The Spanish Experience

Squeezing Line Ampacities Through Dynamic Line Rating

DYNAMIC LINE RATING (DLR), ALSO KNOWN IN some instances as *real-time thermal rating*, is becoming a key component of modern energy management systems for transmission system operators (TSOs) or independent system operators (ISOs) to use transmission assets more efficiently while maintaining current reliability standards. However, the need for this tool will be even more overwhelming in a decarbonized future, given the foreseeable line congestion originating from the coincidence of several factors: 1) significant growth of the share of intermittent renewables; 2) the further electrification of the residential, transportation, and industrial energy demand; and 3) increasing difficulties and costs for the construction of new transmission assets.

Network congestion may force system operators to implement some preventive or corrective measures, such as generation rescheduling, with undesirable economic consequences for the system as a whole. Therefore, to minimize the impact of those actions, TSOs/ISOs are focused on making better use of the available infrastructure, which calls for more sophisticated tools capable of permanently monitoring the thermal status of transmission lines and transformers. The urgency for better utilization of the existing assets has prompted specific actions from regulators. For example, the U.S. Federal Energy Regulatory Commission is evaluating the economic benefits and challenges of applying DLR compared to the traditional static line rating (SLR).

Broadly speaking, the capacity of a transmission system can be directly associated with the transfer capacity of its individual

Digital Object Identifier 10.1109/MPE.2022.3219167
Date of current version: 30 December 2022

By José A. Rosendo-Macías, Antonio Gómez-Expósito, Alfonso Bachiller-Soler, Miguel Á. González-Cagigal, Gabriel Álvarez-Cordero, Lucía Mateo-Sánchez, and Antonio Useros-García

> The U.S. Federal Energy Regulatory Commission is evaluating the economic benefits and challenges of applying DLR compared to the traditional static line rating.

components, whether they are underground lines (UGLs) or overhead lines (OHLs). In the simplest case, the operating procedures adopted by TSO/ISOs assume that the rated capacity of transmission lines is determined by a single SLR. Also common is the use of several SLRs throughout the year, normally chosen on a seasonal basis. For UGLs, the International Electrotechnical Commission (IEC) standard IEC-60287-3-1-2017 includes a list with the ambient temperature and soil properties to be used for the calculation of these thermal ratings in several countries. As these procedures do not consider the state of the system and weather conditions at any given time, over the last decades, researchers have explored more innovative approaches, collectively known as *DLR*, aimed at obtaining the thermal capacity of transmission assets in real time to squeeze out their real capacity. However, applying DLR involves the installation of new and costly monitoring equipment, along with the development of suitable data analytics algorithms. Therefore, several research lines are currently focused on minimizing the required investment without jeopardizing the safe system operation or the integrity of assets.

A key concept related to UGLs is the current carrying capacity of the conductor (also known as the *ampacity*). This concept is defined in IEC 60287 as the maximum permanent current that asymptotically heats the conductor insulation to its maximum temperature. For example, for low-density degassed XLPE-insulated cables, temperatures of more than 90 °C might jeopardize the service life of the cable. The ampacity concept can also be used for OHLs. In this case, the maximum steady-state operating temperature is established to prevent metallurgical damage or violation of critical distances. In the case of Europe, temperatures up to 90 °C are adopted for aluminum-conductor steel-reinforced conductors.

This work presents the recent Spanish experience with the application of DLR for underground and overhead ac transmission lines. For each type of asset, brief descriptions of the methodology adopted and of the main difficulties encountered in the practical implementation are first provided. Next, practical experience gained in the pilot projects undertaken by the Spanish TSO Red Eléctrica de España (REE) is presented, showing that the proposed techniques improve the utilization of existing assets as compared to traditional solutions. In the UGL case, dynamic state estimation (DSE) is used to obtain an accurate model of the temperature evolution, where the involved parameters are simultaneously estimated. Although similar methods could be used, in theory, for OHLs, measurement sampling rates are typically low when compared to the thermal time constant. Therefore, in this case, steady-state conditions are assumed for the DLR calculation. Finally, the conclusions derived from the obtained results and suggested future lines of research related to DLR are outlined.

Underground Transmission Lines

In the particular case of Spain, the risk of steady-state thermal overload for UGLs is quite low under normal operating conditions. This low risk is due to the relatively low average typical load (below 30% of the rated capacity), which leaves spare capacity for N-1 outages, especially when facing peak load conditions.

DLR for UGLs

The rated ampacity of UGLs is usually a conservative value because it does not take into account the high thermal inertia of the materials involved. Indeed, a buried conductor subjected to a load step can take years to reach the maximum steady-state operating temperature. Among the factors affecting both the steady-state and transient thermal behavior of UGLs, the following stand out: the burial depth, ambient temperature, and soil thermal properties. Note that the latter two are time varying, which should be considered by the DLR methodology.

Several strategies are used to duly consider the thermal inertia of UGLs for the estimation of their ampacity for a few hours, days, or even months ahead. In the case of cyclic loads, a first strategy consists of calculating a so-called "increased ampacity," either using a load factor or a cyclic rating factor, as described in IEC 60853. This standard is dedicated to the calculation of the cyclic and emergency current rating of cables.

A second strategy can only be applied if soil parameters are known or assumed (from actual measurements or considering the same parameters used to calculate the conventional ampacity). The following load scenarios are considered, where different information related to the conductor temperature can be numerically calculated:

- ✔ For a load step, it is possible to calculate the time it takes for the cable to reach the steady-state operating temperature from its previous value. This time constant can be used when analyzing network contingencies.
- ✔ A representative cyclic load curve can be designed to make the cable reach its maximum operating temperature. This value can be used as the base ampacity for further studies.

