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Review

Dynamic Line Rating: Technology and Future Perspectives

Raúl Peña [1], Antonio Colmenar-Santos [1,*] and Enrique Rosales-Asensio [2,*]

[1] Department of Electrical, Electronic, Control, Telematics and Applied Chemical Engineering, UNED, Juan del Rosal, 12—Ciudad Universitaria, 28040 Madrid, Spain; rpena218@alumno.uned.es
[2] Department of Electrical Engineering, University of Las Palmas de Gran Canaria, Campus de Tafira S/n, Canary Islands, 35017 Las Palmas de Gran Canaria, Spain
* Correspondence: acolmenar@ieec.uned.es (A.C.-S.); enrique.rosales@ulpgc.es (E.R.-A.)

Abstract

Dynamic Line Rating (DLR) technology is presented as a key solution to optimize the transmission capacity of power lines without the need to make investments in new infrastructure. Unlike traditional methods based on static estimates, DLR allows the thermal capacity of conductors to be evaluated in real time, considering the environmental and operational conditions. This article presents a state-of-the-art analysis of this technology, including a review of the main solutions currently available on the market. Likewise, the influence of variables such as ambient temperature, wind speed and direction or solar radiation in the determination of dynamic load capacity is discussed. It also reviews various pilot and commercial projects implemented internationally, evaluating their results and lessons learned. Finally, the main technological, regulatory, and operational challenges faced by the mass adoption of DLR are identified, including aspects such as the prediction of the dynamic capacity value, combination with other flexibility options, or integration with network management systems. This review is intended to serve as a basis for future developments and research in the field.

Keywords: dynamic line rating; meteorology; sensor; calculation; prediction; conductor

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1. Introduction

DLR systems are designed to allow a more efficient operation of power lines, taking advantage of real-time information on the variables that allow maximizing the load that the lines can withstand. The solution is usually supported by the installation of a series of meteorological and operational sensors on power lines (generally overhead) to evaluate, in real time, the capacity of the cables for the transfer of electricity.

Ampacity is defined as the maximum capacity of lines, whether bare conductors or wires, to carry current at any given time, depending on the conditions. The DLR is the calculation of that ampacity dynamically considering the actual load and environmental conditions, which vary constantly over time. The rated capacity provided by the manufacturer usually coincides with high ambient temperature conditions, low wind speed, and high solar radiation levels; so, the calculation usually yields a higher capacity value than the nominal one provided by the manufacturer.

There is some variety in the composition of DLR systems, but the most frequent elements are:

1. Sensors: Hardware component that is installed on or near overhead power lines to collect measurements of line current intensity, conductor temperature, line inclination, vibration, ambient temperature, wind speed, solar radiation, etc.

2. Data acquisition and transmission: Hardware and software component that collects information from all devices and sends it to the application that processes it.
3. Application: Software component that collects DLR data, performs the necessary calculations, and allows interaction with users through a graphical interface. It will mainly present the measures of dynamic rating, available capacity, and clearance.

The topic related to sensors is the most controversial one, as there are many ways (variety of sensors and equipment) to find out where the real load limit of the conductor is, there are many variables (climatological and operational) that affect this limit, and there are also indirect ways to know the state of use of the cable.

Grid congestion occurs when large current flows cause any of the components of the grid to reach their thermal limits. This is the main criterion for not overloading a circuit anymore, although it is not the only one to consider.

Weather (wind, solar radiation, snow, ice, etc.) has the ability to displace the thermal limit of a line, which will allow more electricity to flow through it. On the other hand, the flow of current through the conductor causes heating and losses. In addition, the physical and electrical properties of the conductor, the insulation, the voltage of the line, and the deflection condition determine the operating limit.

Traditionally, system operators have used "static thermal limits," based on expected extreme local weather conditions, to calculate their theoretical ampacity (maximum line capacity), rather than the actual one. However, the ampacity of a conductor is variable.

The DLR is the dynamic calculation of ampacity, taking into account actual load and environmental conditions, which vary constantly over time. The nominal capacity provided by the manufacturer usually coincides with conditions of high ambient temperature, low wind speed, and high solar radiation levels (usual reference: wind speed 0.6 m/s, solar radiation of 1000 W/m^2, and temperature 40 °C according to [1]); so, the actual calculation usually provides a higher capacity value than the nominal one provided by the manufacturer.

In general, when a power plant is connected to the grid, it is conservatively sized or given an access point where there is sufficient capacity to serve it, but over time, the owner of the plant considers repowering, i.e., the replacement of existing wind turbines with new generation equipment [1,2]. Replacing those old turbines with modern ones has advantages, such as new reactive power control systems or their immunity to voltage dips, but it can leave the grid close to limits or even require grid repowering. On the other hand, the transmission capacity of the lines increases with wind speed, due to cooling. The correlation between the wind energy measured in the power plants and the evacuation capacity of the nearby lines has been confirmed (dynamic nature of the boundary and correlation) by various sources [3–9].

DLR systems are an option to delay the construction of new lines. The cost of monitoring a circuit, including the installation of equipment and software, is less than 2% of the cost of achieving an equivalent gain using conventional techniques, as indicated in [3].

For all the above, in the last 2 decades, technologies and strategies have emerged to measure in pseudo-real time the climatic conditions and estimate the limits of the use of the line [2,10]. It has been studied what should be measured, which sensors can be used, what precision is achieved, the dependence between apparently unrelated variables, or the relative relevance of them, etc., and with these works, many possibilities have opened up that are worth reviewing.

Furthermore, several studies have shown that DLR not only enhances the operational flexibility of the power system but also delivers significant economic benefits. In particular, its potential to reduce the need for and cost of energy storage has been highlighted, as it helps alleviate network congestion and facilitates the integration of renewable energy sources. In [11], an investment model is presented that includes DLR in the German power system and demonstrates that the implementation of this technology, together with an 80% renewable share generation, saves 1.15 bn€ of annual operation and capital system costs and reduces the need for battery storage by one third. Additionally, in [12] it is demonstrated that DLR and Battery Energy Storage Systems (BESS) complement each other, so while DLR allows increased power delivery, it may favor conventional generation over wind, reducing renewable penetration. Nevertheless, BESS helps counter this by time-shifting wind power, reducing reliance on costly generators. The article [13] studies the effects of BESS settings and DLR system and concludes that the degree of improvement on power system reliability depends on how the BESS is configured and how DLR is applied, so proper coordination is key to maximizing benefits.

The purpose of this article is to present a state of the art of the different fields of study that are part of DLR technology, among which are the importance of the precise calculation of climatological variables, the lines of research that are currently being followed, or the different technologies (very different from each other) that are found in the market.

This article is structured as follows: Section 2 provides an overview of the DLR calculation standards currently used in the industry (IEEE and CIGRÉ). Section 3 describes the measurement technologies (temperature, vibration, conductor deflection, etc.) currently available on the market. On the other hand, the peculiarities of the climatological variables most influential in the calculation of the dynamic limit are explained in Section 4. Section 5 gives an overview of the most relevant DLR projects developed in the global industry. Finally, Section 6 offers, on the one hand, the main lines of research that are being carried out to date, and on the other hand, the main challenges and difficulties faced by this technology. The most important conclusions drawn from this DLR state of the art are detailed in Section 7.

2. Standards for DLR Calculation

The methods for calculating DLR are based on international standards that provide frameworks and mathematical models to assess the thermal capacity of conductors. To date, the two most widely used standards in the industry are IEEE 738 [14] and CIGRÉ TB 601 [15]. These standards have evolved significantly over time, incorporating more sophisticated models and considering a greater number of variables to more accurately reflect the real operating conditions of power lines.

The DLR calculation models perform a heat balance of the conductor. This model states that heat gain from the Joule effect and solar radiation should be equal to heat loss from convection and radiation:

$$P_J + P_S = P_C + P_r \quad (1)$$

Being:

- P_J: power dissipated by the Joule effect [W/m].
- P_S: power captured by solar radiation [W/m].
- P_C: loss of heat by convection to the environment [W/m].
- P_r: heat loss by radiation [W/m].

As specified by the CIGRÉ standard, the Joule heating term (P_J) results from the conductor's intrinsic electrical resistance and increases linearly with resistance and quadratically with the current flowing through the conductor, as shown in (2).

$$P_J = I^2 \cdot R_{AC} \quad (2)$$

Additionally, the effect of solar heat gain (P_s) is proportional to the intensity of the global radiation (I_S) in [W/m^2], the absorption coefficient of the conductor's surface (K_a), and its diameter (D) in [m], as expressed in (3).

$$P_S = I_S \cdot K_a \cdot D \quad (3)$$

The absorptivity factor, a non-dimensional parameter, varies based on the condition of the conductor's surface—mainly affected by its aging and the environmental conditions in which it operates. CIGRÉ Technical Brochure [15] offers recommendations for estimating this factor.

On the other side of the equation, the specific expression for P_C according to the CIGRÉ formulation for natural convection (most common under standard, wind-free conditions) is expressed in (4).

$$P_C = h_C \cdot \pi \cdot D \cdot (T_s - T_a) \quad (4)$$

In this expression, h_C denotes the convective heat transfer coefficient [W/m^2 K]; D, the outer diameter of the conductor [m]; T_s, the conductor surface temperature [K or °C]; and T_a, the ambient air temperature [K or °C].

The radiative cooling power (P_r) is determined based on the Stefan-Boltzmann law, which describes the heat emitted by a black body as a function of its absolute temperature. This relationship is given by Equation (5).

$$P_r = \pi \cdot \sigma_B \cdot D \cdot K_e \cdot \left[\left(T_c + 273 \right)^4 - (T_a + 273)^4 \right] \quad (5)$$

where σ_B is the Stefan-Boltzmann constant [W/m^2 K^4], D is the conductor's diameter [m], K_e is the emissivity factor of the conductor surface, T_c is the conductor temperature [°C], and T_a is the ambient air temperature [°C].

From Equation (1), the maximum permissible current for a given conductor temperature can be determined [14,15]:

$$I = \sqrt{\frac{P_C + P_r - P_S}{R(T_{cond})}} \quad (6)$$

The meteorological variables that influence the heat balance of the conductor are listed below. The study by Alessandrini et al. [16] highlighted the following aspects of each variable:

- Ambient temperature: Has an almost linear influence on the load capacity, with an error of 1 °C in its prediction being acceptable.
- Wind speed and direction: These are the most influential factors in the load capacity, presenting a notable spatial variability along the line, which represents a major challenge for the accuracy of the models. In addition, in the study presented by Martínez et al. [17], it was observed that the greatest temperature deviations occur at low wind speeds, due to the difficulty of accurately modeling the convective effect under these conditions.
- Solar radiation: It can represent a significant limiting factor in conditions of low wind speed.

The IEEE 738 and CIGRÉ TB 601 standards, although they share the objective of calculating the load capacity of airlines, present significant differences in their models and assumptions. For example, the IEEE standard does not include the conversion of alternating current to direct current, while the CIGRÉ model does. In addition, the absorption coefficient of the conductor and the impact of solar radiation are treated differently in both standards [18].

Table 1 presents a comparison between the IEEE 738 and CIGRÉ TB 601 standards, focusing on the different methodologies they use to calculate the thermal behavior of overhead conductors. Both standards address key thermal processes such as convection cooling, radiation cooling, solar radiation thermal gain, and Joule effect heating, but apply different empirical models and parameterizations. For example, convection cooling in the IEEE 738 standard considers natural and forced convection using specific formulas based on Reynolds number and temperature differences, while CIGRÉ uses Nusselt number in its formulations. Similarly, radiation cooling in both standards considers emissivity and temperature differences, albeit with slight variations in constants and approaches. Solar radiation and the Joule effect are also treated with different formulas in each standard, reflecting different empirical perspectives. This comparison highlights the subtle differences in how these standards model the thermal dynamics of conductors, which can lead to variations in the calculated thermal limits [14,15].

Table 1. The differences between IEEE and CIGRÉ standards [18].

