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A Review of Dynamic Thermal Line Rating Methods with Forecasting

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***Abstract*—Power flow, on both AC and DC overhead transmission lines, is limited to keep the conductor temperature below a maximum (TC_{MAX}) specified to limit both conductor sag and the aging of conductors and splices over time. This power flow limit (line thermal rating) varies with weather conditions along the line corridor but, for simplicity, static line ratings (SLR) are normally calculated for "suitably conservative" annual or seasonal weather conditions. Dynamic line ratings (DLR) change with the real-time weather conditions along the line, are usually higher than SLR, and are more complex to use in system operation. Forecasting of DLR requires forecasting of line corridor weather conditions but makes DLR more useful to power system operations. This paper discusses DLR methods including forecast techniques and presents various field applications.**

***Index Terms*—Static Line Rating (SLR), Ambient-Adjusted Dynamic Line Ratings (DLR-AA), DLR with Real-Time Monitors (DLR-RTM), Maximum Conductor Temperature (TC_{MAX}), effective perpendicular (EP) wind speed, Continuous/Long-Time/Short-Time Emergency Rating.**

I. Introduction & Background

Power flow on overhead transmission lines is limited for both electrical and thermal reasons. Electrical power flow limitations concern voltage-drop and phase shift along the line. Thermal power flow limitations are intended to keep the line's phase conductor temperatures below a maximum conductor temperature, TC_{MAX}, in every span along the line.

By keeping the line power flow below the line thermal rating, power system operators ensure that adequate electrical clearances are maintained, and that cumulative aging of the conductor system is managed over the life of the line. Typically, while system operations is aware of the line current in the phase conductors, it is not aware of the actual phase conductor temperatures as they vary along the line.

While electrical quantities such as MVA power flows and bus voltages have traditionally been measured remotely and communicated to system operations in real-time, line thermal ratings have generally been held constant. Line thermal ratings which remain constant over time (either for a season, or a whole year) are called "static line ratings" (SLR). SLRs are calculated for "suitably conservative weather conditions" [1] (i.e. high air temperature, maximum solar heating, and an EP wind speed close to zero) and the line's a maximum conductor temperature (TC_{MAX}), using a heat balance method such as IEEE 738 [2].

To gain additional overhead line thermal capacity, in either temperate or tropical climates, various methods of calculating line ratings as weather conditions vary from day to day and hour to hour have been developed. In this paper, these methods are referred to as Dynamic Line Rating (DLR) methods. The goal of such methods is to provide power system operations with higher line thermal ratings during favorable weather conditions and more accurate line ratings under unfavorable weather to safely allow increased power flow without exceeding the line's maximum conductor temperature, TC_{MAX}.

Whether line ratings are static or dynamic, system operators need to perform short-term operational planning studies to determine that normal and post-contingency circuit power flows do not exceed line and substation equipment ratings, both now and in the immediate future. This operational planning process requires prediction of circuit loading and, if ratings are dynamic, forecasts of circuit ratings. Errors in dynamic rating forecasts have financial consequences which depend on the cost of needing to make changes in circuit loading on short notice vs. the financial benefits of realizing more of the available network capacity.

In order to understand DLR methods, the user may have to access topics such as: Requirements for power system operation; operational planning for day ahead loading conditions; remote measurement of conductor temperature; and real-time monitoring of line corridor weather conditions (air temperature, solar radiation, wind magnitude and direction) References [3], [4], and [5] provide much of this understanding.

II. Static Line Rating (SLR)

As noted in the Introduction, Static Line Ratings (amperes or MVA) are calculated with a bare conductor heat balance thermal model [2], using a low perpendicular wind speed (e.g. 0.61 m/s), a near-maximum seasonal air temperature (e.g. 35ºC or more in summer), with full solar heating (e.g. 1000 watts/m^2) as described in CIGRE Technical Brochure 299 [1]. The assumed or measured suitably conservative weather conditions used for SLR ratings vary with the regional climate and risk

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tolerance of power utilities.

Any transmission line may have more than one SLR. Typically, utilities may calculate a Normal (or Continuous) rating, a Long-Time Emergency (LTE) rating and a Short-Time Emergency (STE) line rating which apply to actual power flows, and to post-contingency power flows that persist for several hours or 10 to 15 minutes, respectively. The assumed weather conditions may be less conservative (e.g. 0.9 m/s for emergency ratings) and conductor temperature limits higher (e.g. 125°C rather than 95°C) for limited time emergency ratings. In no case, however, may TC_{MAX} exceed that required to assure adequate line sag clearances.

If the SLR of an existing line is not sufficient to allow adequate power flow during normal or emergency system operation, the line's TC_{MAX} may often be increased by various physical modifications of the line or reconductoring with High-Temperature, Low-Sag (HTLS) conductors. These methods of increasing the SLR are line-specific, generally producing a relatively large and permanent SLR increase (30% to 100%) and requiring no change in traditional planning and operation procedures other than changing the SLR value. The drawbacks to physical line uprating, however, involve the need for an extended line outage, significant capital investment (30% to 50% the cost of a new line), and time delays involved in gaining regulatory permission to proceed. CIGRE Technical Brochure 763 [6] provides a detailed discussion of physical methods for the uprating of existing lines.

Also, in temperate climates, SLR ratings may be recalculated for each season (typically summer and winter) rather than remaining constant for the entire year. Seasonal SLRs are widely used as they apply to all lines in the system or region and no physical modification of lines is required. For example, winter SLRs based on a near-maximum air temperature of 10°C are typically 15% to 25% higher than summer SLRs based on a near-maximum seasonal air temperature of 35°C.