- ✔ It is possible to combine the two previous scenarios so that a balance is achieved between the ampacity increase and the operational security.
- ✔ The temperature of the conductor can be updated based on real-time current measurements. Given the slow evolution of the temperature, this provides a reaction margin of hours.

A third strategy, more accurate and flexible, consists of monitoring the cable temperature in real time by using a distributed temperature sensing (DTS) system based on optical fiber (OF), which is embedded in the sheath or the jacket of the cable. The measurements provided by this device, updated every 5 min, include the average temperature for every meter of the OF. Both spatial and time steps are tunable. These measurements allow underground cables to operate according to the actual temperature evolution. The operating principle of the DTS system is based on Raman or Brillouin effects, which estimate the conductor temperature through changes in the frequency bands produced by light scattering.

An alternative for temperature monitoring in the case of thermally limiting and accessible sections of cables without OF is the use of a temperature probe in the jacket of those accessible cable sections, which are considered limiting in terms of the overall ampacity. This strategy has been applied by REE on more than 20 220-kV and three 66-kV UGLs.

DTS-Based Methodology for DLR

To properly use the DTS measurements for the DLR calculation, a thermal model of the cable is required. In this context, several models have been developed for underground cables using the finite-element method (FEM), which can be numerically solved using simulation tools, such as COMSOL (Figure 1).

However, these simulations are not appropriate for real-time applications due to the calculation time required and the difficult integration into the utility's software. To overcome this problem, simpler models can be used to describe the thermal dynamics of the cable. Particularly suitable for this purpose is the ladder-type discrete dynamic model of the cable and the surrounding soil, leading to the well-known state–space representation characterizing linear systems. The state vector includes the cable temperatures (the conductor and sheath) and those of several concentric slices of the soil. The input is composed of the currents causing the heating and the ambient temperature. The model also depends on the geometry of the cable and the soil thermal properties (the resistivity and capacity). In the applications we discuss here, much more complex ladder-type models have been considered, including the effects of convective cooling for cables with protective pipes and the mutual heating for three-phase configurations. In practice, the innermost insulator temperature, which can be approximated by the conductor temperature, is the limiting factor for ampacity.

To assess the accuracy of this analytic model, the results obtained for the conductor temperature were compared with those provided by the FEM-based simulation. This comparison was conducted under different load scenarios and changing values for the ambient temperature, soil thermal resistivity, and volumetric thermal capacity. The maximum estimation error was around 0.8 °C, as shown in Figure 2 for an example scenario covering one week.

Hence, for a given current profile, the ladder-type model has proven to be sufficiently accurate for calculating the evolution of the temperature in each section of the cable, allowing a simpler way to assess if the maximum operating temperature is exceeded.

Parameter Estimation

A potential limitation of the ladder-type discrete model is that it involves a set of parameters that are not necessarily known. To address this issue, a DSE model together with a nonlinear Kalman filter (KF) has been used for joint state and parameter estimation. In the DLR application, the DSE model can be used for the estimation of the temperatures and the unknown parameters in the presence of measurement and model noises. For this purpose, an augmented state vector is defined, including the state variables of the model and the whole set of parameters to be estimated. This way, the KF

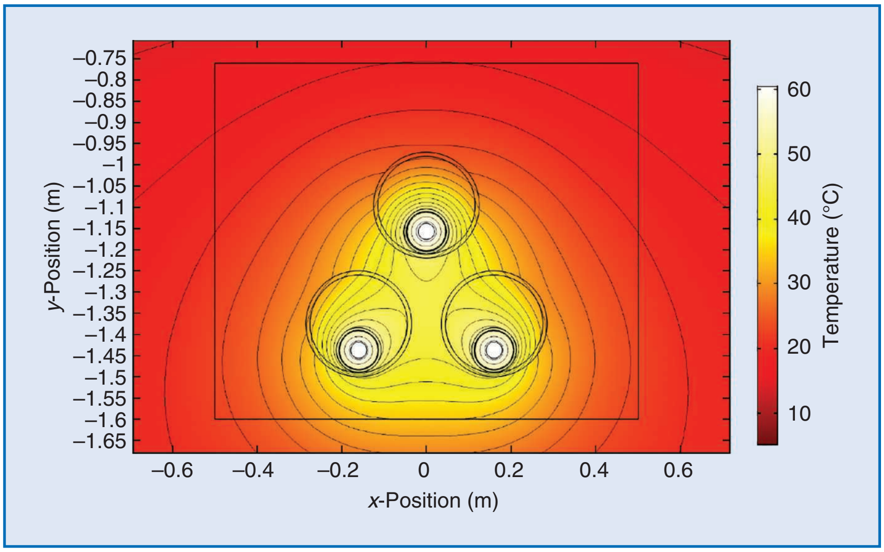

figure 1. An example of a COMSOL thermal simulation.

Several research lines are currently focused on minimizing the required investment without jeopardizing the safe system operation or the integrity of assets.

process updates the whole state vector with each new sample provided by the DTS.

The overall process of the DTS-based method, including the estimation of parameters, is illustrated in the flowchart of Figure 3, and summarized here:

- ✔ Initial estimations of the state variables and parameters are introduced in the KF algorithm, along with the corresponding covariance of the initial estimation error.
- ✔ Then, the DTS measurements are processed by the KF to obtain estimates of the parameters involved in the model.
- ✔ Finally, given the expected current profile, the estimated model is used to predict the temperature of each section of the underground cable and to check whether the maximum operating temperature is exceeded.

