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Reliability assessment of dynamic line rating methods based on conductor temperature estimation

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ABSTRACT

Dynamic line rating techniques are increasingly prevalent in the computation of ampacity for overhead transmission lines. Some of these methods, commonly employed by system operators, rely on real-time measurements to calculate conductor temperature, either directly or indirectly. Despite their widespread usage, the susceptibility of these techniques to measurement errors has been largely disregarded in prior research. In this regard, this paper includes a groundbreaking reliability analysis addressing the impact of measurement errors on various dynamic line rating techniques in overhead lines, based on conductor temperature estimation. Two case studies are presented, incorporating typical errors from simulations. The first case study adopts a standard 24-hour profile for the variables involved in the conductor ampacity calculation. In the second study, Monte Carlo simulations are conducted, in which meteorological variables are randomly assigned with five load levels to evaluate the current's influence on measurement noise sensitivity. The resulting ampacity errors across all methods considered are remarkably high, with mean values exceeding 150% in specific scenarios. This unequivocally demonstrates that the commonly accepted levels of measurement accuracy in these widely used rating techniques yield estimations falling far below acceptable reliability standards.

1. Introduction

Overhead transmission lines (OHTLs) play an important role in the correct operation and control of electric power systems. These assets must be adequately design in order to guarantee that the transmission network can meet the increasing demand, without additional economic outlay for new facilities.

In this regard, OHTLs are required to withstand not only currents derived from normal operating conditions, but also those related to N-1 outages, so that the conductor integrity is not jeopardized and the minimum electrical clearance is not violated due to excessive sag, [1,2]. A key concept in this field is the so-called ampacity, or rating, of OHTLs, defined as the maximum current that can permanently circulate through the conductor without causing overheating, and therefore, the previously mentioned problems.

Static line rating (SLR) is the traditional approach considered by transmission system operators (TSOs), where worst-case conditions are assumed to calculate a constant value of the ampacity either for the whole year, or for each season, [3]. In order to improve the efficiency of this approach, the so-called dynamic line rating (DLR) has arisen as the best suited alternative to enhance the OHTL utilization, maintaining the reliability standards, [4,5]. DLR is based on real-time calculation of the ampacity, considering the measured external conditions (e.g., ambient temperature and solar radiation).

Several techniques for DLR can be found, such as that based exclusively on measurements of the meteorological variables, obtained from weather stations, [6,7]. The main drawback of this approach relies on the high variability of the wind speed and direction, so that the corresponding measurements can only be used locally. Additionally, as presented in [8], the value of the wind speed and its variation have a remarkable influence in the ampacity of the OHTL. To overcome this issue, some DLR methods have been proposed and are used nowadays by TSOs, based on real-time conductor temperature estimation (CTE), [9], using measurements from the OHTL. In this regard, spot and distributed conductor temperature measurements are compared in [10] for DLR in overhead lines. Indirect readings (such as sag or tension of the conductor) can also be used for ampacity calculation, as stated in [11], where the conductor temperature is dynamically estimated using these measurements. With these techniques, the values of wind speed and direction are not required for the DLR calculation. An important observation is that both CTE-based and weather station-based methods for determining DLR fall short in terms of accurately

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representing the entire OHTL using local measurements. This issue can be addressed by increasing the number of monitored spans along the circuit under study, with the ultimate DLR being determined by that of the most critical (limiting) span.

However, the sensitivity to measurement errors of CTE-based techniques must be assessed, given the intermediate calculations used in these methods, in order to evaluate their reliability to properly determine the DLR. In this context, an analysis is presented in this work, where different environment conditions are taken, together with customary ranges of error in the involved measurements. A typical 24-h profile and a set of Monte Carlo simulations are considered as case studies. For each scenario, the real DLR is compared to that calculated using the flawed observations. The obtained errors in the ampacity are grouped according to different levels of load in the OHTL, so that the influence of the current through the conductor can also be analyzed.

