure a desired confidence factor, C, is achieved for the forecast DLR. By default, the system uses C=98%. Therefore, the actual DLR has only a 2% likelihood of being below the forecast DLR for that moment in time. If desired, higher or lower values of C may be used. The system is designed to collect the needed data pairs and expand the statistical data set continuously.

As with the line DLR, a forecast DLR is computed for each monitored span, and the forecast line DLR is set to the lowest of any of the component forecast DLRs. Fixed capacity forecasts, that is, forecasts good for a defined period of time, may be developed by computing the forecast DLR for every time period during the forecast duration window, then setting the forecast at the lowest level forecast during that window.

SAMPLE DATA AND OUTPUT

Showing real world application in North America, Figure 4 shows output from installation on a 138kV line with a 76°C maximum operating temperature (MOT), showing both 24-hour ahead and 2-hour ahead forecasts of the line’s capacity. Figure 5 is similar but shows data from a 735kV line. For this line, the static is developed with a 49°C MOT and the forecasts were developed using a 100°C MOT due to available span clearances.

The 24-hour forecast means the line may be operated at the forecast level for the next 24-hours. The 2-hour forecast means the line may be operated at the forecast level for the next two hours. Note that the 24-hour forecast is more conservative than the 2-hour forecast. This reflects the greater uncertainty associated with longer term weather forecasts. Conversely, a 1-hour forecast would be higher than the 2-hour forecast shown as the uncertainty of the forecast weather data is less in the shorter term. The forecast accuracy is not impacted by the line conductor temperature rating as the system develops its ratings to ensure compliance to minimum clearance limits and the conductor’s maximum operating temperature. Either parameter may the limiting factor in the forecast rating at any moment in time.

The graphs shown in the figures are typically most useful to line engineering personnel. The discrete numbers at the top of the displays are what would normally be imported into an EMS display or EMS system. EMS operators would typically not wish to deal with the depth of information presented by the charts nor would they need to as part of an operational deployment.

DLR has a long history in transmission engineering and implies the type of rapidly fluctuating line capacities seen in the upper traces of both figures. This has been previously noted as one of the factors resulting in slow adoption of DLR. However, the forecast DLR system described herein provides a stable forecast of transmission line capacity with very high reliability (i.e., confidence factor). Therefore, it is suggested that this type of DLR forecast system be termed a transmission capacity forecasting system, or TCF, to better represent its output and potential uses.