Parameter	*IEEE 738* (2012)	*CIGRÉ TB 601* (2014)
Convective cooling	$q_{c1} = K_{angle} \cdot [1.01 + 1.35 \cdot N_{Re}0.52] \cdot k_f \cdot (T_s - T_a)$ $q_{c2} = K_{angle} \cdot [0.754 \cdot N_{Re}0.6] \cdot k_f \cdot (T_s - T_a)$ $q_{cn} = 3.645 \cdot \rho f^{0.5} \cdot Do^{0.75} \cdot (T_s - T_a)^{1.25}$	$P_{cf} = \pi \cdot \lambda_f \cdot (T_s - T_a) \cdot Nu_\delta$ $P_{cn} = \pi \cdot \lambda_f \cdot (T_s - T_a) \cdot Nu_\beta$
Radiative cooling	$q_r = 17.8 \cdot D_o \cdot \varepsilon \cdot [((T_s + 273)/100)^4 - ((T_a + 273)/100)^4]$	$Pr = \pi \cdot D \cdot \sigma_B \cdot \varepsilon_s \cdot [(Ts + 273)^4 - (Ta + 273)^4]$
Solar heating	$q_s = \alpha \cdot Q_{se} \cdot \sin(\theta) \cdot A'$	$P_s = \alpha_s \cdot I_T \cdot D$
Joule heating	$q_j = I^2 \cdot R(T_{avg})$	$P_{J\_NF} = k_j \cdot I^2 \cdot R_{dc} \cdot [1 + \alpha c(T_{av} - 20)]$ $P_{J\_F} = {I_{dc}}^2 \cdot R_{dc} \cdot [1 + \alpha c(T_{av} - 20)]$

Regarding the line rating, the study by Szabo et al. [19] states that the ampacity calculated under typical weather conditions and with wind speeds below 5 m/s can differ by several hundred amperes. In the comparison surface plot presented in that study, the maximum line rating deviation reaches approximately 9% for a wind speed of 5 m/s and a wind direction of 0°, for ACSR-type conductors.

The main findings of various studies comparing both standards are summarized below. Martínez et al. [17] analyze the difference in calculated temperature between the IEEE and CIGRÉ standards, finding that the temperature error is less than 5 °C in 85% of cases. The study by Meegahapola and Simms [20] indicates that the CIGRÉ standard tends to offer more conservative temperature estimates compared to the IEEE standard. In addition, CIGRÉ incorporates an albedo factor to take into account the reflection of solar radiation, which is not considered in the IEEE standard. It also shows increased sensitivity to wind speed in determining load capacity. Finally, significant differences are observed in the recommended values of solar absorption and emissivity between the two standards, which may affect the estimation of heat loss by radiation. Another study by Martínez et al. [21] compares different analysis algorithms and concludes that the Time-Dependent Algorithms (TDA) used in the CIGRÉ standard provide greater accuracy in the estimation of temperature.

3. DLR Technologies

3.1. Direct Measurement Methods

Direct methods are those in which the equipment for line monitoring is installed directly on the conductor. In this way, the capacity of the line can be inferred with direct measurements on it, usually current and temperature, but in some cases also angle and relative position.

3.1.1. Conductor Temperature

This section shows the technologies that directly measure the line's temperature with a sensor placed on its surface. These devices have the advantage of reducing uncertainty in the calculation of the conductor's temperature thanks to direct measurement. However, it has the disadvantage that the temperature can change along the line depending on the weather conditions. The accuracy in temperature measurement is usually between 1 °C and 2 °C for measurements taken on the surface of the conductor. The same happens with the current, although the conductor's span depends on the average temperature and the sensor only measures at a specific point; precision is lost in the calculation of the DLR if it is carried out only by this method [22,23].

These devices are used in both transmission and distribution networks. Some of the most commonly used devices today are detailed below:

1. Power Donut

It is one of the first devices developed for DLR application, being developed in the early 80s and operational in the early 90s. This toroid-shaped device is placed directly on the line. In addition to measuring its temperature, it measures the current that flows through it and the angle of inclination, which is related to the sag of the span [24]. It is powered by the current induced from the conductor's magnetic field and needs a minimum current of 70 A to operate. It also has an internal battery that keeps the device running for an hour in case the minimum current for activation is not reached [23]. This is one of its main disadvantages, since, as it is fed directly on the line, if the minimum current is not reached for a while, the equipment does not take measurements.

It can measure temperatures up to 150 °C and, for calculating the conductor capacity, apart from temperature, current, and inclination angle, it needs values of ambient temperature and solar radiation [24,25]. Figure 1 shows an installed Power Donut.

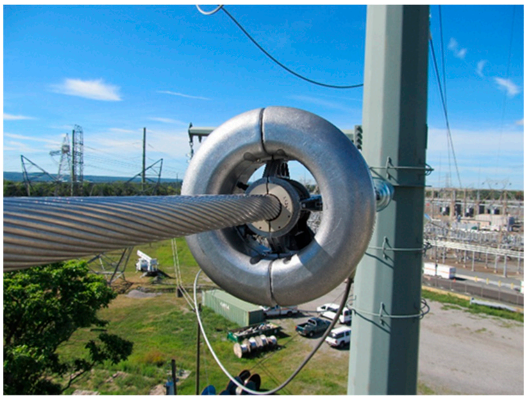

Figure 1. Power Donut from USi (Atecnum Corp., Boynton Beach, FL, USA) [24].

2. Temperature Monitoring System (SMT)

This system is similar to the Power Donut, so it measures the current through the conductor in addition to its temperature. It is powered by the induced line current, and needs a minimum value of 100 A, and withstands temperatures up to 250 °C. An installed SMT (Arteche, Mungia, Spain) can be seen in Figure 2 and an application example in [26].

3. FMC-T6

This device measures both the temperature and the current flowing through the conductor. It is capable of measuring amplitude and phase thanks to the 32 samples per cycle it records. Like the previous ones, it is powered by a minimum induced current of 10 A and 30 A for the "300" and "600" models, respectively. These names refer to the maximum current it can measure. In terms of voltages, it is capable of operating on lines between 0.48 and 140 kV [27] and can measure a surface temperature in the conductor of up to 85 °C [23].

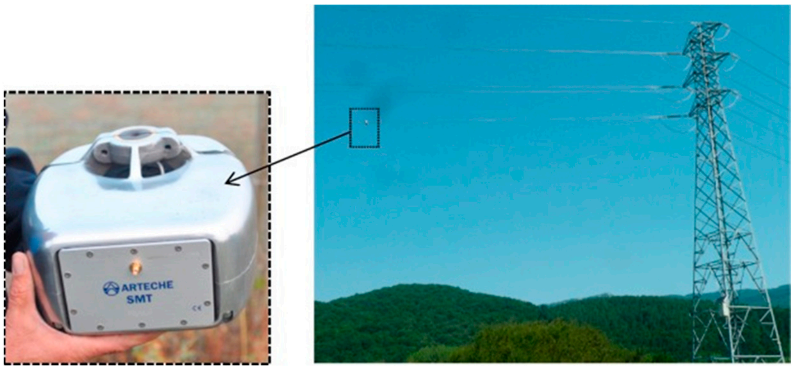

Figure 2. SMT from Arteche [23].

It is part of the Multilin Intelligent Line Monitoring System, a General Electric (Boston, MA, USA) [27] system for network monitoring. Communications are carried out by radio signal at 2.4 GHz. The device is shown in Figure 3, and an application example is described in [28].

Figure 3. FMC-T6 from General Electric [23].

4. Transmission Line Monitor (TLM)

This device, in addition to measuring the temperature and current from the conductor directly, uses LIDAR technology to measure the distance of the conductor to the ground. It also measures the conductor's tilt and displacement with a dual-axis accelerometer and receives perpendicular wind speed and ambient temperature data. The Smartline (Lindsey, Azusa, CA, USA) system gathers data and calculates the deflection and line capacity continuously [29].

It is powered by conductor-induced current, with a minimum current of 100 A, and measures temperatures up to 250 °C [23,30]. The device is shown in Figure 4.

5. Ritherm (Surface Acoustic Wave)

This device is called Ritherm (Ningbo Rising Instrument Co., Ltd., Ningbo, China), and its operation is based on measuring the surface acoustic wave. To do this, a radar sends high-frequency electromagnetic waves, and a piezoelectric receives the waves sent by the radar. By measuring the propagation times, the elongation of the conductor can be calculated, which is associated with its temperature [31]. This sensor can measure temperatures up to 150 °C.

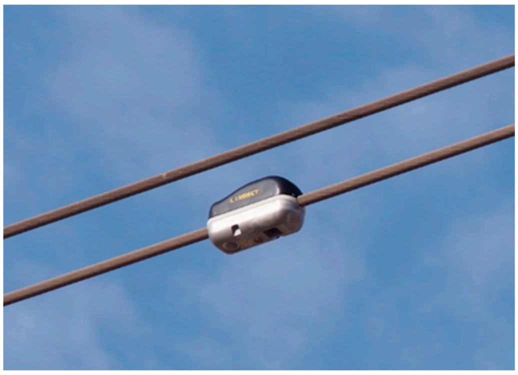

Figure 4. TLM from Lindsey [29].

6. Distributed Temperature Sensors (DTS)

First, it is important to emphasize that this system is not a DLR as such, but rather a method used for distribution temperature measurement. Its operation is based on sending laser pulses through an optical fiber that runs through the element for which the temperature is to be measured. By measuring the reflections of the pulses, the temperature at the point and the distance to the emitter can be obtained [32].

The main advantage is that it is a very flexible device, as it can measure temperatures in cables, overhead lines, or even conduits and pipes. If a user wants to obtain current or deflection values in overhead conductors, this system must be combined with others, so it is more suitable for locating hot spots in cables. This device has good measurement resolution (up to 0.01 °C) and it is applicable over long measuring distances (up to 60 km). However, the parameters depend on each other, so a compromise is necessary. For example, a system capable of taking measurements with an accuracy of 0.3 °C at 5 km in 10 s (with a resolution of 1 m) can reduce the reading period if the resolution is extended to 10 m. Figure 5 shows the relationship between temperature accuracy and measurement distance according to the time spent.

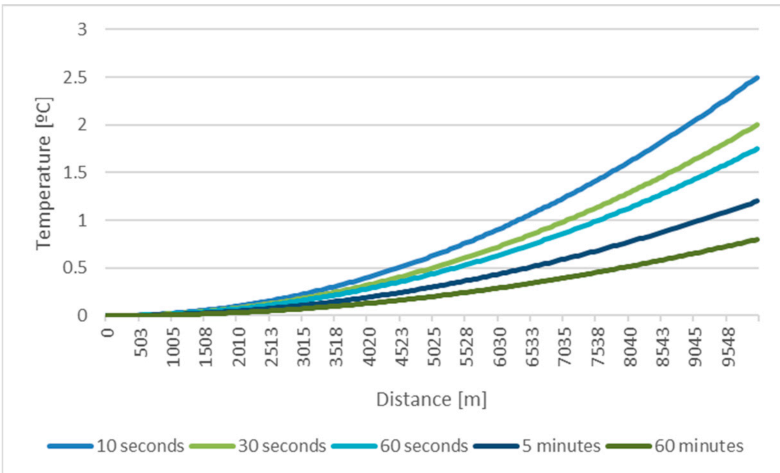

Figure 5. Sentinel DTS Range (Sensornet Ltd., Watford, UK). Temperature resolution vs. distance measured and sampling time [33].

Although the system seems more interesting for cables, there is already experience in using this technology to control temperature in overhead lines. With a fiber cable inserted into the conductor, it was possible to locate hot spots, which were more prone to problems with the span sag. Among the conclusions, it was detected that the highest temperatures occur in a wooded area where heat dissipation is worse, and the temperature in electrical towers is lower.

3.1.2. Mechanical Stress in the Conductor or Tower

1. CAT-1

For this DLR method, the most common commercial solution is called CAT-1 and is manufactured by Valley Group (Nexans, Paris, France). It is a system that, by means of a load cell, relates the mechanical stress between the conductor and the electrical tower to its temperature [34]. The system is calibrated to establish the relationship between the (mechanical) tension and the temperature of the conductor. This calibration is based on the measurement of stress-temperature value pairs. On the one hand, a reference to conductor temperature and tension is established. On the other hand, the value of the stress section is obtained. Once calibrated, the temperature is calculated through tension measurement.

This method has the advantage that, while temperature measurement methods provide measurements of specific points of the conductor, this one gives the average stress value of the span between two towers.

In [35], the critical spans to locate the monitoring systems are identified, and in [36], the installation of this method is studied, among others. To obtain the DLR value, it is necessary to apply the equations based on the IEEE or CIGRÉ methods. An example of an application can be seen in [4] on a Transpower grid in New Zealand.

2. Tension and Ampacity Monitoring

It is a method similar to CAT-1, developed by the University of the Basque Country UPV/EHU (Bilbao, Spain), through which the maximum capacity is calculated based on the values of voltage, ambient temperature, solar radiation, and current. In addition to these measurements, it needs other values such as conductor cross-section, elastic modulus, coefficient of thermal expansion, length of the span, or maximum deflection [37].

It represents an improvement of the CAT-1 since it considers the line's aging factor in the calculation. To do this, the stress-temperature curve is calibrated considering the creep deformation of the conductor over time.

3.1.3. Conductor's Sag

1. Sagometer

This system consists of placing a camera at the midpoint of the span to monitor the vertical movement of the conductor and thus calculate the span's sag. Its advantage is that it provides information on the thermal state of the line along its entire length instead of giving a local value [23]. However, it is a system that may have problems performing the measurement on days with adverse weather conditions when visibility may be low [38]. The system has an accuracy in the measurement of the sag of 15 mm.