The uncertainty in the meteorological variables and its influence in the calculation of DLR has been previously addressed in several studies, [12–14]. Nevertheless, to the best of the authors' knowledge, this is the first analysis regarding the impact of measurement errors in CTE-based techniques where wind speed and direction are not considered in the calculation process. Consequently, the main contribution of this study lies in exposing the weaknesses of the DLR methods based on CTE, quantifying their sensitivity to the typical measurement errors provided by customary equipment. The significance of this analysis is even greater when considering that these CTE-based techniques are recommended in a considerable number of publications as suitable for determining the capacity of overhead power lines.

The remainder of the paper is organized as follows: Section 2 describes the overall procedure of DLR calculation, while the specific methods based on CTE are included in Section 3. The general aspects of the analysis conducted in this work are detailed in Section 4 and the considered case studies can be found in Section 5. Finally, the paper conclusion is included in Section 6.

2. Dynamic line rating

As stated in the introduction of this paper, DLR methods are aimed to calculate the ampacity of the conductor under specific external conditions, given the value of the maximum temperature that the considered conductor can endure permanently, namely T_c^{max}. For this calculation, the thermal equilibrium equation is considered as presented below in its differential form:

$$m \cdot c_p \cdot \frac{dT_c}{dt} = P_r(T_c) + P_c(T_c) - P_s - P_J(T_c, I), \quad (1)$$

where m and c_p are the mass per unit length and the thermal capacity of the conductor, while T_c corresponds to its temperature. P_r and P_c are respectively the radiative and convective heat losses, P_s is the solar heating and P_J is the Joule heating, which can be obtained, for a given value of the current I, using the following expression:

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

with $R_{AC}(T_c)$ being the AC resistance of the conductor at temperature T_c. The values of P_s, P_c and P_r in Eq. (1) depend on the following meteorological variables: ambient temperature, T_{amb}, solar radiation, I_r, wind speed, v_w, and wind direction, α_w. The ampacity of the conductor is obtained assuming steady-state conditions in Eq. (1), yielding the following expression where the value of P_J from Eq. (2) has been substituted:

$$P_r(T_c) + P_c(T_c) - P_s - I^2 \cdot R_{AC}(T_c) = 0. \quad (3)$$

Finally, the DLR of the OHTL is taken as the value of I which satisfies Eq. (3) when $T_c = T_c^{max}$,

$$I = \sqrt{\frac{P_r(T_c^{max}) + P_c(T_c^{max}) - P_s}{R_{AC}(T_c^{max})}}. \quad (4)$$

In general terms, two main categories of DLR methods can be found, [15]: ambient-adjusted DLR (AA-DLR) and DLR with real-time monitoring (DLR-RTM). These approaches are described in the sequel.

2.1. AA-DLR

This method lies on taking the maximum ambient temperature in the region under study, so that the static rating of the OHTL can be accordingly modified. This temperature can be updated with different time scales, leading to daily AA-DLR or even hourly AA-DLR. Although this technique is very easy to be implemented by TSOs, it has proven reduced improvement with respect to SLR, close to 5%, as presented in [16].

In addition, AA-DLR assumes constant wind speed for the whole OHTL, which might lead to inaccurate values of DLR, given the high temporal and spatial variability of this magnitude and its remarkable impact in the calculation of the conductor ampacity, [8].

2.2. DLR-RTM

This approach is based on the use of real-time measurements to calculate the ampacity of the line using Eq. (4). In this context, two techniques of DLR-RTM are highlighted in this paper:

– Methods based on using weather stations to monitor ambient temperature, solar radiation, wind speed and wind direction, [6]. These variables are directly used to calculate the terms P_r, P_c and P_s in Eq. (3). The main disadvantage of this technique relies on the high variability of the wind speed and direction, so that these variables might not represent adequately the thermal state of the conductor.
– CTE-based methods have arisen as an alternative to overcome the above-mentioned variability problem of the wind speed and direction, since these variables are not required in this case for the derivation of the conductor ampacity. These technique are described in detail in the next section.