III. LINE CORRIDOR WEATHER VARIATION [1], [3], [4]

Overhead transmission lines may be hundreds of km (miles) long, traversing various types of terrain. A line that starts at a generation station near the seacoast and goes over a mountainous area to reach an inland load center, may experience variations from span to span along the line and from minute to minute at any span as air temperature and solar heating change with elevation and convection cooling varies with wind speed and direction as line direction changes, foliage and terrain shield the line, and wind speed at phase conductor height varies with atmospheric conditions.

The line's static thermal rating is constant with time and equal to the minimum thermal rating for all spans in the line over the entire year or season. The line's dynamic thermal rating varies over time but is also equal to the minimum thermal rating for all spans in the line. At least theoretically, the minimum DLR should equal the SLR but, if the EP wind speed used in the SLR calculation is above 0.6 m/s (2 ft/s), the DLR may be less than the SLR.

Transmission lines are built with line sections consisting of multiple "suspension spans" terminated by "tension structures". In reasonably level terrain, the sag in any of the suspension spans is determined by the average conductor temperature in the line section not by the conductor temperature in any single span or in any portion of a single span. In mountainous terrain and in lines where the suspension span lengths vary greatly, tensions equalization between suspension spans does not work as well.

Bare overhead conductors are very poor longitudinal heat conductors [7], [8], so under high current conditions, temperature differences within a single span may be on the order of 10°C or more. For this reason, point monitors (anemometers or conductor temperature monitors) may yield different EP winds than sag-tension-clearance monitors which respond to average temperature over multiple spans.

System operations typically has access to both real-time (momentary) and forecasted weather data for regions within the power transmission area. This information is used to mobilize maintenance and repair crews prior to severe weather conditions and to predict overall system peak load.

Forecast and real-time air temperature data obtained from commercial/government weather services may be suitable for dynamic line rating methods that do not require real-time wind speed & direction. Air temperature varies slowly and is predictable over time being nearly the same within and without line corridors.

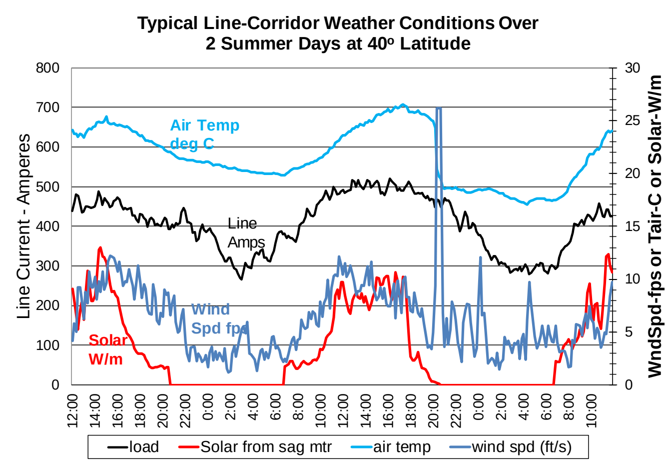

Figure 1 -Typical daily variation in line corridor weather parameters and line current.

Regional wind speed and direction forecasts provided by weather services can be quite different from that measured in line corridors for several reasons: (1) overhead conductors are relatively close to the earth (e.g. in comparison to wind turbines) and typical commercial or government forecast wind speeds do not reflect sheltering by terrain and foliage; (2) transmission line spans are relatively small (e.g. 200-400 m) in comparison to mesoscale meteorological atmospheric model typical cell dimensions of 10km (though recent models allow cell dimensions approaching 1km). Therefore, dynamic line rating methods which include wind speed and direction require

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real-time measurement of line corridor wind data and DLR forecasts require significant data.

The low wind speeds of interest in determining line ratings are strongly influenced by the diurnal cycle as well as the movement of large masses of air and moisture modeled by typical atmospheric models. A diurnal cycle is any pattern that recurs every 24 hours because of one full rotation of the Earth with respect to the Sun. In climatology, the diurnal cycle is one of the most basic forms of climate patterns. The most familiar such pattern is the diurnal temperature variation. Such a cycle may be approximately sinusoidal or include components of a truncated sinusoid due to the sun's rising and setting. A typical line corridor weather and line current cycle is shown in Figure 1.

In this example, the wind speed is determined based on-line-tension measurements. The sudden increase in calculated wind speed at 21:00 on day 2, is due to precipitation (which causes evaporative cooling) which correlates with a sharp drop in air temperature.

IV. TC_{MAX} Exceedance Risk

With the power system operating normally, the power flow on most overhead transmission lines is almost always less than 1 A/mm² of aluminum (0.5 A/kcmil). Given typical, rather than worst-case, weather conditions, the corresponding conductor temperature rise above ambient is usually less than 10°C.

During power system emergencies and for lines carrying highly variable loads (e.g. wind farm generation), the line current may approach the line's static or dynamic rating. Infrequently, unfavorable weather conditions along the line (low wind speed, high air temperature) may coincide with such high currents and the conductor temperatures may approach the line's TC_{MAX}. Much more commonly, overhead conductors are well below TC_{MAX} and field measurements showing a low conductor temperature is not an indication that the line rating(s) are adequately conservative.

Rather than measure line temperature, CIGRE Technical Brochure 299 [1] suggests that a line's calculated thermal rating is sufficiently conservative if it is less than the real-time line rating at least 95% of the time.

The physical consequence of exceeding TC_{MAX} depends on the reason for the temperature limit:

- If the conductor temperature is limited to maintain electrical clearances along the line, allowing the average line section temperature to exceed TC_{MAX} by more than 10°C for even a very brief period (e.g. minutes) may result in injury to the public or flashover to a distribution line or building directly below.
- If the conductor temperature is limited to avoid aging of connectors or annealing of the aluminum conductor strands, then allowing the local conductor temperature at any span to exceed TC_{MAX} by more than 20°C may accelerate long-term aging effects causing premature line failures over time.