GridWatchRT is the name of the trading system for span's sag in real time [39]. It was developed by the Electric Power Research Institute (EPRI) (Palo Alto, CA, USA) and other public utilities. The Sagometer device is currently marketed by EMD International INC (Aalborg, Danmark). Figure 6 shows a camera installed to monitor the span's midpoint.

Figure 6. GridWatchRT from Sagometer [23].

3.1.4. Vibrations

1. ADR Sense

One option for the application of DLR by vibration measurement is the ADR Sense device from Ampacimon (Ans, Belgium) [40]. This equipment was developed by the University of Liége (Liège, Belgium) in 2010 and tested by Elia (Brussels, Belgium) and RTE (Puteaux, France) in their transmission grids between 2008 and 2010.

These are devices placed directly on the conductor and equipped with accelerometers that are capable of accurately measuring line movements with an accuracy of up to 1 mm. It analyzes the vibrations of the conductor and detects the fundamental frequency, and then calculates the deflection from it [41–43]. Figure 7 shows a perspective of this meter installed on a conductor [41,42].

Figure 7. ADR Sense from Ampacimon [40].

The equipment does not need external power as it has a current transformer, so it is powered through the power line current to which it is connected. As far as telecommunications are concerned, this equipment performs initial data processing and can then be sent via GSM/GPRS to a remote server where the data is stored. The ADR Sense equipment determines the ampacity of the line based on thermal models in accordance with IEEE and CIGRÉ recommendations. In addition, Ampacimon has a predictive model to estimate ampacity up to 4 h in advance, so it is an interesting functionality for grid operation tasks.

3.2. Indirect Measurement Methods

Indirect DLR methods are those that calculate the capacity of the line using parameters that are not measured directly on the conductor. Although there are several methods, the most relevant ones are detailed in this section. On the other hand, weather measurements can be used independently or, better yet, in combination with some direct method to improve the calculation result.

3.2.1. Simulation Monitoring

For this method, there is a commercial solution called ThermalRate, by Pike (Charlotte, NC, USA) [44]. By means of two rods, placed as can be seen in Figure 8, which act as a replica of the existing conductor, the capacity of the line is calculated indirectly. One end is heated by an internal resistance at constant power, and the other is not, and comparing the temperatures at both ends measures how the conductor evacuates heat to the environment. In this way, the temperature and current circulating through the conductors and the permissible current are deducted [23].

Figure 8. ThermalRate from Pike [44].

This method is the simplest to apply, as well as being the least invasive, as no device needs to be installed directly on the line. Another advantage is that, unlike other methods of measuring voltage, deflection or conductor temperature, it does not present problems in the measurement with low line load (<1 A/mm^2 or <35% of nominal capacity are considered low), for which the temperature difference between the conductor and the environment is very small.

The main drawback of this system is that weather conditions can change along the line. In addition, for wind speeds below 1 m/s, measurement errors may occur. When the wind speed exceeds 3 m/s, the temperature of the conductor is practically independent of the wind speed.

The method uses the standard IEEE 738 equations and has been tested in the laboratory. Nominal values appear to be conservative in almost all cases, reducing the risk of overestimation of capacity [45]. In addition, it can be easily integrated into SCADA systems.

3.2.2. Weather Monitoring

Meteorological information is a fundamental data source for the determination of DLR value, or for the determination of other specific warnings, such as ice overload. An example of weather monitoring is the one offered by the supplier General Electric (G.E.)

(Boston, MA, USA). Its system collects measurements such as wind speed and direction, ambient temperature, dew point, or solar radiation.

G.E. offers a compatible weather station (called Davis) as an option for the FMC-T6 sensor, although the system can be installed with or without a weather station, depending on customer requirements. This optional station connects to the Sensor Network Gateway (SNG), which incorporates a dedicated communications port for the station.

With the input data collected by the station, the T-NET software (https://www.gevernova.com/grid-solutions/sites/default/files/resources/products/brochures/ilms_gea12689c.pdf accessed on 8 July 2025) (the user interface) provides a DLR value for the study line. A Windsonic anemometer (Gill Instruments, Lymington, UK) can also be equipped to support the T-NET software with better wind measurements in low-speed situations, although it is only compatible with the Davis model.

3.3. Technical Comparison of DLR Implementation Approaches

This section presents a comparative technical analysis of the aforementioned DLR sensors, focusing on their differences in terms of directly measured parameters, measurement ranges and accuracy, as well as the type of power supply employed, as shown in Table 2.

Table 2. Comparative analysis of direct DLR device characteristics.

	Sensor	**Power Donut**	**SMT**	**FMC-T6**	**TLM**	**Ritherm**	**DTS**	**CAT-1**	**Sagometer**	**ADR Sense**
Direct measured variables	Conductor temperature	X	X	X	X	X	X	-	-	-
	Current	X	X	X	X	-	-	-	-	X
	Inclination angle	X	-	-	X	-	-	-	-	-
	Sag	-	-	-	-	-	-	-	X	-
	Mechanical tension	-	-	-	-	-	-	X	-	-
	Vibration	-	-	-	X	-	-	-	-	X
Conductor temperature	Minimum (°C)	−40	0	−10		−35	5			−40
	Maximum (°C)	250	250	85	180	150	650			200
	Precision	±0.05 °C		±2 °C		0.5 °C	±1 °C		<20 cm	<10 cm
Current	Minimum (A)	0	100	10	50					65
	Maximum (A)	3000	1400	600	1500					3000
	Precision	±0.5%	-	±1%	±1%					
Power supply	Feeding	Autonomous	Autonomous	Autonomous	Autonomous	Passive	External	Autonomous	External	Autonomous
	Activation current (A)	70	100	10	50				0.5 A/kcmil	30–60
	Back-up battery (hours)	12		48						

If a sensor with direct conductor measurement is required—providing temperature, current, sag, and vibration monitoring—without the need for an external power supply and allowing installation on live lines, the Power Donut stands out as one reliable and comprehensive solution, despite its high cost (USD 40,000–80,000).

To obtain a distributed thermal profile with maximum temperature resolution, Sentinel DTS excels; its precision and long-range coverage make it ideal for hot spot detection, although it only provides temperature data and relies on an external power supply.

If the primary objective is to estimate sag or mechanical tension indirectly, and the line topology is suitable, CAT-1 offers a robust and cost-effective per-kilometer option.

For applications focused exclusively on sag measurement, where a stable power supply is available and temperature or current data are not required, the Sagometer presents a proven and field-tested compromise.

Other options such as FMC-T6, Ritherm, SMT, and ADR Sense may be considered for pilot projects. However, a direct technical and commercial validation is required to select the most suitable option, depending on factors such as site-specific characteristics—for example, the need to install many sensors on lines with significant elevation changes or highly variable wind conditions along its route—or the preferences and policies of the end user, such as the requirement to host the database on-premise rather than in the cloud. All these considerations introduce a degree of price variability that must be assessed on a case-by-case basis.

4. Meteorological Values Relevant for Calculation

According to [23], the essential factors to be taken into account in order to determine the operating limits of a line are the maximum permissible temperature of the conductor, to avoid a loss of cable characteristics (tensile strength), and the height of the conductor with respect to the ground or other obstacles necessary to comply with the law and protect the environment from accidents.

These values (cable temperature and ground height) can be measured directly or calculated from measurements of other magnitudes. This leads to the use of various measurement and estimation methods, including weather monitoring, voltage monitoring, cable drop monitoring, and line temperature monitoring [4,46,47].

Meteorological variables evolve rapidly and dynamically and have a direct impact on the condition of power lines. During the actual operation of the network, these variables must be monitored and foreseen, so that the operator knows in advance the current margin available when operating the network.

An illustrative example of the above appears in Figure 9, where the evolution of meteorological variables (ambient temperature, wind speed, and solar radiation) and the parameters of the example line (height profile of each span, circulating current and available capacity) is observed as a function of the climatology [48].

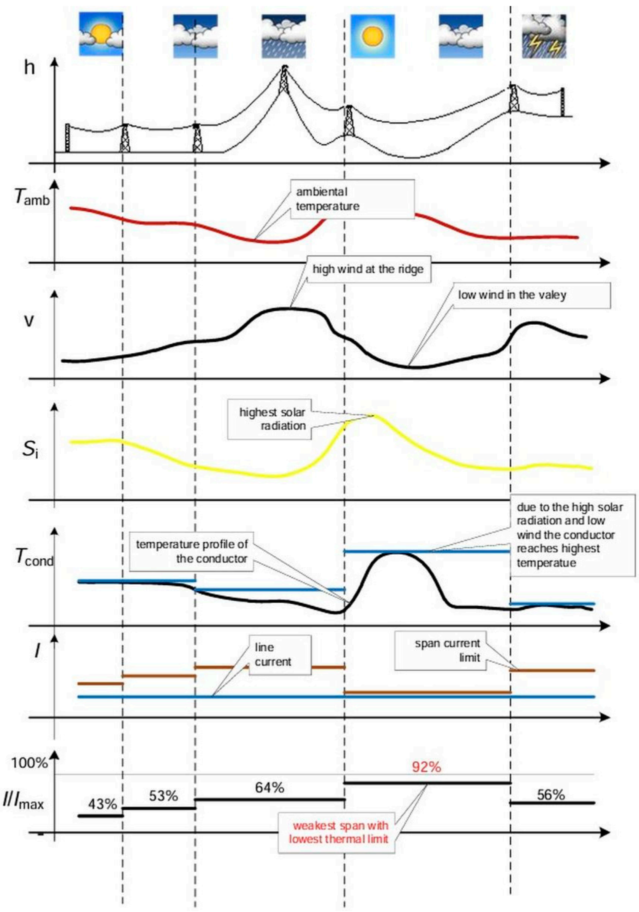

Figure 9. Influence of meteorology on DLR value.

The first significant event in the figure occurs in the span where the height of the line is greater and there is rainfall. This event, coinciding with an increase in wind speed (due to the height of the span), causes the temperature of the conductor to decrease ("T_{cond}"), and thus the current limit for that span to increase (represented by the brown line in the current graph ("I")). In the next period, the weather becomes sunny, so solar radiation increases. On the other hand, the line has descended in height, causing the wind speed to be lower than in the previous period. This means that the line's temperature is the highest of all the periods represented, and the overload of the line reaches up to 92%, which means that the operator, if necessary, has very little additional capacity.

The figure reflects how environmental and orographic factors influence the line's overload level. However, not all factors have the same impact. International literature distinguishes different levels of importance and studies the relationship between them.

4.1. Wind Speed and Direction

Wind speed and direction can change considerably along an overhead transmission line. In fact, the extra capacity unlocked by the DLR corresponds to the minimum value of those calculated for each critical span of the line. Therefore, a DLR system and a DLR forecast should take this phenomenon into account and provide estimates of the actual current carrying capacity for the entire line [16].

Wind speed has a predominant impact on the ampacity of the power line and represents the main variable responsible for the cooling of the conductor, and therefore the sag value of the conductor.

Although the relationship between wind speed and ampacity is clearly defined in the IEEE and CIGRÉ standard models, in practice, such dependence can be more complicated to establish and observe, since wind speed varies over time along the length of each span and vertically.

Wind speed exhibits significant temporal variability in magnitude and even in the nature of its dynamics, evolving significantly in a matter of minutes [49]. It therefore challenges the steady-state representation of the IEEE and CIGRÉ models.

The spatial variability of the wind is such that the wind speed also varies along the span. Wind vortices are typically several tens of meters in size, so a typical span, several hundred meters long, is subject to variable wind speed in its path.

Wind speeds can also vary due to other local external agents, such as the presence of trees and buildings in their vicinity. It should be noted that the line's elevation can vary by more than 15 m along a span. Such elevation differences so close to the ground can have important effects on wind characteristics, which are very noticeable at this level.

The wind angle is defined as the angle between the wind vector and the axis of the conductor of the span of interest. Figure 10 shows the relationship between wind angle and ampacity, based on the IEEE and CIGRÉ standard models, and considering different wind speeds.

In addition to wind speed, the angle of incidence can also have a non-negligible impact on ampacity, especially for the wind flows almost parallel to the line. In practice, due to wind turbulence, the effect of steering on conductor temperature and capacity is substantially less than assumed in theoretical calculations. Therefore, conservative assumptions are generally made.