The reliability of CTE-based methods will be assessed in this paper when typical errors are considered in the variables involved in the calculation of the DLR.

3. CTE-based methods

The general approach of CTE-based techniques for DLR, as summarized in the flowchart of Fig. 1, is described as follows. First, real-time measurements from the OHTL under study are used to estimate the temperature of the conductor, namely $\hat{T}_c$. In this regard, three techniques are considered for the analysis included in this work:

1 Direct measurements of the conductor temperature, e.g., through distributed temperature sensing (DTS) methods, [17]. This is the simplest approach for CTE-based methods, since the measurements of T_c are used with no additional calculation.
2 Sag monitoring, [18]. The maximum sag of the conductor is directly related with its tension in a certain line section. For this purpose, the mechanical properties and the geometry of the span are considered to be known. Once the tension is obtained, the conductor temperature can be calculated using the linear elastic model, [19], together with reference values of the conductor temperature and tension. The maximum sag measurements can be obtained in real time using sagometers.
3 Tension monitoring, [20]. In this case, the tension of different line sections are measured using dynamometers. Then, as in the previous technique, the linear elastic model is used to calculate the temperature of the conductor.

Once the conductor temperature is obtained, the so-called effective wind speed, $\hat{v}_{ef}$, is determined. This variable is defined as the value of the wind speed perpendicular to the span under consideration which causes the same convective cooling as the real wind speed and direction. Finally, the effective wind speed is introduced in the thermal equation, jointly with the ambient temperature and the solar radiation, to calculate the ampacity of the OHTL. The maximum operating temperature of the conductor is considered in this step of the process.

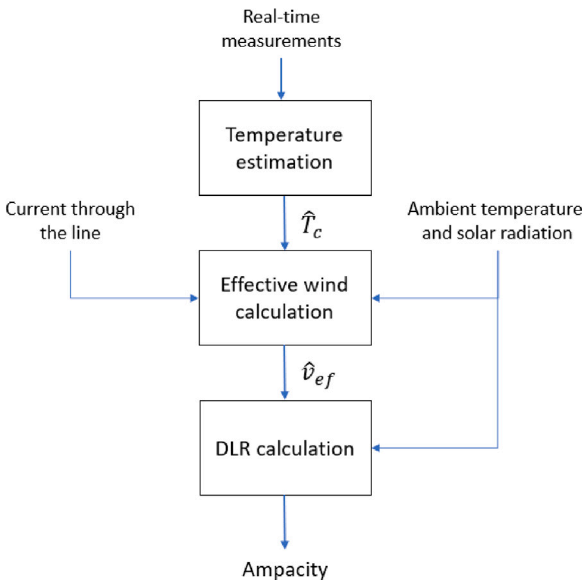

Fig. 1. Flowchart of the CTE-based methods for DLR.

4. Generation of simulated scenarios

In this section, the generalities of the case studies presented later in the paper are described.

In all cases, the CIGRE guide has been considered in this paper to obtain the elements involved in the thermal equilibrium equation, [21]. Similar results were obtained when IEEE standard, [3], was used for the analysis. Maximum operating temperatures up to 90 °C are adopted in Europe for aluminum-conductor steel-reinforced (ACSR) conductors. In this work, the limiting temperature is set to 75 °C, which is considered to be a conventional value for this variable, [22]. In all cases, the direction of the span under study has been taken as reference.

For each simulation, the values of the meteorological variables, together with the current through the conductor, are used to obtain the actual value of the conductor temperature, T_c, by using the thermal equilibrium equation (3) with steady-state conditions. The value of the line ampacity can also be calculated with the simulated meteorological variables and Eq. (4).