The accuracy of the KF-based technique has been evaluated in a set of simulated scenarios, where an FEM-based tool is run with different parameter values to emulate the DTS measurements included in the KF algorithm. The maximum estimation error for each parameter can be taken as a metric of the overall method performance.

Field Application

The DTS technology presented previously has been used in a pilot project in the Balearic Islands, Spain. The DTS information is complemented with the real-time estimation

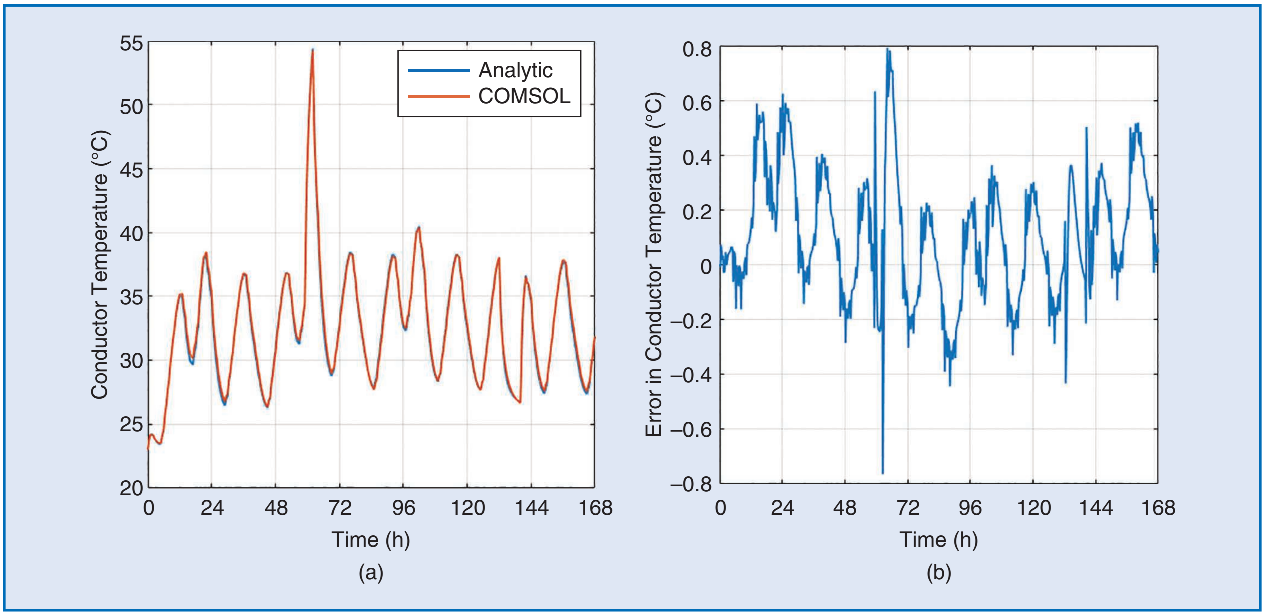

figure 2. The conductor temperature with (a) a ladder-type model and FEM and (b) the resulting error.

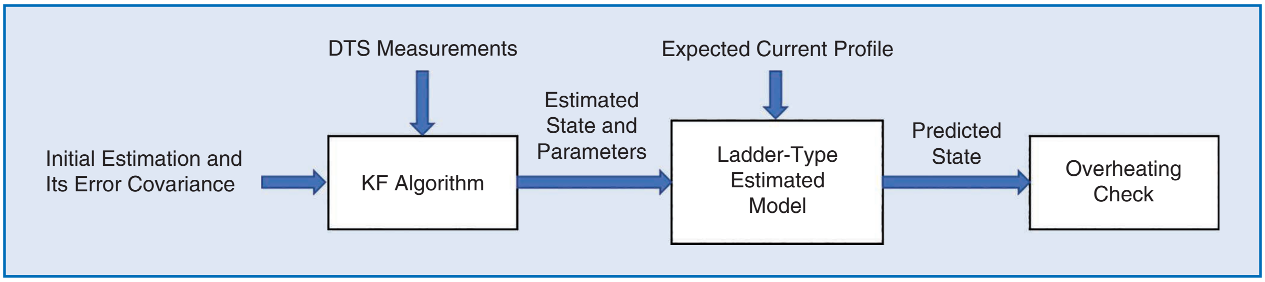

figure 3. A flowchart of the DTS-based method using KF.

> The rated ampacity of UGLs is usually a conservative value because it does not take into account the high thermal inertia of the materials involved.

of three parameters external to the cable, leading to a more accurate prediction of the conductor temperature for future load curves. This more sophisticated estimation technique has been tested on three operative UGLs, namely, two 220-kV circuits in Barcelona, a 66-kV short cable in Mallorca, and a 132-kV circuit in the Mallorca–Ibiza interconnection. The goal was to make 48-h predictions of conductor temperature with an error of less than 3 °C.

For the current profile presented in Figure 4(a), the sheath temperature measurements provided by the DTS are those shown in Figure 4(b), which is the only information used for the parameter estimation carried out by the KF-based DSE.

The time evolution of the estimates for the three parameters to be estimated is represented in Figure 5(a)–(c). Notice that the estimated values remain within an acceptable range, except for the ambient temperature T_a. Finally, the DSE-based model was used to predict the sheath temperature for the next 48-h period, which can be compared with the actual DTS measurements to test the accuracy of the model. The difference between both values (estimation error) is represented in Figure 5(d), where it can be observed that the resulting errors remain below 1.4 °C in all cases. This confirms the suitability of both the ladder-type discrete model and the KF-based DSE for DLR of UGLs.