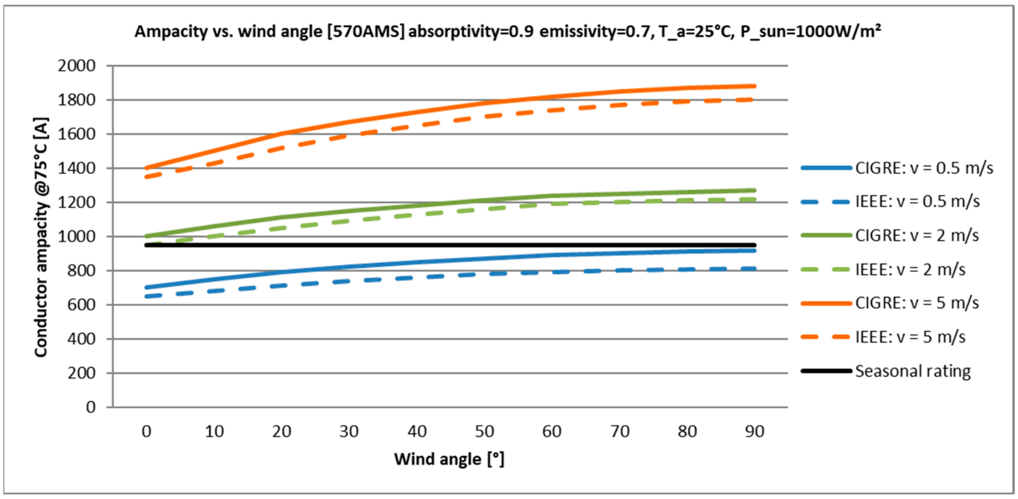

Figure 10. Relation between wind angle and line current [16].

4.2. Ambient Temperature

Ambient temperature has a significant impact on ampacity, as shown in Figure 11. This effect is quasi-linear considering a limited range of temperatures, but substantial if several temperature levels are considered. A mean square error (RMSE) of <2 °C in ambient temperature modeling or prediction is adequate. This is easily achievable using state-of-the-art weather stations and weather prediction approaches.

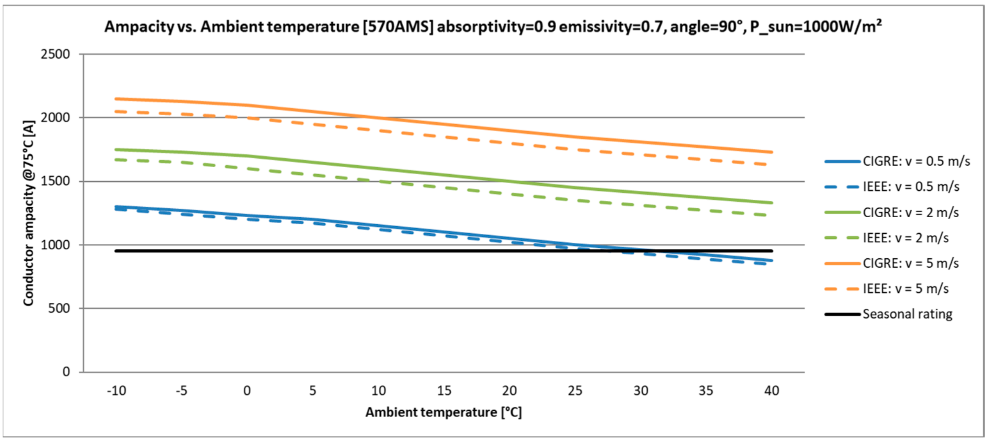

Figure 11. Relation between the ambient temperature and line current [16].

Another aspect to consider is the fact that the temperature varies little over time for space points located at the same level. However, in steep areas where valleys coexist with mountainous terrain, these differences are more significant [21].

4.3. Precipitation

Rain has a significant impact on the cooling of conductors, although its relevance is often not accurately assessed in line design standards. The reason is that the parameters that affect the thermal conditions of the conductor (the physical state of the water, the relative humidity, the precipitation rate, or the air pressure) are not considered.

However, for the calculation of the DLR, since ampacity is dynamically calculated, rainfall cannot be completely ruled out. Precipitation information, collected from observations or forecasts, can be valuable in calculating a conservative DLR value using a simplified model. An example of a capacity model for overhead conductors (incorporating the role of precipitation) can be found in [26,50].

4.4. Solar Radiation

Similar to wind speed, measuring the actual incident solar radiation at a single point is not sufficient to calculate the combined effect of solar irradiance and albedo over a span. However, its influence can be considered linear in this application. Under reduced wind speed conditions (approx. 5 m/s), solar radiation can become a limiting factor for the calculation of the overhead line's DLR, as it can raise the conductor temperature well above the air temperature.

5. Project Expertise

5.1. Projects in Europe

A European Network of Transmission System Operators (ENTSO-E) survey in 2015 [48] attempted to get an overview of the number of electricity transmission companies that had DLR devices installed in Europe, indicating whether they were in operation or in a trial period and what type of devices were installed. These were the results obtained: 11 Transmission System Operators (TSOs) had DLR operating at that time, 5 had DLR in the testing phase, and 9 were planning DLR integration.

On the other hand, among the technologies used, 9 TSOs used weather stations, 6 used temperature or current sensors on their conductors, 3 used a thermo-mechanical model, 2 measured cable clearance, 1 TSO used dynamic limits depending on the season of the year, 3 TSOs used data measured by Phasor Measuring Units (PMUs) and 1 TSO used vibration sensors in the conductors.

Currently, several transmission networks are conducting DLR pilot projects to decide which of the technologies on the market they should operate their network with. The emergence of new technologies is expected soon. The data collected from the DLR system is used both to collect information about the network, to warn of possible alarm states, or to give new instructions to elements of the grid.

There are many research projects in different regions of the world, which show the growing importance of DLR in achieving a more effective operation of the electricity system.

Some European companies have installed DLR technology based on the measurement of mechanical parameters (mechanical tension, vibrations, elongation) of the line. The transmission company Elia (Brussels, Belgium) installed a mechanical system during a research project, in collaboration with the University of Liège, in 2008 [51,52]. A similar implementation was carried out in 2010 by RTE (TSO of France) [51,53] on 150 kV, 245 kV, and 400 kV transmission lines. Scottish Power (Glasgow, UK) installed, as Distribution System Operator (DSO) and TSO, a DLR system on a 33 kV network between the Cupar and St Andrews TSs in North Wales, as well as on a part of the 132 kV transmission system [54].

On the other hand, there are several DLR projects that can be considered operational deployments due to the volume of equipment installed, although most are pilots to test the technology. In Italy, the transmission system, operated by Terna Rete (Rome, Italy), was equipped with DLR technology based on a synchrophasor measurement system at the end of 2015 [55]. In the interconnection between Belgium and France, DLR systems were installed on 27 lines, which collected real-time and forecasted DLR measurements for planning, operating, and allocating capacity in the market. Sensors were installed to directly measure the deflection of conductors on 70, 150, 245, and 400 kV lines. In addition, a prediction module of up to 60 h was developed. The increase in nominal capacity was up to 130% [45].

Several recent field deployments and pilot projects across Europe have demonstrated practical implementations of DLR technologies under real operating conditions, validating both sensor-based and data-driven approaches. In Spain, a field study evaluated the application of DLR systems to High-Temperature Low-Sag (HTLS) conductors. The research compared different ampacity calculation methods and thermally validated the line behavior using real-time measurements. This project, funded by European programs and a Spanish utility company, confirmed the reliability of DLR calculations under high-load conditions and highlighted the importance of matching thermal models to actual conductor characteristics [56].

In Hungary, researchers from the Budapest University of Technology and Economics implemented an innovative DLR pilot project as part of the GridGuard (Budapest, Hungary) platform. Their system integrates distributed physical sensors with AI-based algorithms for critical span identification and virtual sensor deployment. Additionally, the system includes anti-icing capabilities and enables both real-time ampacity evaluation and short-term forecasting. The solution was validated in a real low-voltage grid, representing a fully operational European testbed [19].

Another notable approach was demonstrated in Estonia, where Manninen et al. developed a DLR system based entirely on weather data and topographic information, without any line-mounted sensors. Their model combines hyper-local weather forecasts with elevation profiles and land cover data to provide short-term ampacity predictions using machine learning techniques. The method includes confidence interval estimation and was validated on a real transmission corridor, making it a cost-effective alternative for rural or hard-to-access regions [57].

An indirect DLR system based on macro and micro meteorological models is applied in Slovenia. The system allows for defining calculations and maximum temperatures for each span. All this is monitored by a SCADA system. This system covers 27 lines (6×400 kV, 4×220 kV, and 17×110 kV) and is used for the daily operation of the network. They are mainly used in N, $N - 1$ situations and in the calculation of transmission capacity for the next 2 days. The system also features a reverse DLR algorithm to prevent lines from freezing and an alarm for potential extreme weather conditions. On average, for 92–96% of the time, the grid increases its capacity by 15–20%. In turn, thanks to this system, it is estimated that about 20 N events and more than 500 $N - 1$ events were mitigated [45].

In 2015, Viesgo (Santander, Spain) implemented DLR technology in a 132 kV network located in northern Spain. The calculation of the DLR was carried out by means of weather stations, while the conductor temperature was estimated through the combination of meteorological measurements with the current measured by the grid analyzers. Following the implementation of the DLR, from January 2015 to September 2018, 4100 h of wind generation curtailment could be avoided, and an additional 70.9 GWh of renewable energy was transmitted, according to their reports [58]. Another large-scale deployment effort in Spain, performed by Red Eléctrica de España, S.A.U. (Madrid, Spain), rolled out more than 750 DLR devices in 2024 across its high-voltage grid. The system, combining IoT-enabled sensors with remote weather stations, aims to increase line capacity by up to 30% under favorable cooling conditions. This initiative reflects the growing trend toward integrating DLR into national-level grid operation strategies, enhancing grid flexibility [59].

In countries such as Austria [60] and Finland [38], there are also other reports on the application of DLR solutions, where the analysis in [60] offers an additional comparison with respect to the field data collected by the DLR, in mountainous and flat terrains.

In the FARCROSS project [61], research on DLR has been carried out through PMU. This solution provides a lot of information for the operator. Operating independently from the current flowing through the line, measurements are continuously received and can be used to monitor the lines. In one of the publications [62], the methodology for the detection of critical spans for the implementation of DLR systems is studied, and the importance of the proper location of the sensors along the line is highlighted. Another publication [63] concludes that DLR can be a good tool to increase safety on transmission lines. In work-package number 5 of this project, DLR sensors were installed on the border transmission line between Hungary and Slovakia (400 kV to improve transport capacity, reduce curtailment, and predict dangerous situations) [64]. TRL 5 is currently considered to be this technology, although thanks to the FARCROSS project, these technologies are expected to reach TRL 8 [65].

The BEST PATHS project [66] tested different innovations, including a DLR prototype based on sensors that would allow existing grids to have greater capacity operating under current conditions. In one of the project's deliverables, it was concluded that, after its implementation, the capacity of the lines could be increased by between 10 and 15%.

ENTSO-E set up a working group on DLR. Their inputs can be seen in both webinars [67] and publications [48], where they review the different existing DLR methods and their application in various locations.

5.2. Projects in America

As regards the Americas, several applications are at the planning stage, as DLR investments in the Americas lag behind Europe, as indicated in [68].

The United States and Canada are the countries that lead the implementation of DLR projects on the continent. In the US, the DLR Idaho project, in collaboration with Idaho Power (Boise, ID, USA) and the Idaho National Laboratory (Idaho Falls, ID, USA), was carried out along 450 miles of a transmission line, between 2013 and 2018 [69]. Furthermore, Idaho Power initiated in early 2025 a field project funded by the U.S. Department of Energy involving drone-mounted sensors developed by Pitch Aeronautics (Boise, ID, USA). A total of 35 WireWarrior units were deployed to measure sag and weather conditions over long spans. The project aims to support predictive DLR, Ambient-Adjusted Ratings (AAR), and emergency ratings, with drone technology allowing for rapid deployment and lower installation risks [70].

In March 2024, Heimdall Power (Charlotte, NC, USA) deployed 52 Neuron sensors across Great River Energy's network, marking the largest DLR installation in the US to date. The system, based on conductor-mounted inductive sensors, enabled the shift from static seasonal ratings to real-time dynamic ratings, delivering an average 42.8% increase in line capacity. This project demonstrated full-scale operational integration without the need for external weather feeds, as the sensors themselves measure line temperature, current, angle, and vibrations in real time [71].

In May 2024, National Grid (Waltham, MA, USA) scaled up its previous DLR pilots by installing LineVision's non-contact, image-based monitoring systems on four 115 kV lines in upstate New York. These hybrid systems, combining sag-based sensing with weather and load data, were fully integrated into the control center, enabling 20–30% capacity increases and operational decision-making based on real-time ampacity [72]. Other LineVision's sensors were installed by AES Energy (Arlington, VA, USA) in Indiana and Ohio in a field trial, showing that DLR enabled a 141% increase in peak ampacity on a 345 kV line and facilitated targeted reconductoring in a 69 kV feeder. This underscores DLR's dual benefit: operational flexibility and capital planning efficiency [73].