Then, given that the radiative losses; solar heating; and Joule heating are not significantly affected by the wind speed and direction, the following equation is used to obtain the actual value of the effective wind speed, v_{ef}:

$$P_c(T_c, v_w, \alpha_w) = P_c(T_c, v_{ef}, 90°) \quad (5)$$

Please note that on the left-hand side of the equation, the convective heat losses are computed using the actual values of wind speed and direction, while on the right-hand side, the wind direction is fixed at 90°, and the wind speed, as per the definition provided in Section 3, represents the effective wind speed.

Finally, with the previous information and assuming that the mechanical properties and the geometry of the simulated span are known, the linear elastic model can be considered to determine the real values of the conductor tension and maximum sag.

Once the simulated values of the variables involved in the different DLR algorithms are calculated, the process of obtaining the measurements corresponding to each of the methods presented earlier was carried out. In this context, Table 1 includes the observational errors for the variables provided by the weather station, thermal sensor, sagometer and dynamometer. All of these errors are taken as customary values from commercial sensors, and the percentage values are referred to the corresponding readings. The involved magnitudes are considered as normal random variables, the mean values being those calculated in the previous step and the standard deviations are obtained from the values in Table 1. For a generic variable x:

Table 1
Measurement errors of the variables involved in the DLR calculation.

Variable	Error
Ambient temperature	0.1 °C
Solar radiation	1%
Wind speed	0.1 m/s
Wind direction	1°
DTS temperature	1 °C
Conductor sag	0.1 m
Conductor tension	3%

$$x^{meas} \sim \mathcal{N}(x^{sim}, \sigma)$$

where x^{meas} and x^{sim} are the measured and simulated values of the variable x, respectively, and σ is the corresponding standard deviation of the measurement error.

With the previous distribution, noisy values are randomly assigned to the measurements and the DLR is calculated according to the procedure presented in Fig. 1 for the three CTE-based methods presented in the previous section. Finally, these values are compared to the real ones in order to obtain the corresponding errors.

5. Case studies

In this section, two case studies are presented to assess the reliability of CTE-based methods, compared to DLR-RT techniques using measurements of wind speed and direction.

5.1. 24-h lasting simulation

In the first case study of this paper, typical 24-h profiles have been considered for the variables involved in the calculation of DLR. Fig. 2 includes the evolution of the environment variables, obtained from real-time measurements from a weather station Froggit hp1000se PRO. In this context, even though these meteorological variables are obtained from an actual weather station, the readings associated with them are presumed to be flawless. Subsequently, artificial noise is introduced following the procedure outlined in the previous section. Otherwise, the true value of the DLR would remain unknown, rendering error assessment unfeasible. Finally, Fig. 3 represents the variation of the current through the line, in percentage with respect to the rated current of the OHTL, I_n.

For the DLR calculation, the considered conductor is an ACSR 455-54/7 (CONDOR), although similar results were obtained for different conductors. Regarding the OHTL under study, a leveled span has been analyzed, its length being 250 m. The rated power and voltage are taken as 400 MVA and 220 kV, respectively. Finally, the sample period has been taken as 5 min.

The DLR values obtained for the three CTE-based methods are represented in Fig. 4, where a zoom plot of is included to enhance the clarity. The ampacity calculated using measurements of wind speed and direction, taken from the weather station (labeled as WS in Fig. 4), is also included for comparison purposes, together with the simulated DLR. It can be noticed that the evolution of the real DLR in Fig. 4 (dashed-black line) is mainly influenced by the variation of the wind speed presented in Fig. 2, giving evidence of the importance of this particular variable in the line ampacity.

In light of the representation in Fig. 4, extremely high errors are observed in the calculated DLR, particularly when the load of the OHTL is reduced. In order to quantify these errors, Fig. 5 represents, in descending order, the absolute values of the relative errors, $|E_r|$, for the same four techniques included in Fig. 4. The x-axis in this graph stands for the total number of cases in which the DLR is calculated.