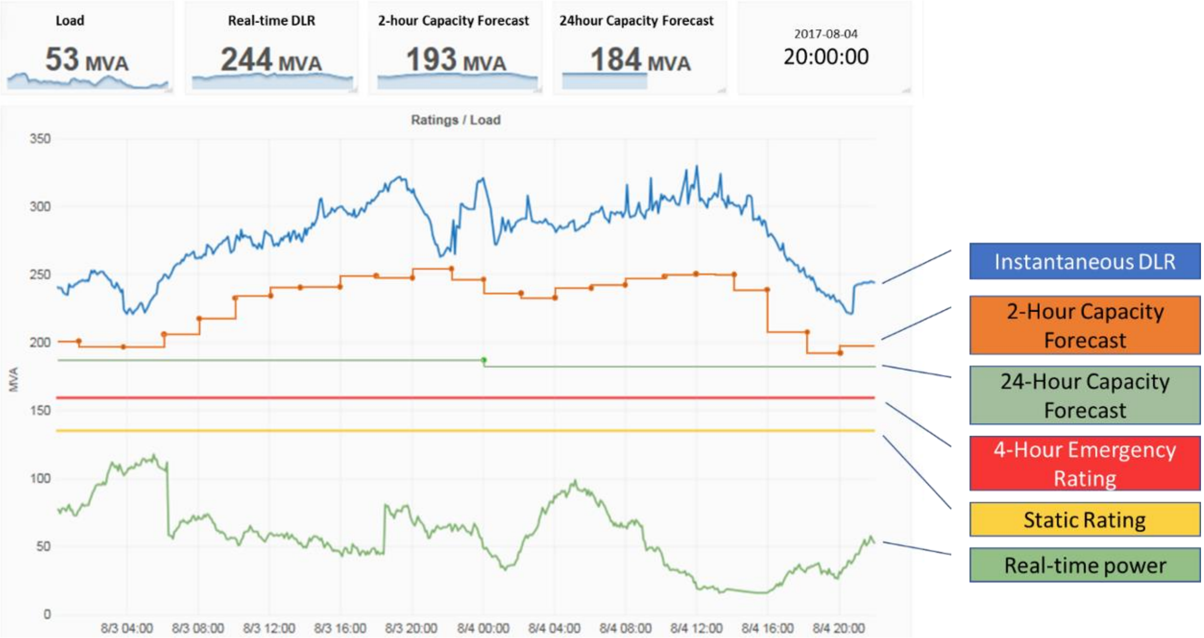

Figure 4: Forecast DLR Output showing 2- and 24-hour ahead forecasts on a 138kV line. Ratings in MVA.

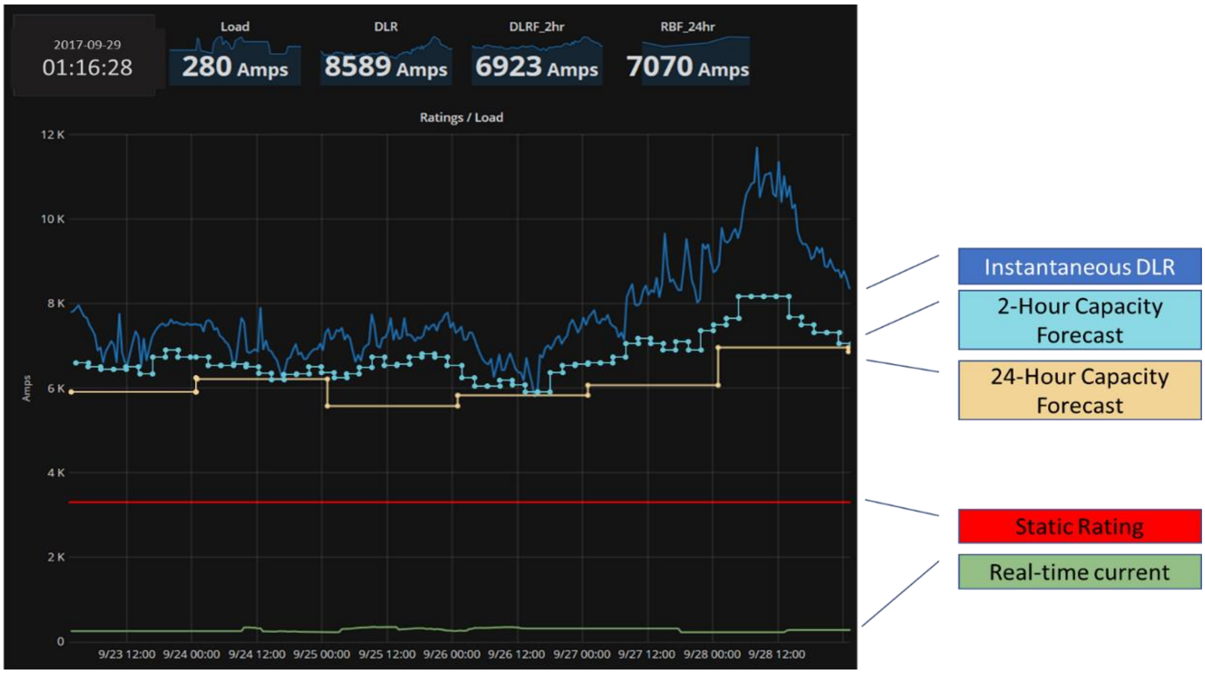

Figure 5: Forecast DLR Output showing 2- and 24-hour ahead forecasts on a 735kV line. Ratings in Amperes.

CONCLUSIONS

A highly functional and operationally useful system to develop forecasted transmission line capacity ratings built on a reliability-based DLR forecasts has been described. The system incorporates several novel features; learning-based software, statistical reliability-based methods, and transmission line conductor monitors that directly measure the most critical parameters governing line ratings; clearance to ground and conductor temperature. This system has been successfully deployed at various voltages.

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