Pennsylvania-Jersey-Maryland Interconnections (PJM -Audubon, PA, USA) and American Electric Power (AEP—Columbus, OH, USA) collaborated to implement DLR solutions on the 345 kV Cook-Olive transmission line between Michigan and Indiana. The results showed more than USD 4 million reduction in congestion costs in the first year of its application in the field [74].

The New York Power Authority (NYPA—White Plains, NY, USA) conducted multiple DLR projects, usually near large hydroelectric power plants, on the Niagara-Rochester (345 kV), Gilboa-Fraser (345 kV), and Modes-Willis-Plattsburgh (230 kV) power lines [75].

Oncor (Dallas, TX, USA) installed DLR technology on eight different transmission lines between 138 kV and 345 kV voltage levels, increasing the line's capacity by up to 14% [76]. Kansas City Power and Light (KCPL—Kansas City, MO, USA) investigated DLR due to congestion along the LaCygne-Stilwell line (345 kV), which avoided significant costs related to generation redispatch [77].

In terms of application examples in Canada, AltaLink (Calgary, AB, Canada) invested in the DLR concept in 2015 to improve wind energy integration, resulting in a 22% increase in line capacity [78]. Hydro Quebec (Montreal, QC, Canada) also implemented DLR solutions based on SMARTLINE technology for a 735 kV transmission line in Quebec [79].

One of the few DLR applications implemented in the southern part of the American continent was carried out in Brazil, for a repowering project, where a section of the line crossed the Paraná River. Specifically, it was built on the Jupiá-Três transmission line (138 kV) [80], on the border between the states of São Paulo and Mato Grosso do Sul. Due to environmental problems, it was not possible to replace the towers at the river crossing. The solution found consisted of replacing the conductor with a special cable and monitoring the conductor's deflection over the river using DLR.

5.3. Projects in Asia and Oceania

The known references from Asia are mostly old and correspond to small pilots. The Korea Electric Power Corporation (KEPCO—Naju-si, Jeollanam-do, Republic of Korea) application can be considered as one of the pioneering DLR installations in Asia, allowing an increase in line capacity of up to 35% [81]. A World Bank initiative for Smart-Grids, based on power transmission solutions in Vietnam, included a DLR application to address capacity problems on the line due to rapid load growth [82].

A more recent project was conducted by researchers from Tenaga Nasional Berhad (TNB—Bangsar, Kuala Lumpur, Malaysia), who conducted a full-year pilot applying DLR technology to a 275 kV Zebra-type ACSR line. The DLR system installed offers 2-h and 24-h forecast data, and, based on data from a week of June 2020, the maximum capacity registered was 1976A, which was 542A higher than the static line rating value [83].

In Oceania, Transpower New Zealand Limited (Wellington, New Zealand) began exploring the potential benefits of DLR within transmission system operation in 1996, with field trials starting in 2012 [84]. In Australia, TransGrid (Sydney, Australia) also developed DLR applications on environmental states based on the concept of improvements in system efficiency [85]. Also, Griffith University (Brisbane, Australia) and Powerlink (Smithfield, Australia) performed a study focusing on a 275 kV renewable energy zone in Queensland. This modeling study compares static versus real-time dynamic line ratings. It finds that switching to DLR can increase wind power hosting capacity from ~1700 MW to over 2800 MW—a ~65% uplift—without major infrastructure upgrades [86].

6. The Future of the Technology

6.1. Lines of Research

Below is an overview of the main topics under investigation in relation to DLR. In general, a lot of work has been done on the relevance topic of some measurements versus others, in the study of sensors, algorithms, and alternative methods to the existing ones. Furthermore, the detection of critical spans and the integration of renewables (in particular, wind energy) has received a lot of attention. Finally, the prediction of the DLR value is another relevant chapter in the research. Below are described several of the major lines of research:

- DLR measurement using phasor monitoring units (PMUs): PMUs have usually been installed on power lines for other purposes, but allow estimating line parameters directly related to the resistance and temperature of the conductor, such as DLR. The study by Coletta et al. [87] investigated different phasor measurement units as a method for calculating DLR through the estimation of conductor temperature. Subsequently, the accuracy of DLR's different PMU technologies was analyzed in a real project in a transmission line with thermal restrictions, delving into the impact of uncertainties on the operation of the system. Another review on the use of PMUs for DLR calculation is given in [88,89]. The estimation of the line parameters to be considered for monitoring the thermal conditions of a transmission line can be seen in [89]. The study concludes that with the appropriate algorithms for PMU equipment, the need to install additional weather or voltage monitoring sensors is eliminated.

- Optimal integration of wind energy supported by DLR: Wind farms cause greater load on the lines at times of greater wind, and, precisely because of the presence of intense wind, the line can be operated with greater overload if there are monitoring elements. The study of the relationship between DLR and wind energy integration, with practical evidence, can be seen in [23]. A review of the earlier study was also presented by the same group of authors in [90].
- Ampacity prediction: To estimate the evolution of the available capacity of the line in the hours following the time of measurement, prediction algorithms have been developed, which are often based on historical series and weather forecasts. A detailed review of the application of DLR forecasting techniques is presented in [16,91]. The impacts of each weather variable are analyzed in detail, as is the efficiency of different weather forecasting methods. Economic aspects and constraints to be taken into account during the implementation of DLR are also exposed. A prediction model of ice formation can be seen in [92]. In this model, the thermal behavior of the conductor is simulated, and real-time values of the conductor's sag are obtained. The reliability of climate data is discussed in [93]. The authors state that the climatic variations between the route of the line and the open areas are different, and that a significant difference can be observed by the fact of installing the weather stations on the supports of the transmission lines or outside them.

According to Hall and Deb [94], Douglass [95], and Foss [96], in order to incorporate DLR into grid operation, reliable ampacity forecasts must be available for specific lines or for the entire network. Foss and Maraio [97] also report the results of a temperature monitoring campaign at different points along an overhead line and propose a method of forecasting DLR based solely on weather forecasts.

- Identification of the critical span: Due to its cost, it is not possible to place sensors everywhere, and this is solved by choosing the right critical span to monitor at the most sensitive point of the line. The criteria for locating critical spans vary from one study to another, but they usually focus on the orography or the local climate. It seems clear that both must be considered, and depending on the area, one or the other will be more relevant. In [98,99], an analysis of methods for identifying the critical span is carried out from microclimatic models, which use interpolations to find out the meteorological conditions along the route of the line, with a spatial resolution of hundreds of meters.

Article [93] proposes a new method of identifying critical sections, which only takes into account compliance with the legal technical restrictions of a given line. The proposed methodology is based on the simulation of the "sag-clearance" of each span. This approach may be valid in some cases.

- Probabilistic methods: When making a prediction of the conductor's dynamic capacity, it is very important to make a conservative calculation, since the difference between measured, estimated, and actual data can be large and lead to significant errors. Apart from the error in the prediction of the input data itself, the heterogeneity of the line must be taken into account. Environmental data are taken at specific points, and the conditions change for each span (relative wind direction, height, ambient temperature) as well as the limits in the current (ground clearance is different between spans depending on the orography and vegetation). A probabilistic prediction of DLR in probabilistic environmental data is presented in [100]. Environmental values are obtained from measuring stations placed on certain supports. For the rest of the network, values are obtained by interpolating between nearby stations and weather forecasts, using a neural network with a Kalman filter. The values of temperature, wind speed, and irradiance follow statistical distributions with mean and standard deviation. Once these data are available, the DLR is calculated with the CIGRÉ heat balance equation. The capacity applied to the line will finally be the smallest of all the spans.

- Machine Learning methods: Machine Learning techniques have undergone significant development in recent years, serving for the correlation of data in a multitude of fields of knowledge. There are several articles that refer to its use for the prediction of DLR, as always, from the measurements of environmental parameters. The article [42] provides a comparison of various neural network and machine learning methods for the calculation of DLR from historical weather data, in order to predict the capacity of the lines both in real time and one day in advance. The methods studied are: MultiLayer Perceptron (MLP), Group Method Data Handling (GMDH), Support Vector Regression (SVR), Back-Propagation Neural Network (BPNN), Extreme Machine Learning (ELM), and Hierarchical Extreme Machine Learning (H-ELM). The latter is the method proposed in this article, and its operation is verified against the rest. Data for half a year is available at 10-min intervals. For all methods, 70% of the data has been reserved for training the networks, and the remaining 30% has been left to test their operation. The H-ELM method turns out to be the best of them all in both runtime and accuracy. Data is tested for two 400 kV lines located in Iran, and a possible 30% increase in the capacity of the line is obtained without compromising it, avoiding a repowering of the substation they feed.

Table 3 provides a comparative overview of forecasting methodologies applied to DLR, drawn from both foundational literature and recent developments in machine learning. The comparison focuses on key aspects such as forecast horizon, input variables, accuracy metrics (when reported), and computational requirements. This synthesis aims to clarify the capabilities and limitations of various approaches, supporting researchers and system operators in selecting suitable forecasting models according to operational and computational constraints.

Table 3. Comparative overview of DLR forecasting methods.

Study	Forecasting Horizon	Input Variables	Computational Load
Schell et al. (2008) [42]	Short-term (1–4 h)	Real-time sag, current, and weather: ambient temperature, wind speed and direction, solar radiation	Moderate: time-series + ML
Michiorri et al. (2015) [16]	Short-medium term (up to ~48 h)	Conductor temp, sag, tension, weather	Moderate to high
Douglass et al. (2019) [91]	Various, from minutes to days	Surveyed models: incl. weather + line sensors	Varies

Table 3. *Cont.*

Study	Forecasting Horizon	Input Variables	Computational Load
Rácz et al. (2018) [92], Szabó et al. (2020) [93]	Critical span analysis, not specific forecasting	Span geometry, weather, tension	Low-medium (analytical)
Hall and Deb (1988) [94]	Hour-ahead (1 h)	Weather, conductor temperature, current	Low (stochastic/deterministic)
Douglass (1988) [95]	Hour-ahead	Ambient temp, wind, solar radiation	Low
Foss and Maraio (1990, 1992) [96,97]	Minute-to-hour scales	Weather + conductor variables	Low-medium
Phillips (2013) [100]	Instrumentation evaluation	Sensor outputs + weather	Field level
Saatloo et al. (2021) [101]	Hour-ahead and day-ahead	Air temp, wind speed/direction, solar radiation	High: hierarchical neural network
Other recent ML (AE-BiLSTM, XGBoost, etc.)	Short (0–6 h), medium (6–48 h), or up to 6 months	Forecasted weather variables	High: deep ensembles

More recent contributions, such as Saatloo et al. [101], introduced H-ELM using ambient temperature, wind speed and direction, and solar radiation as inputs. While these models demonstrated superior performance compared to traditional ML approaches, specific RMSE values were not reported. Similarly, deep learning frameworks like AE–BiLSTM and XGBoost have been tested for horizons ranging from several hours to several months, offering improved accuracy at the expense of higher computational complexity.

6.2. Main Challenges

The successful implementation of DLR presents several technical and regulatory challenges. Here are the main hurdles to overcome:

- Infrastructure and Data. The installation of a monitoring infrastructure is not always necessary. However, in many cases, specific sensors will be required to measure variables relevant to DLR, such as wind speed when wind speed is low [102]. Data quality and accuracy are critical to ensuring the reliability of the results of the DLR calculation.
- Integration with Existing Systems and Model Improvement. Integrating DLR into existing grid management and control systems requires adaptation of current thermal models. The accuracy of these models needs to be improved, especially regarding the influence of low wind speeds on transmission capacity. In addition, DLR systems should be developed to include functionalities such as real-time control, verification of results, historical databases, feedback, and error correction [103].
- Regulatory and Economic Aspects. In 2020, the International Renewable Energy Agency (IRENA) highlighted the need for regulatory changes in electricity distribution companies whose remuneration is linked to investment in infrastructure, so that they could be considered modern technologies [104]. However, for example, in Spain, DLR has been recognized as a remunerative network asset since 2019. Through Royal Circular Decree 6/2019, of 5 December, digitalization elements were established as remunerable assets, including DLR and other smart grid solutions such as grid batteries.

Other challenges identified by the authors of this article, based on the bibliographic review carried out, are detailed below:

- DLR forecast. In advance, the value of DLR lies in providing an accurate measure of the possibilities of actions that the grid operator has, to take advantage of the real available operating margins, instead of protecting the assets using fictitious rigid margins that are far from reality. However, for an effective operation, it is necessary to know not only the real margin at the time of the consultation, but also the margin that will foreseeably be available in the following hours. With this information, the network operator can consider performing a grid maneuver, knowing if it will solve the problem, since normally, grid problems have a long duration over time.