A pilot implementation of the DLR methodology described previously has been thoroughly tested. To give an idea of the information the user can access in real time, Figure 6 shows a sample with the spatial distribution of the real-time estimation of the conductor temperature using the DTS measurements.

So far, the proposed technique has been tested on several 132- and 220-kV UGLs. Future research efforts will be oriented to fully assess the DSE-based estimation technique with higher conductor currents and different layouts of cables, such as those including galleries and overhead-to-underground transmission towers.

In summary, the main innovations currently being investigated in Spain are the simultaneous, real-time estimation of the external parameters arising in the thermal cable model considered and the improvement in the operation of UGLs by means of DLR.

Overhead Transmission Lines

This section presents the application of DLR techniques to OHLs, paying special attention to distinguishing features that are not found in the case of UGLs.

DLR for Overhead Transmission Lines

In Spain, owing to the relatively short length of OHLs, rarely exceeding 200 km, the main restriction in the transfer capacity is related to their thermal limit, i.e., to the conductor temperature at a given time, which needs to be compared to the maximum operating temperature of the corresponding circuit. Conductor overheating can be the cause of the following two undesirable phenomena:

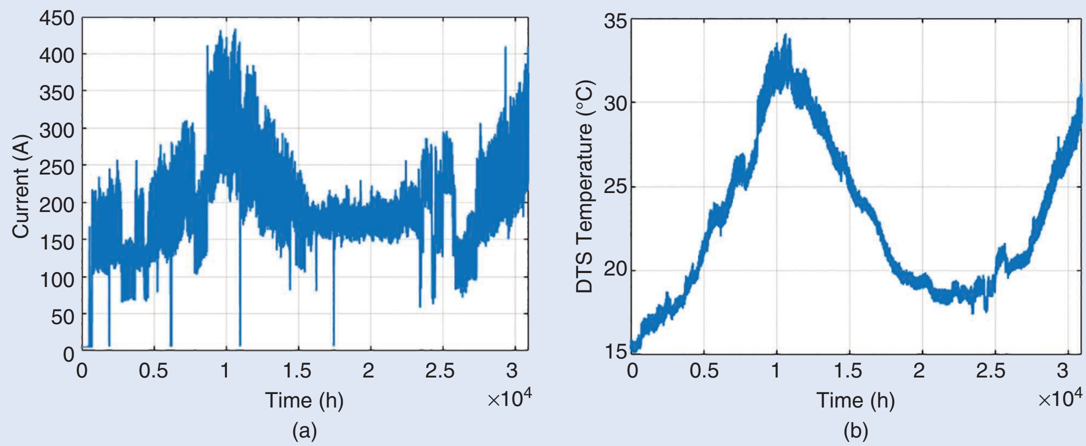

figure 4. The (a) current profile considered and (b) DTS measurements in the presented application.

✔ An excessive increase in the maximum sag of any line section may result in violations of the mandatory minimum electrical clearances.

✔ There may be deterioration of the conductor by annealing of the aluminum wires, eventually reducing the breaking load of the material.

The operational impact of these phenomena depends largely on the type and properties of the conductor.

Several techniques make it possible to increase the maximum operating current for a given line, such as increasing the height of the towers, substituting the conductors with a different type of material with higher operating temperatures (for some options, more than 100 °C), or adding more conductors per phase. However, all of these strategies require circuit disconnection for relatively prolonged periods and the corresponding administrative authorization. The