With real-time DLR, the rating calculation method and the real-time weather data measured along the line corridor must be accurate to avoid exceeding TC_{MAX} during periods of high current loading (e.g. system emergencies). With forecast DLR, there is no risk of physically exceeding TC_{MAX} unless system operators apply such forecasts without real-time measurements. That is, DLR forecasts are helpful in short-term planning but should not be used for actual system dispatch without real-time DLR verification.

The use of forecasted DLR implies the need for a real-time measurement system with weather stations, conductor temperature monitors, or sag/tension/clearance monitors at multiple points along the line corridors to be rated. The DLR monitoring system is needed to determine accurate real-time ratings and to calibrate and verify the DLR forecast values.

V. Dynamic Line Ratings

Any dynamic rating method requires a specification of TC_{MAX}. **T**he risk associated with exceeding ratings depends not only on weather data accuracy but on the accuracy of TC_{MAX} which should be calculated based on updated line surveys with the uncertainty regarding clearance well understood by utilities. Initial line survey data may have changed over time due to line modifications, conductor creep or ground level changes in the line corridor.

Dynamic Line Ratings fall into multiple categories but generally are either "Ambient-Adjusted" (DLR-AA), where only real-time variations in air temperature are considered, or "Dynamic Line Ratings with Real-Time Monitoring" (DLR-RTM) where the line rating considers both real-time air temperature and Effective Perpendicular (EP) wind speed in the line corridor.

Table 1 - Impact of Air Temp and EP Wind on SLR (Drake ACSR @100°C)

Air Temp °C	EP Wind m/s	% of SLR
35	0.61	100% ~~(SLR)~~
30	0.61	104%
30	1.22	121%

DLR-AA methods are in wide use, can be implemented rapidly (provided all upstream necessary precautions have been taken and line surveys have been updated) but produce only modest increases in rating (e.g. see Table 1 where a 5°C reduction in SLR air temperature produces a 4% change in line rating). DLR-RTM methods, which consider real-time measure EP wind speed as well as air temperature, usually produce higher-magnitude line ratings. For example, as shown in Table 1, the same 5°C reduction in air temperature combined with a modest increase in EP wind speed to 1.2 m/s, produces a 21% increase in rating. However, inclusion of EP wind speed requires remote line corridor monitors, real-time communication of data, and produces higher rating volatility.

1) Real time monitoring [3], [4], [5]

Dynamic Line Ratings cannot be measured directly but the weather parameters along the line corridor and the conductor temperature or sag and tension variation along the line can be measured in real-time and reported to the operations center where the line rating can be calculated and displayed. Forecast weather parameters can also be developed and used to calculate forecast DLR-RTM ratings. There are many types of commercially available remote line corridor sensors:

- The simplest monitor is a weather station which measures air temperature, solar heat intensity, wind speed, and wind direction. Modern stations incorporate an ultrasonic anemometer which has a very low stall speed and does not require frequent maintenance such as the older cup-type and propeller instruments did.
- Real-time temperature monitors [9] mount on the phase conductor and measure the local conductor temperature. A nearby base unit measuring air temperature and solar heating is also required. In combination with the real-time line current, a heat-balance equation such as that in IEEE 738 [2] can be used to calculate the EP wind speed where the monitor is mounted.
- Real-time sag/tension/clearance (distance) monitors [10], [11] mount on the conductor or on a supporting structure at multiple places along the line (also with a nearby air temperature and solar sensor). Knowing the state equation relating sag/tension/clearance to average conductor temperature and the real-time line current, the average conductor temperature for a span or line section can be calculated and the average EP wind speed determined.

In lines where TCMAX is chosen because of sag clearance concerns, the use of sag/tension/clearance monitors may minimize the risk of clearance violations during periods of high line current such as post-contingency power flows. In lines where TCMAX is chosen to avoid local aging of connectors and conductor annealing, the placement of temperature monitors or weather stations in sheltered spans may minimize the risk of aging or annealing during similarly high current events or daily and seasonal load peaks. As mentioned above, bare overhead conductors are poor longitudinal heat conductors, so the choice of monitor type must be done carefully.

Data acquisition and communication systems used by the monitors are similar (e.g. carrier, cell phone, satellite, GPRS, etc)

Finally, in lines that are heavily loaded, either electrically or environmentally, sag/tension/clearance monitors can be used to detect changes in the line's state equation over time.

Dynamic line ratings are updated at least once a day or as frequently as every 5 to 10-minute time interval. For system operations to operate the transmission system reliably, it is necessary to calculate DLR ratings in real-time but also to forecast them for the next 1 to 48 hours.

2) Ambient-Adjusted Line Ratings (DLR-AA)

Many utilities utilize DLR-AA ratings based on a maximum regional air temperature but there are many variations in how this is done. DLR-AA has several clear advantages:

- Since differences in air temperature between locations within the transmission system are typically small, the rating of multiple lines can be adjusted simultaneously by use of a single maximum regional air temperature.
- Air temperature variation along lines is not influenced by sheltering and line direction so that a single real-time value may be assumed to apply to the entire line.
- Air temperature varies slowly and predictably with time, so rating volatility and forecasting errors are small.
- Both real-time and forecast air temperature data is routinely available to operations so there is no need for dedicated remote monitors, real-time communication links, or sophisticated weather forecasting schemes.

The main disadvantage of DLR-AA is that they typically exceed SLR by less than 5% to 10% [12] depending on air temperature and the line's TC_{MAX}. Typically, the line rating increases by 0.5% to 1.0% per degree air temperature below that assumed in calculating the SLR.