- Extrapolation to other lines. There is not yet enough experience of exploitation, but the use and improvement studies will lead to practical proposals for the exploitation of DLR. A promising line of research is the extrapolation of DLR data to nearby lines or installed in areas that share climatic or operating conditions. Perhaps, a line without DLR can be temporarily overexploited, if necessary, if it shares, for example, certain climatic conditions with another that does have DLR and shows favorable conditions.

To what extent can the information be extrapolated and under what conditions it occurs (ranges of variables, climatic or orographic similarity, geographical proximity, etc.) are some of the topics that should be explored.

- Equipment, sensors, and manufacturers. A certain variety of equipment from different manufacturers is available on the DLR market. Each one has opted for a type of sensor, analyzes a set of parameters, and gives different importance to climatological data, line operation, etc. The scientific world sees possibilities in several of these systems and has provided useful knowledge about some variables and their relationships, but there is no consensus on which is the best proposal.

In this context, it is first necessary to know whether the measurements and estimations provided by the equipment chosen for deployment correspond to reality. To do this, it is sufficient to compare the values collected under different working conditions with those provided by external sensors of direct measurement, duly calibrated. In addition, it must be considered that some are estimates or indirect calculations from the measurements of other magnitudes. It is necessary to check that the results produced by the algorithms are correct throughout the range of action and measure their error.

Secondly, before making a massive deployment, it is necessary to know the equipment available on the market and its qualities. To this end, it would be advisable to carry out a pilot in which a significant number of technical alternatives can be compared, or at least the equipment of manufacturers that use sensors of different types, to assess the advantages of each one and the convenience of making specific developments for some of them.

Among other characteristics, it would be necessary to evaluate the sensitivity of the equipment, its precision, robustness of the equipment, and the solution as a whole, the significance of the measurement they provide, the adequacy of the sensor to the characteristics of the problem or the area of application, the ease of installation and maintenance, its ability to operate in adverse conditions, etc.

- Integration with insulation monitoring techniques. DLR aims to optimize line ampacity in real time based on the environmental conditions and conductor state. However, insulation degradation—driven by pollution, moisture, or partial discharge—can limit permissible operating conditions or require derating. By integrating remote insulation sensors with DLR platforms, a more holistic operational strategy is enabled, so that ampacity is not only adjusted for thermal limits, but also for insulation safety margins. Also, this integration enhances risk-aware dispatch decisions and supports extensions of line life through timely maintenance interventions. In Table 4, a comprehensive overview of insulation monitoring techniques is presented.

Table 4. Classification of Insulation Monitoring Methods for Overhead Lines.

Method	Technique	Description
Offline/Manual Inspection	Visual inspections	Performed periodically by ground crews, from towers, or using helicopters to detect cracks, contamination, or damaged insulators.
	Dielectric strength or withstand testing	Applied to disconnected equipment (e.g., during maintenance or testing at substations), this method uses high voltage to assess insulation integrity. Less practical for live overhead lines.
	Ultrasonic inspection for corona and partial discharges	Handheld acoustic devices detect emissions from corona activity or incipient insulation failures. Useful during field inspections and maintenance.
Online/Direct In situ	Leakage current monitoring	Common in polluted or coastal regions, this involves installing sensors (e.g., resistive dividers or Rogowski coils) on insulator strings to measure surface leakage current in real time.
	Partial discharge (PD) detection	High-frequency current transformers (HFCT), UHF sensors, or acoustic sensors are used to detect PD activity. Widely applied in substations and extra-high voltage (EHV) networks.
	Thermal imaging systems	Fixed or tower-mounted infrared cameras continuously monitor insulator surface temperatures to detect hotspots caused by contamination or internal damage.
	Time Domain Reflectometry (TDR)	Uses reflected electromagnetic pulses to detect changes in dielectric properties or moisture ingress along insulation paths. Primarily used in cable diagnostics, but also applicable to composite insulators.
Remote and Automated	Drone-based inspections with thermal or visual cameras	Drones equipped with high-resolution or infrared cameras capture images of insulators, which are analyzed using AI techniques to detect cracks, pollution, or corona discharges.
	Wireless leakage current or PD sensors	Sensors installed at specific towers or insulator strings transmit real-time data via wireless networks, often integrated into Internet of Things (IoT) platforms.
	Integrated condition monitoring platforms	These combine weather sensors, line sag/tension monitors, PD/leakage current sensors, and thermal cameras for holistic health diagnostics of the line. Some systems are already deployed in smart grids and pilot DLR projects.

While manual and in situ methods offer valuable diagnostic capabilities, remote and automated approaches are increasingly favored due to several advantages:

- Continuous coverage and early detection: Unlike manual inspections, remote methods allow for continuous monitoring of insulation degradation—such as increasing leakage currents or surface heating—helping utilities act before faults occur.
- Improved safety and operational efficiency: Remote techniques reduce or eliminate the need for crews to climb towers or operate near energized conductors, lowering both human risk and maintenance costs.

 - ○ Scalability and compatibility with Dynamic Line Rating (DLR): Many DLR systems already utilize weather stations, line sensors, and thermal cameras. Adding insulation health sensors (e.g., PD or leakage current sensors) allows for combined monitoring of conductor ampacity and dielectric condition, without redundant infrastructure.
 - ○ Enhanced asset reliability and optimization: Integrating insulation data with DLR data enables utilities to adjust the ampacity value as well as the maintenance scheduling. For instance, if contamination is detected or leakage current increases under humid conditions, DLR limits can be adjusted to ensure safe operation, thus reducing the risk of flashovers.

- Combination with other flexible assets (BESS). The integration of DLR with BESS offers clear potential for improving grid flexibility and renewable energy integration, but several challenges remain. A key issue is the coordination and optimization of both technologies: studies have shown that the benefits depend heavily on how the BESS is sized, located, and controlled, as well as how DLR is implemented. Without proper coordination, DLR may increase capacity for conventional generators instead of supporting renewable integration. Forecasting uncertainties, particularly in weather conditions and renewable generation, can also limit the effectiveness of DLR and BESS coordination. Additionally, incomplete sensor infrastructure or reliance on virtual measurements can reduce the accuracy of real-time DLR data. On the regulatory side, market mechanisms often fail to incentivize the joint use of DLR and storage, despite their potential for system-wide savings. Lastly, managing the complex interactions between grid constraints, DLR variability, and BESS operation requires advanced control strategies that are still under development. Addressing these challenges is essential to fully unlock the benefits of DLR-BESS integration. In Table 5, the benefits related to combining DLR with other flexibility assets can be seen.

Table 5. DLR interaction with other flexibility options [18].

DLR + Flexible Option	Benefits
DLR + TS TS—Transmission switching	System dispatch rates reduced by up to 23%, congestion reduced by 44%, renewable energy sources enabled by up to 97%, system costs cut by 6.78%, and wind power curtailment minimized.
DLR + RES RES—Renewable energy source	Improve the grid's security.
DLR + ESS ESS—Energy storage system	Reduce the reliability index of expected energy not supplied by 23.6%, scale down operational cost and emissions of the multi-area grid, minimize environmental impacts by 10%, and lower the utilization of ESS.

- Installation. The installation of the system, in some manufacturers, includes the placement of a cabinet in which the remote unit that collects the data, the solar generator, the weather station, is located on the electrical tower, and the fixing of a sensor on the line. The main problem with installing the cabinet at a certain height is its weight and volume, but perhaps also the way it is anchored to the tower. It would be advisable to study the means and methods of installation other than the current ones that facilitate maneuvering and allow quick and safe installation.

As for the equipment that contains the sensor, the best option is to perform the installation without de-energizing the line, so as not to condition the electrical service. Both the method and the means should be reviewed to see if it is feasible to install safely for people and equipment.

- Maintenance. In general, the maintenance of the equipment that is installed on the tower should not be a problem, as it is like that of any other equipment in common use and does not require leaving the line without service for handling. Electronic systems allow a connection to be managed from the ground. Others may require work at height. However, the sensor is fixed to a live line. The foreseeable operations on DLR elements are: (a) periodic calibration of sensors, since the quality of the measurement depends on them. This is a delicate issue, as it requires leaving the line without voltage and should be done frequently enough to ensure that the measurement received is valid; (b) review of the condition of the batteries and replacement in case of deterioration. A remote test is not problematic, although it may require some development, however, the replacement of the sensor battery, in those that have it, has all the problems of an action in voltage, at height, and with equipment of a certain weight; (c) replacement of any element that may be damaged from vandalism, weather or any other cause.

Apart from those already mentioned, this operation should not be complicated. The most problematic procedures should be reviewed if a significant amount of equipment is to be deployed, to improve as much as possible procedures, tools, and requirements to be included in the purchase specifications (such as remote access to the status of the batteries, requesting a charge-discharge cycle, or remote firmware changes).

7. Conclusions

In this article, a review of the state of the art of the Dynamic Line Rating technology has been carried out, mainly exposing the systems currently available on the market and the most notable projects carried out to date, as well as the effect of the different meteorological variables that affect the calculation, which are linked to the research lines and challenges that are raised in the article.

The technologies available on the market are very different from each other, and each manufacturer gives more importance to one meteorological factor or variable than another. As explained in the previous chapter, it would be interesting to carry out a specific pilot that compares the capabilities of each sensor and allows conclusions to be drawn about which technology and which variables are most decisive in the calculation. However, from the analysis carried out, it can be stated that the wind speed on the line and the angle at which it affects it are especially sensitive, although the relevance of other variables increases as the wind speed decreases.

On the other hand, Europe tops the list in terms of the territories that have developed and invested the most in this technology, followed by the United States, from which a significant number of manufacturers belong. It will be especially interesting to observe the evolution with which these countries will implement improvements in technology, especially with the rise of artificial intelligence and Machine Learning techniques that some manufacturers and energy utilities are beginning to implement to collect large amounts of data, especially from historical weather. In this way, the system operators will be able to estimate the maximum capacity available on the transmission lines sufficiently in advance, facilitating real-time operational decision-making during the operation of the grid. Furthermore, future work should focus on developing advanced control strategies and market mechanisms that enable the coordinated operation of DLR and flexible assets such as BESS to fully exploit their combined flexibility and system-level benefits.

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Abbreviations

The following abbreviations are used in this manuscript:

AAR	Ambient-Adjusted Ratings
BESS	Battery Energy Storage System
BPNN	Back-Propagation Neural Network
CIGRÉ	Conseil International des Grands Réseaux Électriques
DLR	Dynamic Line Rating
DSO	Distribution System Operator
ELM	Extreme Machine Learning
ENTSO-E	European Network of Transmission System Operators for Electricity
EPRI	Electric Power Research Institute
ESS	Energy Storage System
GMDH	Group Method Data Handling
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
H-ELM	Hierarchical Extreme Machine Learning
HTLS	High-Temperature Low-Sag
IEEE	Institute of Electrical and Electronics Engineers
IRENA	International Renewable Energy Agency
MLP	MultiLayer Perceptron
P_J	Power dissipated by the Joule effect
P_S	Power captured by solar radiation
P_C	Loss of heat by convection to the environment
PMU	Phasor Measuring Unit
P_r	Heat loss by radiation
RES	Renewable Energy Source
RMSE	Root-mean square error
SCADA	Supervisory Control and Data Acquisition
SMT	Temperature Monitoring System
SNG	Sensor Network Gateway
SVR	Support Vector Regression
T_{cond}	Conductor temperature
TDA	Time-Dependent Algorithms
TLM	Transmission Line Monitor
TRL	Technology Readiness Level
TS	Transmission Switching
TSO	Transmission System Operator

References

1. CIGRÉ. *Guide for Selection of Weather Parameters for Bare Overhead Conductor Ratings*; CIGRÉ Brochure No. 299; CIGRÉ: Paris, France, 2006.
2. Seppa, T.O. Increasing Transmission Capacity by Real-Time Monitoring. In Proceedings of the IEEE PES Winter Meeting, New York, NY, USA, 27–31 January 2002; pp. 1208–1211.
3. Ochoa, L.F.; Cradden, L.C.; Harrison, G.H. Demonstrating the Capacity Benefits of Dynamic Ratings in Smarter Distribution Networks. In Proceedings of the IEEE/PES Conference on Innovative Smart Grid Technologies (ISGT), Gothenburg, Sweden, 11–13 October 2010.
4. Raniga, J.K.; Rayudu, R.K. Dynamic Rating of Transmission Lines–A New Zealand Experience. In Proceedings of the IEEE Power Engineering Society Winter Meeting, Singapore, 23–27 January 2000; Volume 4, pp. 2403–2409.