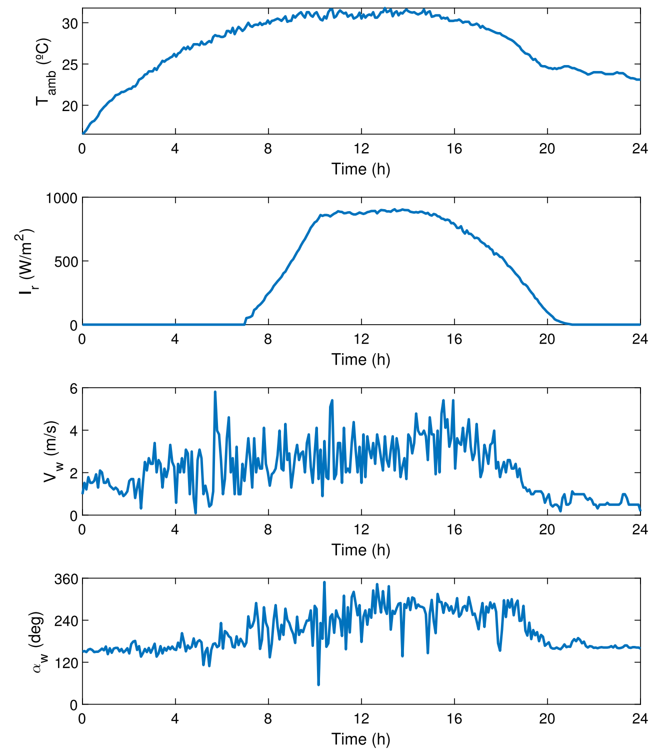

Fig. 2. Evolution of the environment variables for the 24-h simulation.

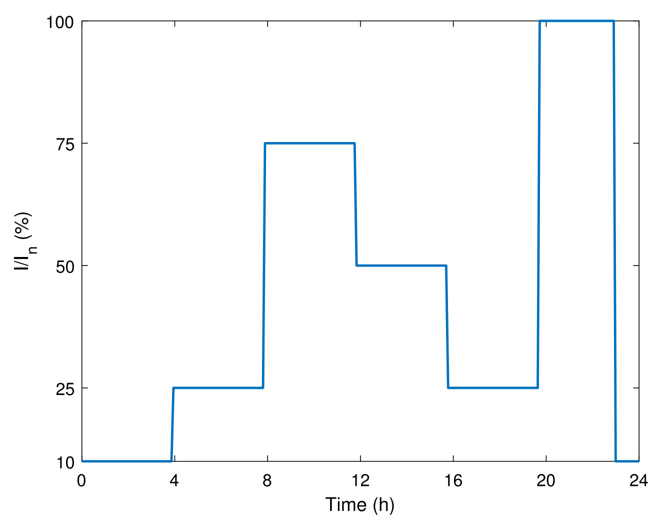

Fig. 3. Current through the line for the 24-h simulation.

It can be noticed that CTE-based techniques provide substantially higher errors in the calculation of the DLR, compared to the method using measurements of wind speed and direction. In order to determine the cause of these errors, the deviations in the estimated conductor temperature and effective wind speed are addressed. In this context, Figs. 6 and 7 include the sorted relative errors in the estimated values of T_c and v_{ef}. In Fig. 7, the y-axis of the graph has been limited to 100% for clarity purposes.

For the three methods, the relative errors obtained are superior to 50% in more than one third of the total cases, giving evidence that the high sensitivity in the calculation of the effective wind speed to the measurement errors. If Figs. 6 and 7 are compared, it can be concluded

Table 2
Variation range of the meteorological variables in the simulations.

Variable	Units	Range
Wind speed	m/s	[0, 10]
Wind direction	deg	[0, 180]
Solar radiation	W/m^2	[0, 800]
Ambient temperature	°C	[0, 40]

Table 3
Mean magnitudes of the relative errors, in percentage.

Load level (%)	WS	DTS	Tension monitoring	Sag monitoring
10	1.02	47.89	124.61	158.99
25	1.05	23.22	88.48	137.20
50	0.93	5.42	35.99	86.04
75	1.15	2.68	13.52	44.11
100	1.06	1.44	6.45	22.78

that relatively small deviations in the estimated (or measured) conductor temperature, lead to high errors in the calculated wind speed and, therefore, the OHTL ampacity.