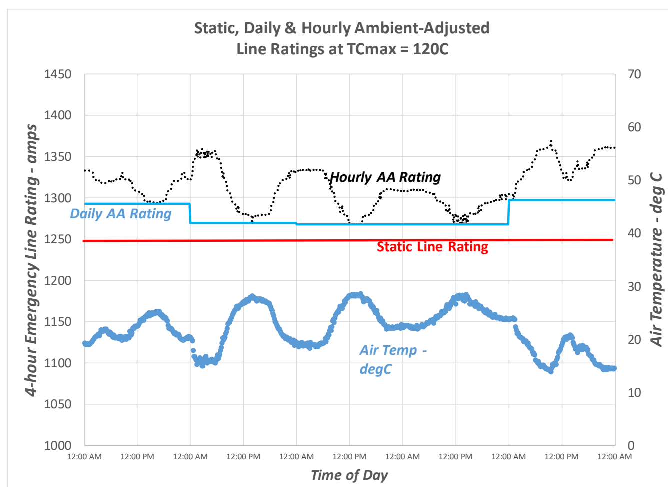

Figure 2 - Typical DLR-AA ratings with an assumed constant wind speed of 0.61 m/s

3) Daily DLR-AA

In the simplest form of DLR-AA, a daily 24-hour line rating is calculated based on the predicted maximum regional daily air temperature while leaving the EP wind speed and solar maximum heating the same as used for SLR. The rating is calculated during the preceding day and applies for 24 hours starting at midnight. An example of daily DLR-AA line ratings is shown compared to SLR in Figure 2.

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4) Hourly (or less) DLR-AA

Many transmission operators use hourly or minute-by-minute maximum regional air temperature rather than the daily maximum. An example of Hourly DLR-AA ratings is also shown in Figure 2. Note that the Hourly DLR-AA rating (calculated 24-hour ahead) is always higher than the Daily DLR-AA and is higher at night when air temperature is low.

Measurements of EP wind speed in typical line corridors show a pattern of low wind speeds at night and maximum wind speeds during the afternoon. CIGRE TB 299 [1] suggests calculating hourly DLR-AA ratings using the SLR EP Wind speed (e.g. 0.6 m/s) during the day and zero wind speed at night. If the wind speed assumption is left constant for all hours of the day, then hourly DLR-AA ratings will be too high at night.

5) Dynamic Line Rating with real-time monitoring DLR-RTM [13] [14]

If the line corridor EP wind (perpendicular to the line) is calculated from line corridor monitors, in addition to the air temperature and solar intensity, the resulting rating, using DLR-RTM, is typically higher than the DLR-AA calculated for the same weather conditions since EP wind speed is more influential than air temperature on the rating. Such ratings are, however, considerably more volatile since wind speed and direction vary more than air temperature along the line corridor.

DLR-RTM ratings are typically recalculated on a 5 to 10-minute time interval based on measurements of at least one physical parameter of the span/section and/or weather data: wind speed and direction, air temperature, and solar heating measured in the line corridor. The rating is “line-specific” since it requires monitors in the line corridor.

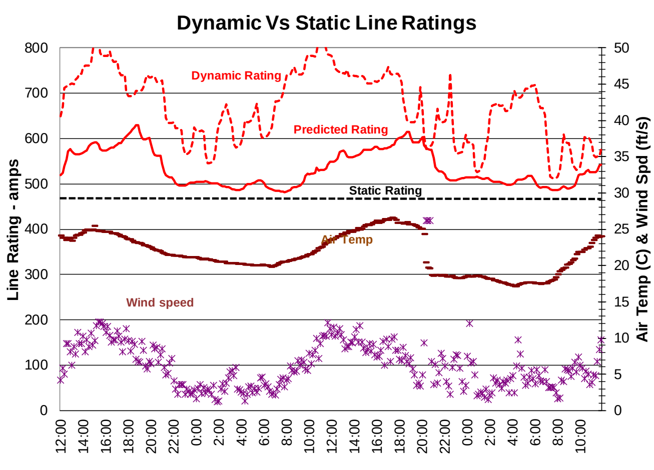

Figure 3 – Typical DLR-RTM and DLR-AA ratings with line-corridor wind statistics

As the length of the line increases, the number of monitoring locations should increase – e.g. 1 location for a 1-km line, 2 monitoring locations for a 10-km line, and 3 or more monitoring locations for a 100-km line. The static rating should be exceeded by the dynamic rating most of the time.

For DLR-RTM, line monitors measure and report real-time sag, tension, or conductor temperature as well as weather data at multiple locations along the line.

The advantages are:

- Safety, accuracy and reliability: the forecast is backed-up by *direct* real-time monitoring, measuring the actual state of the line at any time.
- The increased rating is higher as compared to DLR-AA
- The increase is more fairly distributed throughout the day as compared to DLR-AA.
- Real-time ratings volatility is dealt with in practice by using 1h and up to 4h or 6h forecasts in operation instead of real-time ratings.

VI. FORECASTING DYNAMIC LINE RATINGS

For DLR-AA – the forecast of line ratings is relatively straightforward. Maximum daily air temperature along a line route can usually be predicted with an error (RMSE) of less than 1ºC to 2ºC using commercial weather services. If the line ratings are to be adjusted hourly rather than daily, the forecast of air temperature is less conservative and the diurnal variation in minimum EP wind speed in the line corridor must be considered as determined by statistical analysis of line corridor wind measurements.

The forecast of DLR including wind is more complex and evolving. It requires real-time line corridor wind monitoring and, for forecasts more than 6 hours ahead, requires both weather forecasts and line corridor wind statistical or dynamic numerical analysis. In comparison to DLR-AA or SLR rating methods, forecasting DLR-RTM typically involves additional setup and verification. This increases costs but increases line rating reliability and provides higher real-time and predicted line ratings. This section of the paper identifies some of the present and most promising forecasting approaches.