5. Ringelband, T.; Lange, M.; Dietrich, M.; Haubrich, H.J. Potential of Improved Wind Integration by Dynamic Thermal Rating of Overhead Lines. In Proceedings of the 2009 IEEE Bucharest PowerTech, Bucharest, Romania, 28 June–2 July 2009.
6. Yip, T.; An, C.; Lloyd, G.; Aten, M.; Ferris, B. Dynamic Line Rating Protection for Wind Farm Connections. In Proceedings of the Integration of Wide-Scale Renewable Resources into the Power Delivery System, CIGRÉ/IEEE PES Joint Symposium, Calgary, AB, Canada, 29–31 July 2009; pp. 1–5.
7. Kazerooni, A.K.; Mutale, J.; Perry, M.; Venkatesan, S.; Morrice, D. Dynamic Thermal Rating Application to Facilitate Wind Energy Integration. In Proceedings of the IEEE PowerTech Conference, Trondheim, Norway, 19–23 June 2011.
8. Etherden, N.; Bollen, M.H.J. Increasing the Hosting Capacity of Distribution Networks by Curtailment of Renewable Energy Resources. In Proceedings of the IEEE PowerTech Conference, Trondheim, Norway, 19–23 June 2011.
9. Pytlak, P.; Musilek, P.; Doucet, J. Using Dynamic Thermal Rating Systems to Reduce Power Generation Emissions. In Proceedings of the IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–29 July 2011.
10. Dino, A.; Ketley, A. *Dynamic Transmission Line Rating: Technology Review*; Technical Report No. 208478-CR-001; Hydro Tasmania Consulting: Hobart, Australia, 2009.
11. Glaum, P.; Hofmann, F. Leveraging the Existing German Transmission Grid with Dynamic Line Rating. *Appl. Energy* **2023**, *343*, 121199. [CrossRef]
12. Lai, C.-M.; Teh, J. Network Topology Optimisation Based on Dynamic Thermal Rating and Battery Storage Systems for Improved Wind Penetration and Reliability. *Appl. Energy* **2022**, *305*, 117837. [CrossRef]
13. Teh, J.; Lai, C.-M. Reliability Impacts of the Dynamic Thermal Rating and Battery Energy Storage Systems on Wind-Integrated Power Networks. *Sustain. Energy Grids Netw.* **2019**, *20*, 100268. [CrossRef]
14. IEEE Power and Energy Society. *IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors*; IEEE: New York, NY, USA, 2012.
15. Iglesias, J.; Watt, G.; Douglass, D.; Morgan, V.; Stephen, R.; Bertinat, M.; Muftic, D.; Puffer, R.; Guery, D.; Ueda, S.; et al. *Guide for Thermal Rating Calculations of Overhead Lines*; CIGRÉ: Paris, France, 2012.
16. Michiorri, A.; Nguyen, H.-M.; Alessandrini, S.; Bremnes, J.B.; Dierer, S.; Ferrero, E.; Nygaard, B.-E.; Pinson, P.; Thomaidis, N.; Uski, S. Forecasting for Dynamic Line Rating. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1713–1730. [CrossRef]
17. Arroyo, A.; Castro, P.; Martínez, R.; Mañana, M.; Madrazo, A.; Lecuna, R.; González, A. Comparison between IEEE and CIGRÉ Thermal Behaviour Standards and Measured Temperature on a 132-kV Overhead Power Line. *Energies* **2015**, *8*, 13660–13671. [CrossRef]
18. Abas, N.H.; Kadir, M.Z.A.A.; Azis, N.; Jasni, J.; Aziz, N.F.A.; Khurshid, Z.M. Optimizing Grid with Dynamic Line Rating of Conductors: A Comprehensive Review. *IEEE Access* **2024**, *12*, 9738–9756. [CrossRef]
19. Szabó, D.; Németh, B. A Novel Approach to Dynamic Line Rating Calculation. *Electronics* **2024**, *17*, 1137. [CrossRef]
20. Simms, M.; Meegahapola, L. Comparative Analysis of Dynamic Line Rating Models and Feasibility to Minimise Energy Losses in Wind Rich Power Networks. *Energy Convers. Manag.* **2013**, *75*, 11–20. [CrossRef]
21. Castro, P.; Arroyo, A.; Martínez, R.; Mañana, M.; Domingo, R.; Laso, A.; Lecuna, R. Study of Different Mathematical Approaches in Determining the Dynamic Rating of Overhead Power Lines and a Comparison with Real-Time Monitoring Data. *Appl. Therm. Eng.* **2017**, *111*, 95–102. [CrossRef]
22. Erdinç, F.G.; Erdinç, O.; Yumurtacı, R.; Catalão, J.P.S. A Comprehensive Overview of Dynamic Line Rating Combined with Other Flexibility Options from an Operational Point of View. *Energies* **2020**, *13*, 6563. [CrossRef]
23. Fernandez, E.; Albizu, I.; Bedialauneta, M.T.; Mazon, A.J.; Leite, P.T. Review of Dynamic Line Rating Systems for Wind Power Integration. *Renew. Sustain. Energy Rev.* **2016**, *53*, 80–92. [CrossRef]
24. USi. "USi." [Online]. Available online: https://www.updesigns.com/portfolio-item/underground-systems-power-donut2/ (accessed on 8 July 2025).
25. Atecnum. PowerDonut®PD4 [Online]. Available online: https://www.atecnum.com/services (accessed on 10 July 2025).
26. Pytlak, P.; Musilek, P.; Lozowski, E.; Toth, J. Modelling Precipitation Cooling of Overhead Conductors. *Electr. Power Syst. Res.* **2011**, *81*, 2147–2154. [CrossRef]
27. GE Grid Solutions. [Online]. Available online: https://www.gegridsolutions.com/multilin/catalog/fmc.htm (accessed on 13 May 2025).
28. Black, J.; Colandairaj, J.; Connor, S.; O'Sullivan, B. Equipment and Methodology for the Planning and Implementation of Dynamic Line Ratings on Overhead Transmission Circuits. In Proceedings of the University Power Engineering Conference, Belfast/Shannon, Online, 1–4 September 2008.
29. Lindsey Systems. "SMARTLINE." [Online]. Available online: https://lindsey-usa.com/dynamic-line-rating/ (accessed on 13 May 2025).
30. McLaughlin, R. Extracting Transmission Lines from Airborne LIDAR Data. *IEEE Geosci. Remote Sens. Lett.* **2006**, *3*, 222–226. [CrossRef]

31. Bernauer, C.; Böhme, H.; Grossmann, S.; Hinrichsen, V.; Kornhuber, S.; Markalous, S.; Muhr, M.; Strehl, T.; Teminova, R. Temperature Measurement on Overhead Transmission Lines (OHTLs) Utilizing Surface Acoustic Wave (SAW) Sensors. In Proceedings of the 19th CIRED International Conference and Exhibition on Electricity Distribution, Vienna, Austria, 21–24 May 2007.
32. Sensornet. Sensornet FAQs. [Online]. Available online: https://www.sensornet.co.uk/faqs/#1464184839467-8ffe3516-a864 (accessed on 15 May 2025).
33. Sensornet. Sentinel DTS Range Data Sheet v3. [Online]. Available online: https://www.sensornet.co.uk/wp-content/uploads/2020/07/Sentinel-DTS-range-data-sheet-v3.pdf (accessed on 15 May 2025).
34. Seppa, T.O. Accurate Ampacity Determination: Temperature–Sag Model for Operational Real-Time Ratings. *IEEE Trans. Power Deliv.* **1995**, *10*, 1460–1470. [CrossRef]
35. Teh, J.; Cotton, I. Critical Span Identification Model for Dynamic Thermal Rating System Placement. *IET Gener. Transm. Distrib.* **2015**, *9*, 2644–2652. [CrossRef]
36. Douglass, D.A.; Edris, A.-A. Field Studies of Dynamic Thermal Rating Methods for Overhead Lines. *IEEE Trans. Power Deliv.* **1996**, *11*, 1407–1418. [CrossRef]
37. Albizu, I.; Fernández, E.; Mazón, A.J.; Bengoechea, J.; Torres, E. Hardware and Software Architecture for Overhead Line Rating Monitoring. In Proceedings of the IEEE Trondheim PowerTech Conference, Trondheim, Norway, 19–23 June 2011.
38. Uski-Joutsenvuo, S.; Pasonen, R. *Maximising Power Line Transmission Capability by Employing Dynamic Line Ratings–Technical Survey and Applicability in Finland*; VTT Research Report VTT-R-01604-13; VTT Technical Research Centre of Finland: Espoo, Finland, 2013.
39. EDM. [Online]. Available online: https://edmlink.com/ (accessed on 15 May 2025).
40. Ampacimon. Sense D. Dynamic Line Rating—Asset Monitoring [Online]. Available online: https://cdn.prod.website-files.com/655f66f843cfd117b240a9ea/684863b9c1a43d993f9a1474_Ampacimon%20Sense%20D%20datasheet.pdf (accessed on 10 July 2025).
41. Cloet, E.; Lilien, J.-L. Uprating Transmission Lines Through the Use of an Innovative Real-Time Monitoring System. In Proceedings of the CIGRÉ General Session, París, France, 22-27 August 2010. Paper C2-106.
42. Schell, P.; Jones, L.; Mack, P.; Godard, B.; Lilien, J.-L. Dynamic Prediction of Energy Delivery Capacity of Power Networks. In Proceedings of the CIGRÉ Session, Paris, France, 24-29 August 2008.
43. Lilien, J.-L.; Guérard, S.; Destiné, J.; Cloet, E. Microsystems Array for Live High Voltage Lines Monitoring. In Proceedings of the CIGRÉ Session, París, France, 27 August–1 September 2006. Paper B2-302.
44. Pike Corporation. PIKE [Online]. Available online: https://www.pike.com/ (accessed on 27 May 2025).
45. ENTSO-E. Dynamic Line Rating (DLR). ENTSO-E Technopedia Techsheet. [Online]. Available online: https://www.entsoe.eu/Technopedia/techsheets/dynamic-line-rating-dlr (accessed on 10 July 2025).
46. Albizu, I.; Fernández, E.; Mazón, A.J.; Bengoechea, J. Influence of Conductor Temperature Error on Overhead Line Ampacity Monitoring Systems. *IET Gener. Transm. Distrib.* **2011**, *5*, 440–447. [CrossRef]
47. CIGRÉ. *Guide for Application of Direct Real-Time Monitoring Systems*; Brochure B2-36 (Ref. 498); CIGRÉ: Paris, France, 2012.
48. ENTSO-E. *Dynamic Line Rating for Overhead Lines – V6. RGCE SPD WG Report*; ENTSO-E: Brussels, Belgium, 2015.
49. Vincent, C.; Giebel, G.; Pinson, P.; Madsen, H. Resolving Nonstationary Spectral Information in Wind Speed Time Series Using the Hilbert–Huang Transform. *J. Appl. Meteorol. Climatol.* **2010**, *49*, 253–267. [CrossRef]
50. Pytlak, P.; Musilek, P.; Lozowski, E.; Toth, J. Precipitation-Based Conductor Cooling Model for Dynamic Thermal Rating Systems. In Proceedings of the 2009 IEEE Electrical Power & Energy Conference (EPEC), Calgary, AB, Canada, 26–30 July 2009; pp. 1–7.
51. Cloet, E.; Santos, J.L.D. TSOs Advance Dynamic Rating. Transmission & Distribution World, 2011. Available online: http://www.ampacimon.com/wp-content/uploads/2015/09/TSOs-Advance-Dynamic-Rating.pdf (accessed on 22 May 2025).
52. Elia. Dynamic Line Rating. [Online]. Available online: https://www.elia.be/en/infrastructure-and-projects/our-infrastructure/dynamic-line-rating (accessed on 22 May 2025).
53. RTE France. Innovations. [Online]. Available online: https://media.rte-france.com/innovations/ (accessed on 22 May 2025).
54. SP Energy Networks. Implementation of RTTR System for Cupar–St Andrews 33 kV Circuits. [Online]. Available online: https://www.spenergynetworks.co.uk/userfiles/file/Dynamic%20thermal%20rating%20of%20assets%20Cupar%20and%20St%20Andrews%20RTTR27.10.pdf (accessed on 23 May 2025).
55. General Electric Grid Solutions. "GE Helps Terna Rete Italia Improve Grid Resiliency and Integrate Renewable Energy More Efficiently." [Online]. Available online: https://www.ge.com/news/press-releases/ge-helps-terna-rete-italia-improve-grid-resiliency-and-integrate-renewable-energy (accessed on 23 May 2025).
56. Vejo, L.; Castro, P.; Mañana, M.; Laso, A.; Lecuna, R.; Bustamante, S.; Sainz-Ortiz, E. Experimental Study of Dynamic Line Rating Applied to High-Temperature Low-Sag Conductors. *Energies* **2025**, *18*, 929. [CrossRef]
57. Manninen, H.; Lippus, M.; Rute, G. Dynamic Line Rating using Hyper-local Weather Predictions: A Machine Learning Approach. *arXiv* **2024**, arXiv:2405.12319. [CrossRef]
58. Mínguez, R.; Martínez, R.; Mañana, M.; Arroyo, A.; Domingo, R.; Laso, A. Dynamic Management in Overhead Lines: A Successful Case of Reducing Restrictions in Renewable Energy Sources Integration. *Electr. Power Syst. Res.* **2019**, *173*, 135–142. [CrossRef]