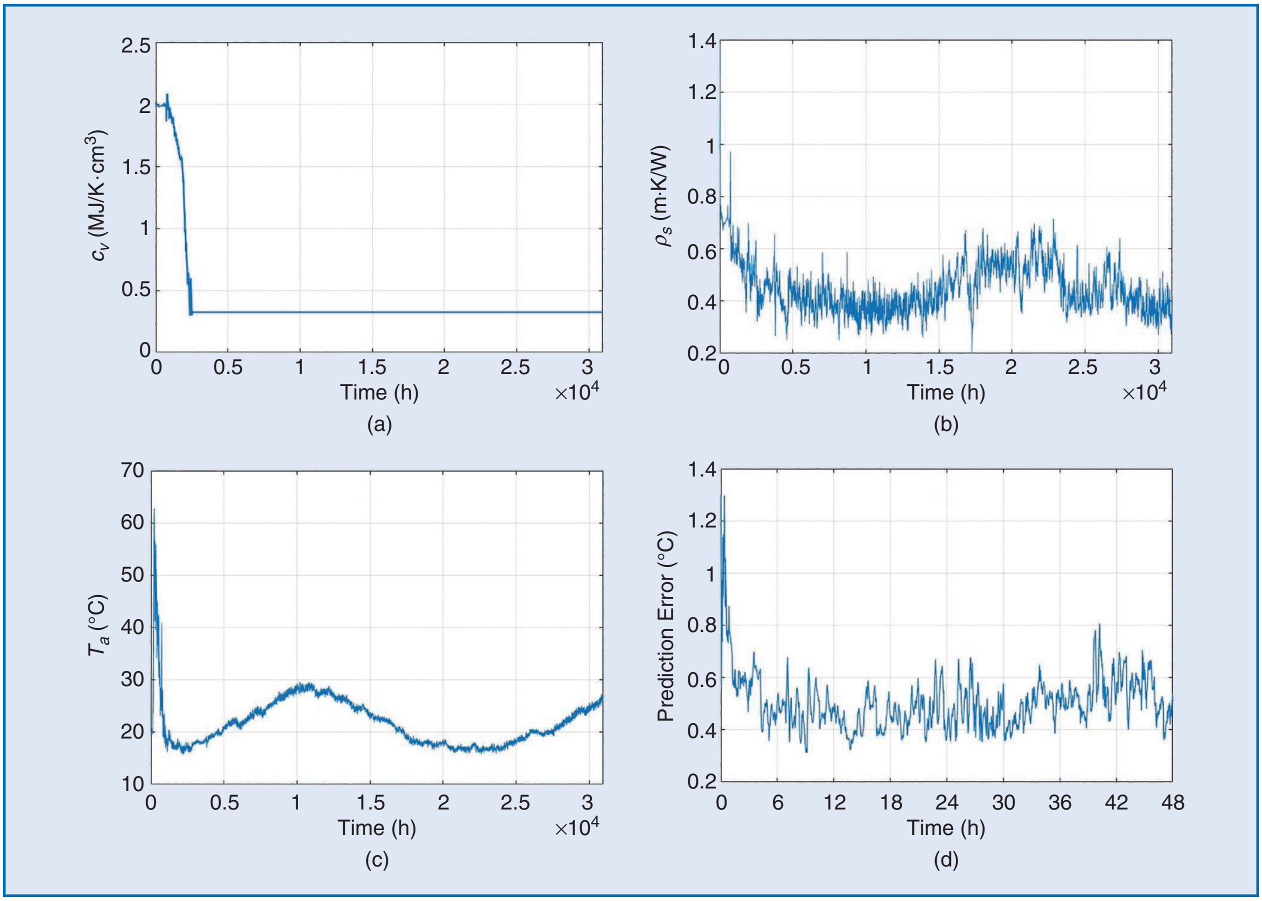

figure 5. (a)–(c) The estimated parameters using Kalman filtering and (d) the sheath temperature prediction error in the 48-h period.

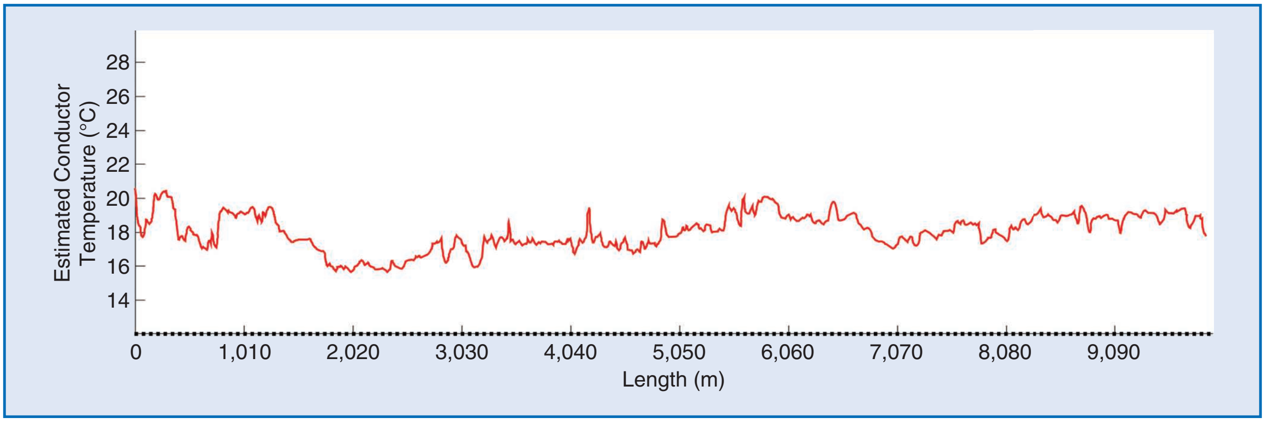

figure 6. The real-time temperature estimation throughout the conductor length.

real-time application of DLR to OHLs can largely overcome these problems since it does not require line disconnections.

The following classification can be made regarding the different methods used to approach the DLR, depending on the information considered:

- ✔ *Weather data*: The meteorological conditions (temperature as well as wind speed and direction) are obtained from weather stations, allowing the maximum current to be calculated given a limiting conductor temperature. This method, along with field results, is described in the next sections. In the context of weather data, the conductor temperature can be updated with real-time current measurements, as in the case of UGLs, increasing the reaction margin in the operation of the monitored asset. This strategy is currently being applied in northern Spain to a subtransmission corridor connecting wind farms to the grid.
- ✔ *Conductor temperature evaluation (CTE)*: This method is motivated by the high variability of both wind speed and wind direction along the OHL. To overcome this problem, the equivalent conductor temperature is estimated online using different measurements of the monitored asset, such as the direct monitoring of temperature, conductor voltage, span sag measurement, etc. Once the equivalent temperature of the conductor is estimated, the ambient temperature and the solar radiation are used to obtain an equivalent wind speed, which is finally used to calculate the actual DLR. The overall process of this DLR methodology, currently being investigated, is summarized in the flowchart in Figure 7.
- ✔ *Distance monitoring*: In this case, either the line sag or the clearance to ground are measured to provide real-time information on the thermal state of the OHL.