Figure 4 shows real-time and forecast line corridor EP Wind Speeds based on measurements with a line “sag-vibration” monitor compared to real-time and forecast EP Wind Speeds based on a commercial, regional atmospheric weather model without line corridor monitors.

Figure 5 illustrates calculated real-time and forecast DLR calculated from the EP-Wind Speeds shown in Figure 4.

Depending on the information available at the time of calculation, DLR forecast models can be developed to minimize risk but beyond a forecast horizon of about 6 hours, weather forecasts are usually required. More details on DLR forecast principles and challenges can be found in [15]. The quality of the forecast ratings is mainly driven by the quality of the weather forecasts. Poor quality forecasts can be used but only if the magnitude of forecast ratings is reduced. A preset reliability of the rating forecast can be observed by design [15].

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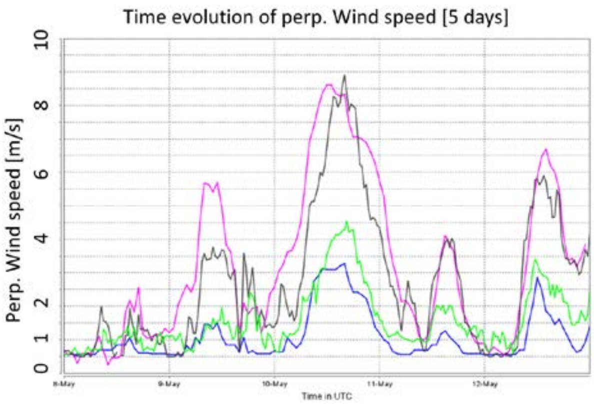

Figure 4 - EP Wind speed calculated in real-time and used as the basis for depicted forecast calculations: Color Coding: -[Blue] - 24h-Predicted P98 (98% probability) with Statistical Downscaling & machine-learning; [Green] -Real-time as measured by the sag-vibration monitor; [Black] - Real-time as calculated by the regional weather model; [Pink] - 24h-Predicted directly calculated from regional weather forecast data (direct model output) [13].

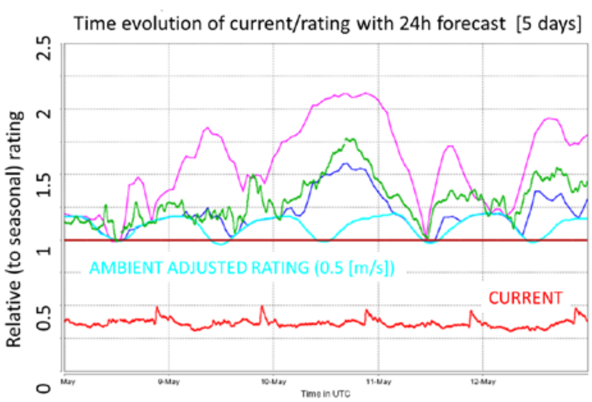

Figure 5 - DLR calculated based on the real-time and forecast EP wind speeds shown in Figure 4 with both real-time and predicted air temperature and solar heating.. Color Coding -[Blue] - 24h-Predicted DLR-RTM (98% probability, “P98”) with Statistical Downscaling and machine learning; [Green] - Real-time DLR-RTM based on sag-vibration monitor measurements; [Cyan] - 24h-Predicted DLR-AA; [Pink] 24-hour predicted rating directly calculated from regional weather forecast data (direct model output) [13].

1) Very Short-Term forecast (1h-6h)

Early models of short-term forecast used lowest DLR values in the previous hours, and possibly seasonal data and daily patterns, to estimate DLR forecast for the next few hours with a security margin.

More recent statistical analysis methods provide probabilistic rather than deterministic forecasts. As forecast time lessens, weather forecast accuracy increases.

The usefulness of very short-term rating DLR forecasts in system operations centers largely on dealing with N-1 post-contingency loads. Static ratings for 2 to 4 hours are often called Long-Term Emergency (LTE) line ratings. Depending on the system operator’s available tools and the economic consequences of making rapid load flow adjustments. Its main advantage is to avoid the need for rapid changes in circuit loading or load-shedding during the first few hours after a system emergency.

2) Short-term “Day-Ahead” forecast (24h-48h)

Power markets usually need transmission capacity forecasts one or two days ahead. With DLR-AA ratings, Day-Ahead forecasts are quite possible with commonly available commercial weather data, both real-time and forecasts. This is especially true with DLR-AA methods that are adjusted daily, since the hour at which air temperature peaks or weather-front driven changes in air temperature have little effect. With hourly adjustment, forecasts of line ratings show an increase in errors related to time-of-day and may require short-term adjustments of rating. [15], [16]

With DLR-RTM methods, Day-Ahead line rating forecasts for next day and day-after, require general-purpose weather forecasts for different locations along the line and a history of previous real-time rating measurements. To date, there are multiple operational Numerical Weather Prediction (NWP) models [13] for the global domain, i.e. covering the whole world, running with horizontal resolutions between 9 and 40 km (e.g. IFS from ECMWF in Europe, GFS from NOAA in USA). For smaller domains, typically a few thousand kilometers in each direction, LAMs (Limited Area Models) run with a horizontal resolution of a few kilometers (e.g. WRF, ALADIN, HIRLAM, COSMO). They are, however, dependent on forecasts from global models at the boundaries of their domains, and so is in part their accuracy. To date, their horizontal resolution is about 1-2 km in operational forecast.

Day-Ahead weather data for forecasting DLR is typically updated every 4 to 8 hours, with a temporal resolution of 1h for a forecast horizon of up to 48 hours. The various DLR forecasting methods described below do not depend on any meteorological data source.