59. Red Eléctrica. Red Eléctrica Installs over 750 Dynamic Line Rating Devices on Overheads. Red Eléctrica 2025. [Online]. Available online: https://www.ree.es/en/news/installations/dynamic-line-rating-overheads (accessed on 25 May 2025).
60. Reich, K.; Mia, G.; Puffer, R. Potential Analysis for Dynamic Optimization Based on Four Years of Operational Experience in Austria. *Elektrotechnik Informationstechnik* **2018**, *135*, 548–555. [CrossRef]
61. FARCROSS Project. FARCROSS. [Online]. Available online: https://farcross.eu/ (accessed on 25 May 2025).
62. Szabó, D.; Németh, B. A Novel Methodology for Critical Span Identification for Dynamic Line Rating System Implementation. *Energy Rep.* **2021**, *7*, 242–249. [CrossRef]
63. Rácz, L.; Németh, B. Dynamic Line Rating—An Effective Method to Increase the Safety of Power Lines. *Appl. Sci.* **2021**, *11*, 492. [CrossRef]
64. FARCROSS Project. "Installation of DLR Sensors on the Hungarian Transmission Network." [Online]. Available online: https://farcross.eu/installation-of-dlr-sensors-on-the-hungarian-transmission-network/ (accessed on 25 May 2025).
65. FARCROSS Project. "DEMO A.2–Technical Factsheet." [Online]. Available online: https://farcross.eu/wp-content/uploads/2022/03/FARCROSS_Factsheet_WP5_v0.4.pdf (accessed on 25 May 2025).
66. BestPaths Project. BestPaths. [Online]. Available online: http://www.bestpaths-project.eu/ (accessed on 25 May 2025).
67. ENTSO-E. "Smart Grid World of Innovations: Dynamic Line Rating Webinar." [Online]. Available online: https://www.entsoe.eu/events/2019/03/20/smart-grid-world-of-innovations-dynamic-line-rating-webinar/ (accessed on 17 May 2025).
68. US DOE. Dynamic Line Rating: Report to Congress, June 2019. U.S. Department of Energy. [Online]. Available online: https://www.energy.gov/sites/prod/files/2019/08/f66/Congressional_DLR_Report_June2019_final_508_0.pdf (accessed on 17 May 2025).
69. Idaho National Laboratory. "Dynamic Line Rating—Innovation for Electrical Transmission Grid Discussed at Workshop." [Online]. Available online: https://inl.gov/article/dynamic-line-rating/ (accessed on 19 May 2025).
70. Idaho Power. Idaho Power Advances Grid Efficiency with Dynamic Line Rating & Drone Technology. Idaho Power, 2025. [Online]. Available online: https://www.tdworld.com/overhead-transmission/news/55273632/idaho-power-advances-grid-efficiency-with-dynamic-line-rating-drone-technology (accessed on 19 May 2025).
71. Heimdall Power. Heimdall Power Launches Largest Dynamic Line Rating Project in the U.S. with Great River Energy. Heimdall Power, 2025. [Online]. Available online: https://heimdallpower.com/heimdall-power-launches-largest-dynamic-line-rating-project-in-the-u-s-with-great-river-energy (accessed on 19 May 2025).
72. Latitude Media. Behind the Scenes of the Country's Largest Dynamic Line Rating Deployment. Latitude Media, 2025. [Online]. Available online: https://www.latitudemedia.com/news/behind-the-scenes-of-the-countrys-largest-dynamic-line-rating-deployment/ (accessed on 20 May 2025).
73. Engel, J. A Utility Tried Out Dynamic Line Ratings—How Did It Go? Renewable Energy World, 2025. [Online]. Available online: https://www.renewableenergyworld.com/power-grid/transmission/a-utility-tried-out-dynamic-line-ratings-how-did-it-go/ (accessed on 20 May 2025).
74. PJM Interconnection. "New Line Technology Boosts Reliability, Reduces Costs." [Online]. Available online: https://insidelines.pjm.com/pjm-finds-opportunities-in-new-dynamic-line-rating-technologies/ (accessed on 20 May 2025).
75. New York Power Authority. NYPA Transmission Projects—A Model of Continuous Improvement. [Online]. Available online: https://www.nypa.gov/power/transmission/transmission-projects (accessed on 20 May 2025).
76. Nexans. "Oncor's Advanced Grid Project Provides Successful Demonstration of How Nexans' Dynamic Line Rating Technology Can Boost the Capacity of Overhead Power Lines." [Online]. Available online: https://www.nexans.us/eservice/US-en_US/navigatepub_158895_-33520/Oncor_s_advanced_grid_project_provides_successful_.html (accessed on 20 May 2025).
77. Nexans. "Dynamic Line Ratings for a Reliable and Optimized Smart Transmission." [Online]. Available online: https://research.ece.cmu.edu/electriconf/2011/pdfs/Nexans_CMU_Presentation_03_09_11.pdf (accessed on 20 May 2025).
78. Bhattarai, B.P.; Gentle, J.P.; Hill, P.; McJunkin, T.; Myers, K.S.; Abboud, A.; Renwick, R.; Hengst, D. Transmission Line Ampacity Improvements of AltaLink Wind Plant Overhead Tie-Lines Using Weather-Based Dynamic Line Rating. In Proceedings of the IEEE Power & Energy Society General Meeting, Chicago, IL, USA, 16–20 July 2017.
79. Transmission & Distribution World. "Hydro-Quebec to Install Dynamic Line Rating System." [Online]. Available online: https://www.tdworld.com/overhead-transmission/article/20966785/hydro-quebec-toinstall-dynamic-line-rating-system (accessed on 9 May 2025).
80. Martini, J.S.C.; Jardinetti, R.B.; Masuda, M.; Saiki, G.Y.; Kayano, P.S.D. Upgrading Transmission Lines in Areas of Severe Environmental Constraints. *IEEE Lat. Am. Trans.* **2012**, *10*, 1931–1939. [CrossRef]
81. Kim, S.D.; Morcos, M.M. An Application of Dynamic Thermal Line Rating Control System to Up-Rate the Ampacity of Overhead Transmission Lines. *IEEE Trans. Power Deliv.* **2013**, *28*, 1231–1232. [CrossRef]
82. World Bank. Smart Grid to Enhance Power Transmission in Vietnam. [Online]. Available online: http://documents.worldbank.org/curated/en/779591468187450158/pdf/103719-WP-P131558-PUBLICVN-Smart-Grid-Book-2-21-16.pdf (accessed on 12 May 2025).

83. Aziz, M.H.A.; Miswan, N.S.; Mohd Kasran, F.A.; Shokri, M.S.M.; Noran, M.N.; Rahim, A.A. Pilot Project on Dynamic Line Rating (DLR) System for Optimal Use of Tenaga Nasional Berhad (TNB) Grid Capacity. In Proceedings of the 2nd International Conference on Technology and Policy in Electric Power and Energy (ICT-PEP), Bandung, Indonesia, 23 September 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 77–81. [CrossRef]
84. Hydro Tasmania Consulting. Dynamic Transmission Line Rating—Technology Review. Rep. No. 208478-CR-001. 2009. [Online]. Available online: https://nanopdf.com/download/dynamic-transmission-line-rating-technology-review_pdf (accessed on 12 May 2025).
85. TransGrid. "Asset Efficiency Improvements." [Online]. Available online: https://www.transgrid.com.au/media-publications/news-articles/transgrid-and-infravision-trial-to-unlock-extra-transmission-capacity/ (accessed on 8 July 2025).
86. Simshauser, P. On Static vs. Dynamic Line Ratings in Renewable Energy Zones. *Energy Econ.* **2024**, *129*, 107233. [CrossRef]
87. Coletta, G.; Vaccaro, A.; Villacci, D. A Review of the Enabling Methodologies for PMUs-Based Dynamic Thermal Rating of Power Transmission Lines. *Electr. Power Syst. Res.* **2017**, *152*, 257–270. [CrossRef]
88. Alvarez, D.L.; Rosero, J.A.; Da Silva, F.F.; Bak, C.L.; Mombello, E.E. Dynamic Line Rating—Technologies and Challenges of PMU on Overhead Lines: A Survey. In Proceedings of the 51st International Universities Power Engineering Conference (UPEC), Coimbra, Portugal, 6–9 September 2016; pp. 1–6.
89. Du, Y.; Liao, Y. Online Estimation of Power Transmission Line Parameters, Temperature and Sag. In Proceedings of the North American Power Symposium, Boston, MA, USA, 4–6 August 2011; pp. 1–6.
90. Fernandez, E.; Albizu, I.; Bedialauneta, M.; Mazon, A.; Leite, P. Dynamic Line Rating Systems for Wind Power Integration. In Proceedings of the IEEE PES Power Africa Conference and Exhibition, Johannesburg, South Africa, 9–13 July 2012.
91. Douglass, D.A.; Grant, I.; Jardini, J.A.; Kluge, R.O.; Traynor, P.; Davis, C.; Gentle, J.P.; Nguyen, H.-M.; Chisholm, W.A.; Xu, C.; et al. A Review of Dynamic Thermal Line Rating Methods with Forecasting. *IEEE Trans. Power Deliv.* **2019**, *34*, 2100–2109. [CrossRef]
92. Rácz, L.; Szabó, D.; Gocsei, G.; Németh, B. Grid Management Technology for the Integration of Renewable Energy Sources into the Transmission System. In Proceedings of the 7th International Conference on Renewable Energy Research and Applications (ICRERA), Paris, France, 14–17 October 2018; pp. 612–617. [CrossRef]
93. Szabó, D.; Rácz, L.; Gocsei, G. A Novel Approach of Critical Span Analysis. In *Lecture Notes in Electrical Engineering*; Németh, B., Ed.; Springer: Cham, Switzerland, 2020; Volume 598, pp. 1025–1031. [CrossRef]
94. Hall, J.F.; Deb, A.K. Prediction of Overhead Transmission Line Ampacity by Stochastic and Deterministic Models. *IEEE Trans. Power Deliv.* **1988**, *3*, 789–800. [CrossRef]
95. Douglass, D.A. Weather-Dependent Versus Static Thermal Line Ratings [Power Overhead Lines]. *IEEE Trans. Power Deliv.* **1988**, *3*, 742–753. [CrossRef]
96. Foss, S.D.; Maraio, R.A. Evaluation of an Overhead Line Forecast Rating Algorithm. *IEEE Trans. Power Deliv.* **1992**, *7*, 1618–1627. [CrossRef]
97. Foss, S.D.; Maraio, R.A. Dynamic Line Rating in the Operating Environment. *IEEE Trans. Power Deliv.* **1990**, *5*, 1095–1105. [CrossRef]
98. Matus, M.; Sáez, D.; Favley, M.; Suazo-Martínez, C.; Moya, J.; Jiménez-Estévez, G.; Palma-Behnke, R.; Olguín, G.; Jorquera, P. Identification of Critical Spans for Monitoring Systems in Dynamic Thermal Rating. *IEEE Trans. Power Deliv.* **2012**, *27*, 1002–1009. [CrossRef]
99. Teh, J. Analysis of Dynamic Thermal Rating System of Transmission Lines. Ph.D. Thesis, The University of Manchester, Manchester, UK, 2016.
100. Phillips, A. *Evaluation of Instrumentation and Dynamic Thermal Ratings for Overhead Lines*; Technical Report; New York Power Authority: White Plains, NY, USA, 2013.
101. Saatloo, A.M.; Moradzadeh, A.; Moayyed, H.; Mohammadpourfard, M.; Mohammadi-Ivatloo, B. Hierarchical Extreme Learning Machine Enabled Dynamic Line Rating Forecasting. *IEEE Syst. J.* **2021**, *16*, 4664–4674. [CrossRef]
102. Keyvani, B.; Whelan, E.; Doddy, E.; Flynn, D. Indirect Weather-Based Approaches for Increasing Power Transfer Capabilities of Electrical Transmission Networks. *Wiley Interdiscip. Rev. Energy Environ.* **2023**, *12*, e470. [CrossRef]
103. European Commission. 2030 Climate & Energy Framework. [Online]. 2024. Available online: https://commission.europa.eu/energy-climate-change-environment/overall-targets-and-reporting/2030-targets_en (accessed on 10 July 2025).
104. IRENA. *Innovation Landscape Brief: Dynamic Line Rating*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2020.