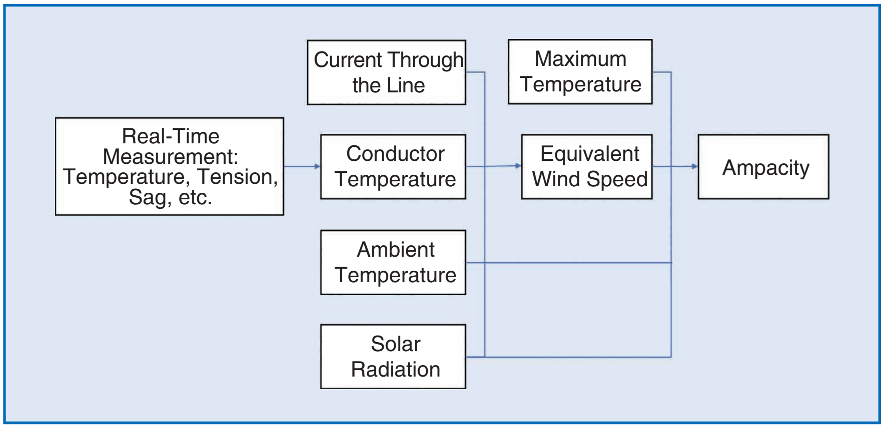

figure 7. A flowchart of the CTE-based methods.

DLR Calculation Based on Weather Data

In this case, the thermal equilibrium between the solar, Joule, and magnetic heat sources, on the one hand, and the convective and radiative cooling mechanisms, on the other, as described by the corresponding IEEE standard 738-2012 or the Conference Internationale des Grands Reseaux Electriques (CIGRE) guide for thermal rating calculations of OHLs (working group B2.43), is illustrated in Figure 8.

Unlike the DSE-based technique presented earlier for UGLs, in the case of OHLs, the weather conditions—namely, the ambient temperature, solar irradiance, wind speed, and wind direction—play a critical role in the problem under study. These magnitudes are generally very different in terms of time scales (minutes and hours) and dependence on position and time, which makes the update rate of external conditions a key factor in the DLR of OHLs.

The weather information can be used either to calculate the conductor temperature, given the value of the line current, or to obtain the current that makes the conductor reach a certain temperature, with the latter being directly related to the calculation of ampacity in OHLs.

If the sampling rate of the measurements provided by the installed weather stations were sufficiently high, then the thermal differential equation could be the basis for the application of DSE to dynamically estimate the evolution of conductor temperature, much like in the UGL case. However, in the OHL case, the rated conductor temperature in the steady state is customarily the only factor considered for DLR calculations, allowing a static thermal balance equation to be used.

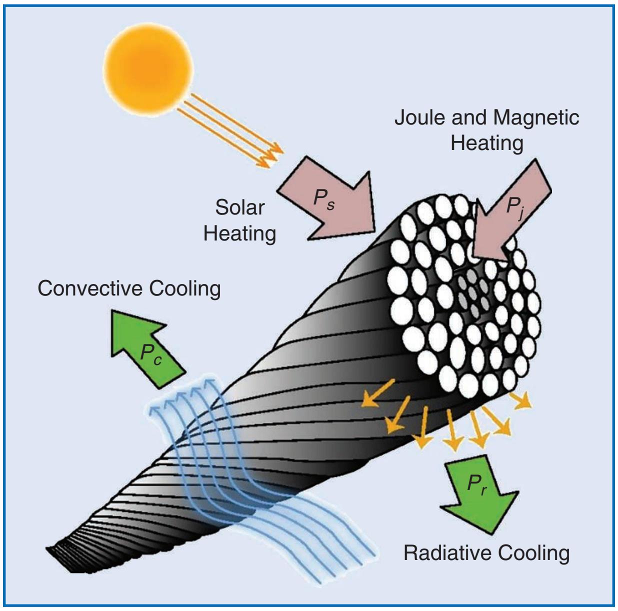

figure 8. A representation of the thermal equilibrium in OHLs (adapted from CIGRE guide).

To assess the accuracy of this analytic model, the results obtained for the conductor temperature were compared with those provided by the FEM-based simulation.

In this work, the CIGRE guide is used to calculate the different terms involved in the static thermal equation. The terms comprise not only meteorological variables but also a series of parameters related to the mechanical (the material, diameter, number of wires, etc.) and thermal (the emissivity, absorptivity, etc.) properties of the conductor. In this regard, several studies have been carried out to determine which of these variables has the greatest influence on the calculated DLR value. Experimental results obtained in these studies show that wind speed and wind direction have the greatest effect on the calculation of the maximum operating current since the convective effect is primarily responsible for the cooling of the conductor.

However, despite its relevance, locally characterizing the wind based on weather stations is challenging. In this regard, two different locations for the weather stations can be considered to obtain the meteorological conditions, as follows:

- ✔ *Remote measurements*: For each section of the OHL, weather information is taken from the nearest meteorological station, and the maximum operating current is calculated for that particular section. Then, the DLR for the whole circuit is obtained as the minimum of these values. In this approach, the distance between each line segment and the corresponding weather station may cause an excessive error in the local meteorological variables, particularly the wind speed and direction. In case of doubt, a conservative value of the DLR can be obtained by taking a reduced value of the wind speed, such as the commonly accepted 0.6 m/s, or even considering natural convection exclusively, since the ambient temperature and the solar radiation are less dependent on position.
- ✔ *Local monitoring*: In this case, the weather stations are installed on one or more towers of the OHL (see Figure 9), and the DLR is only calculated for the respective segments. As in the previous case, the overall ampacity of the circuit is approximated by the minimum of these values. Although more accurate results of weather conditions are provided by local stations, there is still a possibility that the critical segment (i.e., the one with the lowest ampacity) is not monitored, leading to excessive DLR values. To overcome this problem, a security coefficient ranging between zero and one, which can be obtained by using historical data, can be applied to the resulting DLR value.


figure 9. A weather station installed on a tower.