Indeed, wind speed and direction have a high temporal and spatial variability. Significant changes in wind speed and direction in the space of a few meters are caused by obstacles, terrain and roughness changes near the span. To consider these effects in a weather forecast model, meter-sized grid sizes would be required. However, the grid sizes on today’s high-resolution weather forecast models are in the range of about 1 km. Thus, important impact factors are not resolved in the models.

Different methodologies exist to refine the results of weather forecast models. These methods basically fall into two groups: statistical and dynamical downscaling procedures [13].

- Statistical downscaling describes the relationship between the results of weather forecast models and real-time measurements using statistics. They result in significant improvements as compared to direct model output from weather forecast models.
- Dynamical downscaling increases the spatial resolution of weather forecast models by applying higher resolution dynamical models. It is computationally very intensive and is mainly used for theoretical studies. Due to the large

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amounts of computing time, it is currently not possible to run online-forecasts, although a statistical-dynamical approach could be used.

Computation Fluid Dynamics (CFD) models [16] are often used for wind resource assessment to simulate the flow field in complex terrains. CFD models are run with grid sizes as small as a few meters and thus allow a fine resolution of obstacles and terrain features. It can then be coupled with weather forecast models where the flow field is refined by the CFD models. First studies show promising results.

3) Low wind speeds issue

The main issue regarding DLR-RTM forecast is to deal with the uncertainties of wind forecast, as DLR is highly sensitive to the EP wind speed within the transmission line corridor.

"Low Wind Speed" conditions, roughly defined as periods when the mean wind speed at 10 m above ground level is less than 2 m/s, is considered as a critical parameter. Furthermore, low wind speeds are expected to be the limiting parameter in a DLR forecast application. However, in operational practice, the important information is the knowledge of the wind speed value in the future associated with its probability. E.g. a whole set of probable future DLR values with their associated probability can be provided. The operator then picks the most suitable quantile depending on its risk policy. Today, a preset quantile is typically chosen (e.g. 98% probability for DLR forecast to be inferior to the future observation, see Figure 4) but the chosen quantile may vary as well. Research is ongoing to define an optimal quantile, possibly varying through the day, as to minimize the risk and maximize the economic welfare for horizons ranging from a few hours to a few days [17],[18], [19].

VII. Using DLR in System Operations [20] [21] [22]

The usefulness of DLR and the need for forecasted DLR is best understood within the context of system operations, considering human and automation aspects, operating philosophies, operating models and software capabilities and processes.

Power system operation usually applies ratings to establish a normal or emergency time-limited criterion to which present and future power flow can be compared. As this paper illustrates, many equipment parameters and weather variables affect dynamic ratings, including the forecast time-period, the current operating status, current power flows on elements, current system status, current grid topology, and future grid aspects, including: load forecasts, generation levels, operating constraints, scheduled outages, and demand-side management.

An important consideration in risk assessment is the technology available to the system operators and training provided. While all system operators in North America must comply with NERC Reliability Standards, their operating procedures and application may be different. A small local municipal or cooperative may operate primarily with human awareness, anticipation, and response. Larger grids have Energy Management Systems (EMS) monitoring system status, running state estimators in real-time, analyzing contingencies, alerting overload or potential overload and recommending corrective actions. Ultimately, even these "automated" systems rely on operators' experiences with the grid and the impact of various mitigating actions.

Transmission systems are planned and operated with a minimum of N-1 contingency criteria that allows for reliable load supply even when one or more major circuits or generators are out of service. Special operating procedures or automatic load shedding schemes are also in place for the contingencies that would otherwise cause power flow exceed limits. In addition, short-term emergency ratings can be used to gain extra response time (typically 15 minutes) to take actions to reduce flow short term emergency. Therefore, even for ratings forecasted an hour or more ahead, if the actual rating is found to be less, and a system emergency occurs, system operators would apply emergency procedures. The shorter the horizon for which the forecast is made, the more reactive system responses need to be.

For longer term forecasted ratings, such as those whose onset time is a day or more into the future, the adjustments to system operation could be phased in at every rating update, smoothing the operation process. By planning and fine-tuning adjustment in real time, system operation can be significantly improved in terms of reliability and operation efficiency.

Forecast (and real-time) DLR change with time but forecasting for up to 48 hours ahead allows the operator to anticipate problems and respond by mitigating the associated risks. Therefore, it is not a matter of the risk being a constraining aspect, but rather the establishment of accommodating operation process and tools. One option would be to limit the rating to a more manageable level, with measurable benefits and limited risk exposure (e.g. [23].

In the case of very short-term forecasting, minutes to several hours, the collaborative dynamic rating (DLR-RTM) and forecasting protocols provide ratings that deliver increased capacity and increased reliability for the grid, more importantly, through an increased system situation awareness.

For onset times beyond 48 hours, risk mitigation and management are achieved by having periodic review of system operation conditions and corresponding update of operation plan. For onset times less than 48 hours, the uncertainties become less, and risks can be managed through DLR and forecast DLR.

Line ratings are utilized in the following system evaluations:

- Operation software, such as EMS, routinely check actual power flow against limits, include overhead line thermal ratings, and provide corresponding warnings to the operators for over limit or approaching limit.
- This software also performs contingency analysis for the potential loss of system components, (i.e. generation or transmission circuits) and check against thermal limits and stability limits.

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- Planned transmission and generation outages are evaluated to ensure that the power system can withstand such component losses while remaining reliable.
- For efficient day-ahead market operation, forecasted overhead line ratings are needed for the next day (and sometimes for multiple days). Two-day ahead ratings are a major benefit to the economics of the energy markets.

Though system operations use line ratings extensively in their efforts to keep the power system reliable and efficient, they do not normally calculate such ratings, nor do they have any means to detect incorrect ratings. Therefore, dynamic line ratings require the cooperation of engineering and operations to assure that ratings are calculated and employed correctly, as shown in Figure 5.

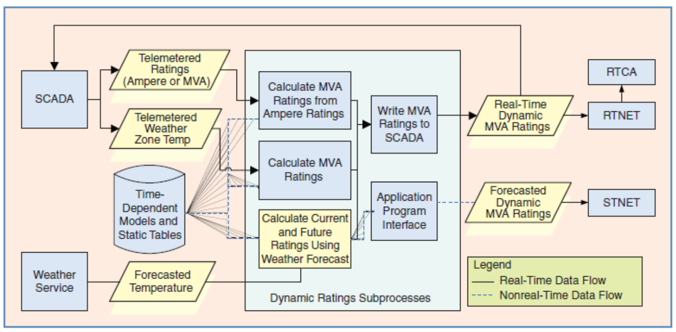

Figure 6 - Integration of Real-time and Forecasted Line Ratings into Operations [22]

VIII DLR APPLICATION EXAMPLES

This section of the paper describes several DLR applications to provide the reader with practical examples.

1) PJM Interconnection

A large Regional Transmission Operator in the US, PJM, has published their line rating method [24] and it is unique. Based on a study of weather data from 1979, they derived a weather data base for their entire transmission system area. Line thermal ratings are determined based on annealing (loss of strength) of various types of conductors with an assumed load pattern.

The temperature limits, TC_{MAX}, correspond to a 10% loss of rated strength over a 40-year life. Normal ratings are calculated for zero wind and Emergency ratings are calculated for 0.7 m/s EP wind. All lines that use these TC_{MAX} values are designed to provide enough electrical clearance at the corresponding high-temperature sag.

PJM employs DLR-AA on multiple lines based on real-time regional air temperatures. Normal ratings, based on zero wind speed, are not excessive at night but the increase in SLR ratings is modest with high TC_{MAX}.

2) Western Canada

In [25] the DLR monitoring is by line corridor anemometers and Computerized Fluid Dynamic modeling to provide more complete corridor weather coverage. This method was applied in Alberta, Canada, to a line near a utility wind generation site as described, in four segments of tie-lines. The application includes forecasting.

3) Hydo One in Eastern Canada

Hydro One (formerly known as Ontario Hydro), Ontario, Canada [26] has adopted the DLR-AA approach for on-line transmission capacity evaluation for decades. The objective is to maximize the thermal capability of the transmission circuits by using real-time meteorological data and forecasting for system operation.

On-line rating monitoring and evaluation method was developed to determine transmission capability using real time weather and operating conditions.

The on-line rating monitoring and evaluation system now in use has three major components, namely;

- Out of Limit Monitoring module
- Meteorological Data System module
- On-line Contingency Simulation module

4) Elia Belgian Interconnections

The outage of three nuclear plants of mid-2014 in Belgium (half of the Belgian nuclear generation) highlighted risks of shortage during the same winter in case of severe weather conditions. Belgium can import electricity from neighbouring countries, but the maximum import capacity based on traditional seasonal ratings could be inadequate in certain operating situations such as an extended cold wave.

As fast action was required, Elia (the Belgian TSO) decided to use real time Dynamic Line Rating on cross-border lines with France and the Netherlands. Elia deployed 38 “sag-vibration monitors~~Ampacimon” sensors~~ on 8 cross-border lines in 4 months. A second objective was to deploy a 2 days-ahead DLR-forecast (forecast horizon of 48h with 1h of resolution, and an update every 6h). As DLR using direct monitoring had been applied in Belgium for 3 years on several domestic lines, using 1h- and 4h- forecast, Elia was aware of its potential. Therefore, both real-time and forecast DLR was deployed to maximize imports and reduce the risk of load shedding during the 2014-2015 winter.

In that case, the 48h forecast provided an average gain of 110% of the static seasonal rating (SLR) for 90% of the time, with a forecast reliability of 98% [15]. DLR forecast has been extensively used since then. Today, the pre-defined acceptable increase in risk has been set by ELIA, in agreement with the Belgian regulator, at 0.1%, corresponding to roughly 9 hours a year. Consequently, the 48h-forecast rating has been capped to 105% of SLR during peak hours and 109% of SLR during off-peak hours. However, up to 130% of SLR (capped) can be used for 1h-forecast and real-time rating [23].

5) Austrian Power Grid

Austrian Power Grid installed DLR monitoring system in two 100 km lines getting information for 5 years. The purpose of APG system in to prevent congestion management [27].

6) Iberdola in Spain

The University of the Basque Country UPV/EHU in collaboration with Iberdrola utility has analyzed the validity of

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the standard weather prediction provided by the Spanish State Meteorological Agency (AEMET) using measurements in a line in operation [28]. The numerical weather prediction (NWP) model is the High-Resolution Limited Area Model (HIRLAM). This model provides the ambient temperature at 2 m, wind speed at 10 m and solar radiation at ground level. The forecast length is 36 h with 3 h of resolution and the forecasts are updated every 6 h. The mesh size is 0.05 º (latitude: 5.5 km; longitude: 4 km). For this analysis, the day ahead 24 h forecast length is considered.

7) Brazilian River crossing

In Brazil a conductor sag meter was installed in a 138 double circuit river crossing up rated using HTLS conductor. The application included one traction meter and one laser distance meter to monitor behavior of this new type of conductor [29]

8) RTE - France [30]

In France, DLR monitoring systems were installed and evaluated in a 225-kV line in the western part of the RTE system and in a 63-kV line in the Southeast. The latter installation was intended to increase line capacity to deal with peak loads during the winter ski season. With the DLR system, the need for re-dispatch by system operations was reduced and postponement of network additions yielded significant savings.