Field Application

The Spanish regulation includes recommended ampacity values for different types of conductors and OHL configurations, allowing the use of alternative models, such as that considered by the Spanish TSO to calculate the seasonal ampacities from historical data. With this model, the particular conditions of each season are taken into account to obtain the maximum current (e.g., the winter ampacity is higher than in the rest of the year since air temperature and irradiation are typically lower during this season).

Although these seasonal values improve the overall utilization of the existing assets, there has been a growing interest related to the incorporation of DLR into the operation of the network. As a result, several research lines have emerged to develop a more accurate methodology for the calculation of the ampacity of OHLs using meteorological data from weather stations without compromising the safe operation of the corresponding lines.

The first case study refers to a 220-kV OHL located in Zaragoza. The goal was to compare several methods for line monitoring to obtain the conductor representative or equivalent temperature. The methods considered were using the information provided by local and remote weather stations, DTS, inclinometers and lidar devices. For this purpose, a set of those devices was installed along the circuit, providing the corresponding local measurements every 10 min. The current through the line was also considered to calculate the conductor temperature from the thermal equilibrium equation. As an example of the results obtained in this comparative study, Figure 10 represents the conductor equivalent temperature calculated using local weather station data, along with that obtained using the geometrical information provided by a lidar device. It can be observed that both values are quite similar during the whole period considered, which demonstrates the accuracy of the information provided by the weather station.

To show the potential advantages of the DLR calculated from weather station measurements (received every 10 min) with respect to the seasonal ampacities customarily used, a case study corresponding to a 220-kV OHL located in La Rioja is presented.

The increase in ampacity provided by the DLR is illustrated in Figure 11, where a load–duration curve is separately represented for each season. It is observed that the DLR calculated from local weather station data for this particular circuit is higher in at least 97% of the cases, even after applying the security coefficients accounting for partial monitoring. These results are encouraging and demonstrate that the application of DLR techniques allows better utilization of transmission assets compared to seasonal ampacities.

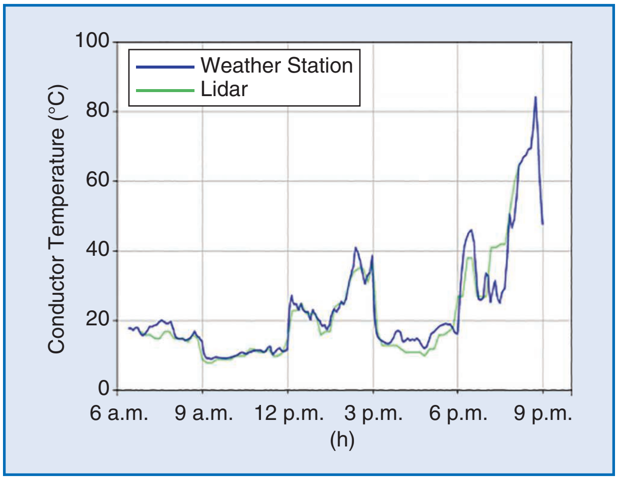

figure 10. A comparison of the conductor temperature calculated using local weather station and lidar methods.