IX SUMMARY, CONCLUSIONS & RECOMMENDATIONS.

Static line ratings (SLRs) are calculated based upon suitably conservative weather conditions and can be adjusted seasonally by using an air temperature which is close to the highest seasonal peak temperature.

To gain additional overhead line thermal capacity, real-time weather conditions and/or the state of the conductors (sag-tension) can be monitored and used to calculate Dynamic Line Ratings (DLRs). The measurement interval can be days or hours for DLR-AA and 5 to 15 minutes for DLR-RTM methods.

If only air temperature is monitored in real-time (while wind speed, wind direction and solar heating are held to suitably conservative values), the dynamic line rating method is referred to here as DLR-AA or Ambient-Adjusted dynamic line ratings. If line ratings are calculated based on real-time line corridor air temperature, wind speed and direction, and solar heating, then rating method is referred to as DLR-RTM ("Dynamic Line Ratings based on Real-time Monitoring").

Various types of monitors can be placed in the line corridor to determine wind speed, etc., but all must be linked to a computer either in the system operations center or linked to it. In either case, system operations must know both the real-time line rating and an estimate of the line rating in the immediate future. Line ratings forecast for the next few hours are useful in dealing with system emergencies which persist for several hours. Those forecast for 24 to 48 hours ahead, are useful operational planning to deal with outages for maintenance and capacity commitments to power markets.

Real-time DLR and forecast DLR are calculated with the same heat balance method using the same conductor TC_{MAX} values but differ in the weather parameters used.

SLR, DLR-AA, and DLR-RTM accuracy requirements are the same - loading the line to its thermal rating should almost never yield a conductor temperature which exceeds the line's TC_{MAX} to maintain minimum electrical clearances along the rated line and to avoid excessive aging of the conductor system.

The accuracy of forecasted DLR-AA or DLR-RTM can only be determined using real-time monitors (RTM). Historical line-corridor weather data can be analyzed statistically to determine the risk associated with EP wind assumptions in DLR-AA methods. Real-time line-corridor weather data is used to calculate DLR-RTM and to calibrate the accuracy of forecast DLR-RTM through either statistical or dynamic "downscaling" of Numerical Weather Prediction data.

If the forecasted DLR is too high, then the orderly operation of the power system may be adversely affected, although any forecast error reduces as the forecast horizon shortens. The consequences of over-estimating forecasted DLR involve the need for intervention by system operations to reduce power flow by changing network topology, re-dispatching generation or by adjusting power flow controls such as series reactors, any of which may yield economic penalties and non-optimum generation dispatch. Conservative values for the forecast reliability are considered today (e.g. 98% of reliability of the forecast), but an economic optimum should be defined in the future.

Ambient-adjusted dynamic line ratings (DLR-AA) are only modestly higher than seasonal SLR. Dynamic line ratings (DLR-RTM) are higher than DLR-AA ratings since they consider real-time line-corridor EP wind speed data as well as air temperature and solar heating. Of course, DLR-RTM ratings require remote line-corridor monitors linked to operations in real-time and are more volatile and line-specific but, as shown in this paper, DLR-RTM ratings can be forecast (and thus anticipated by system operations) by adapting existing commercial weather service forecasts, and real-time line corridor monitor data provides evidence of line rating risk.

If DLR-AA is updated daily, only the daily peak air temperature is needed to forecast DLR-AA for the next day and, if the maximum regional air temperature is used, multiple lines in the same geographical region can be rated without the need for field instrumentation (provided all upstream necessary precautions have been taken and line surveys have been updated).. If hourly DLR-AA are used in combination with a constant EP wind speed, the line ratings may be too high at night. This can be corrected by using conservative line-corridor wind speeds allowed to vary with time-of-day.

DLR-RTM line ratings can be calculated based on a variety of line corridor monitoring methods. Forecasts of DLR for the next 1 to 6 hours can be calculated based on a variety of statistical methods but DLR forecasts ranging from 6-48 hours ahead also require commercial weather forecasts. Direct Model Output of Mesoscale atmospheric calculations are adequate to estimate the wind conditions well above the ground (> 100 meters) but are not adequate to determine weather data (particularly wind speed and direction) at the height of most transmission conductors (10 to 15 meters).

Statistical and/or dynamical downscaling procedures must be applied to weather forecast data to provide sufficient accuracy. Probabilistic forecast of DLR-RTM is calculated (either by providing PDF or quantile forecast). The quantile chosen for operation depends on the risk policy of the operator. It can be set to equal the risk defined for static rating (> P95).

When statistical downscaling is based on direct line monitoring, it typically features a higher gain than DLR-AA and a high reliability in the forecast, backed up by real-time measurements ensuring security and safety; but it is line-specific and requires the installation of monitoring devices.

The risk involved in any forecast of DLRs must consider whether the line is clearance-limited, or conductor-limited due to annealing and connector aging. Clearance-limited lines must be rated such that the worst-case spans exceed the line design maximum average conductor temperature by no more than 10°C, for even a brief period, or it may compromise the public safety.

If the TC_{MAX} for the line is determined by annealing and aging of the conductor system, then the consequence of exceeding TC_{MAX} are less immediately severe as there is no immediate threat to the public safety. In either case, the impact of the risk varies with the type and condition of the line conductors. If the conductor is all aluminum, then the magnitude of excessive sag due to a temperature exceedance is higher than if the conductor is ACSR or ACSS and the degree of excessive aging is less because of the steel core.

In most applications, the percentage increase in line rating obtained by real-time monitoring is less than that obtained with conventional, physical line modification methods of uprating but DLR can normally be implemented quickly without public hearings or the need for regulatory approval and the cost of monitors and communications may be much lower than that of conventional uprating methods.

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