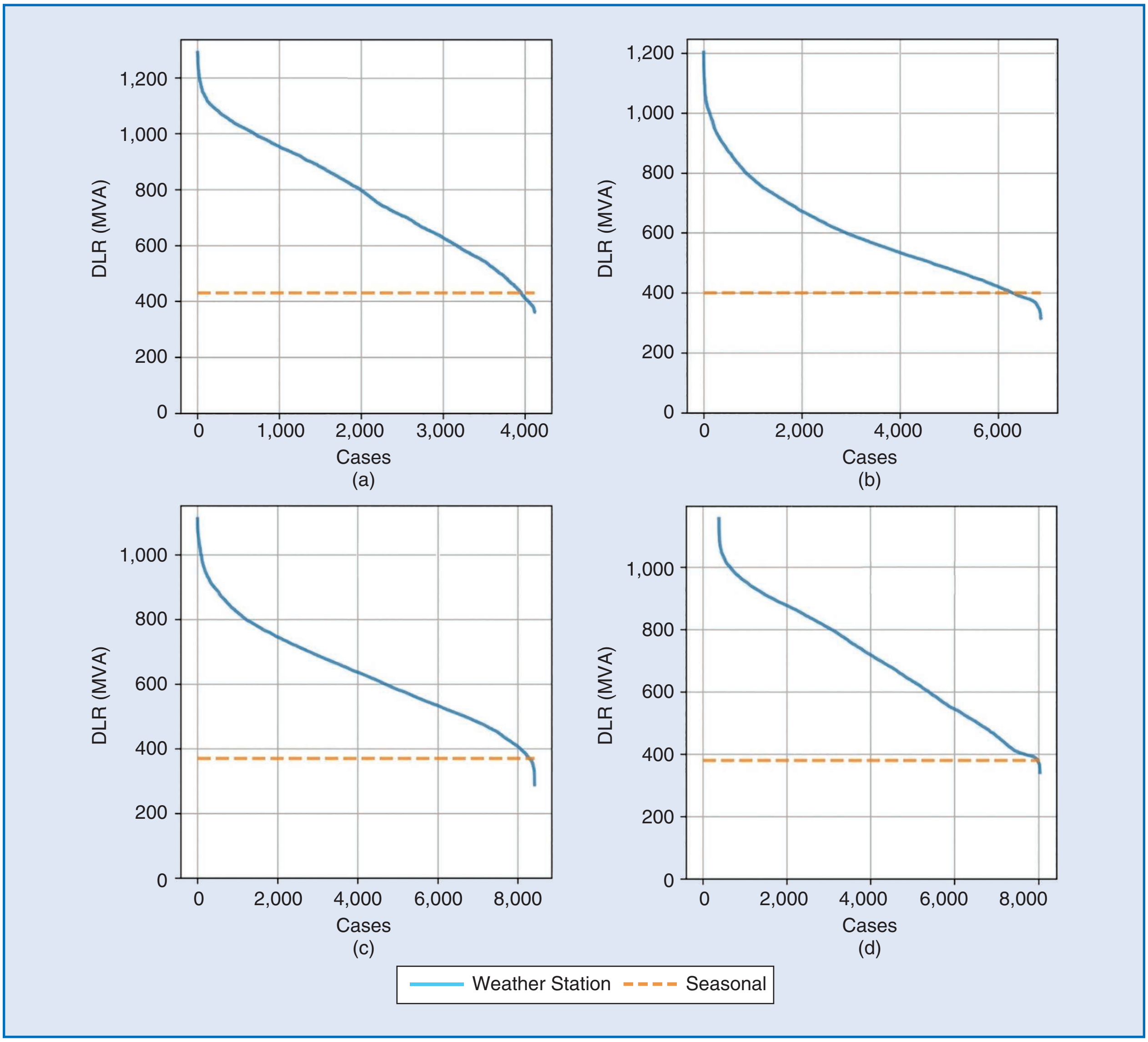

figure 11. The load–duration curves for each season: (a) winter, (b) spring, (c) summer, and (d) autumn.

figure 12. An inclinometer installed on a phase conductor. (Source: Relogable; used with permission.)

As mentioned before, alternative DLR schemes are also being currently tested, including CTE. Particularly, considering the results presented before for the 220-kV OHL in Zaragoza, the Spanish TSO is committed to adopting a double monitoring system, using weather station data jointly with measurements of the conductor sag in critical sections. The latter are provided by locally installed sensors, such as the one shown in Figure 12. The variation of the maximum sag, compared to that calculated in reference conditions, can be directly associated with the temperature of the conductor. When combined with the measurements from the weather station, this obtains the maximum operating current.

Conclusions

This article presents the recent experience of the Spanish TSO in the application of DLR, for both underground transmission cables and OHLs.

First, a method for the calculation of the maximum operating current in UGLs based on dynamic models describing the temperature evolution in different sections of the cable was discussed. The method considers a ladder-type discrete thermal model, which has proven to be accurate enough in simulated scenarios when compared to the results provided by FEM. The problems of parameter uncertainty and time variability were also addressed, as some of the parameters included in the thermal model may be unknown or inaccurate. For this purpose, a DSE based on the Kalman filtering approach has been adopted to jointly estimate the temperatures and parameters. The field results of a pilot project show that the prediction errors of the DSE-based model are less than 1.5 °C in all cases. Future research in this context is oriented to applying this same technique to more complex circuit configurations and other voltage levels.

Regarding OHLs, different possibilities for calculating the DLR are currently being studied and tested. Among these techniques, the one based on real-time information provided by weather stations has so far been the most successful, provided the stations are located closely enough to the critical circuit sections. The approach calculates the ampacity of the circuit through the thermal equilibrium equation. In an attempt to improve the accuracy of the estimated conductor temperature when data from remote weather stations are used, further tests have been carried out combining meteorological data with information collected by other local sensors, such as inclinometers. Both methodologies have been validated by comparing the results with those calculated on the basis of information provided by a lidar device. For the tested circuits, field results show that the ampacity provided by the proposed methodology exceeds the seasonal values customarily used by the Spanish TSO most of the time (up to 97% in an exceptional case).

The experience gained from these pilot projects has proven essential in the progressive evolution of DLR-related know-how. In the case of OHLs, which are by far the most common, one of the main lessons learned lies in the key role of monitoring resources (the latency, availability, accuracy, location, communication coverage, etc.) for a proper calculation of the conductor ampacity. In light of this preliminary experience, rating forecasts are being explored, where the monitored meteorological variables are replaced by predicted values hours or even days ahead. The application of rating forecasts might contribute to reducing the costs associated with the removal of technical constraints in power systems. Another lesson learned is that the potential benefit of using DLR must be analyzed on a case-by-case basis.

For Further Reading

"Guide for thermal rating calculations of overhead lines," CIGRE, Paris, France, CIGRE WG B2.43, 2014.

A. Gómez-Expósito et al., "City-friendly smart network technologies and infrastructures: The Spanish experience," *Proc. IEEE*, vol. 106, no. 4, pp. 626–660, Apr. 2018, doi: 10.1109/JPROC.2018.2793461.

M. W. Davis, "A new thermal rating approach: The real time thermal rating system for strategic overhead conductor transmission lines—Part I: General description and justification of the real time thermal rating system," *IEEE Trans. Power App. Syst.* (through 1985)*, vol. 96, no. 3, pp. 803–809, May 1977, doi: 10.1109/T-PAS.1977.32393.

Biographies

José A. Rosendo-Macías is with the University of Seville, Seville 41092, Spain.

Antonio Gómez-Expósito is with the University of Seville, Seville 41092, Spain. He is a Life Fellow of IEEE.

Alfonso Bachiller-Soler is with the University of Seville, Seville 41092, Spain.

Miguel Á. González-Cagigal is with the University of Seville, Seville 41092, Spain.

Gabriel Álvarez-Cordero is with Redinter (Redeia), Alcobendas, Madrid 28108, Spain.

Lucía Mateo-Sánchez is with Red Eléctrica, (Redeia), Alcobendas, Madrid 28109, Spain.

Antonio Useros-García is with Red Eléctrica, (Redeia), Alcobendas, Madrid 28108, Spain.