5.2. Monte Carlo simulations

In this case study, a set of Monte Carlo simulations are used to characterize the error in the DLR calculation. Five load levels are considered to compare the performance of the different techniques, namely: very-low load (10% the rated current of the OHTL), low load (25%), medium load (50%), high load (75%) and full load (100%). A total number of 10^6 simulations are considered for each load, where the environment variables are randomly selected within the range shown in Table 2. The considerations regarding the OHTL and the conductor are the same as in the previous case study.

Fig. 8 shows, for each DLR technique and load level, a box-plot of the corresponding relative errors. In this kind of representation, the red horizontal lines are the median values, while the blue boxes include the 50% of the resulting relative errors. Additionally, Table 3 summarizes the mean magnitudes of these errors. As in the first case study, the results obtained for the method based on measurements of wind speed and direction have also been included as reference. In light of the presented results, the following comments are in order:

- The errors in the WS method are not influenced by the load level, since it does not require the calculation of the effective wind speed.
- The three CTE-based methods present higher errors than the technique based on measurements of wind speed and direction, regardless the load level.
- In all cases, a performance deterioration can be observed as the load of the OHLT is reduced, the errors being higher and more disperse. With low current through the conductor, its temperature is close to that of the ambient, leading to a higher sensitivity to the measurement errors.
- The DTS-based method has lower errors compared to the other techniques based on CTE, given that no additional calculation is required to obtain the conductor temperature.
- The CTE-based techniques considered in this paper showed clearly unacceptable errors for load levels under 50%, the usual situation when N-1 contingency restrictions apply.

6. Conclusion

In this work, a reliability assessment is presented regarding CTE-based methods for DLR in OHTLs. Two different analysis are conducted where the resulting errors in the ampacity are compared with those obtained using measurements from the wind speed and direction. In all

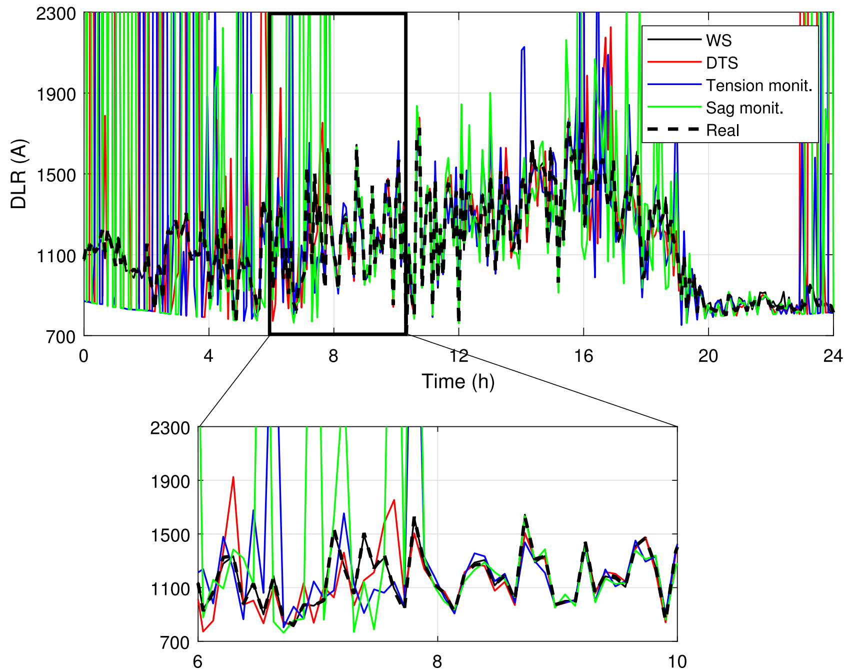

Fig. 4. DLR calculated using CTE-based methods and weather stations.

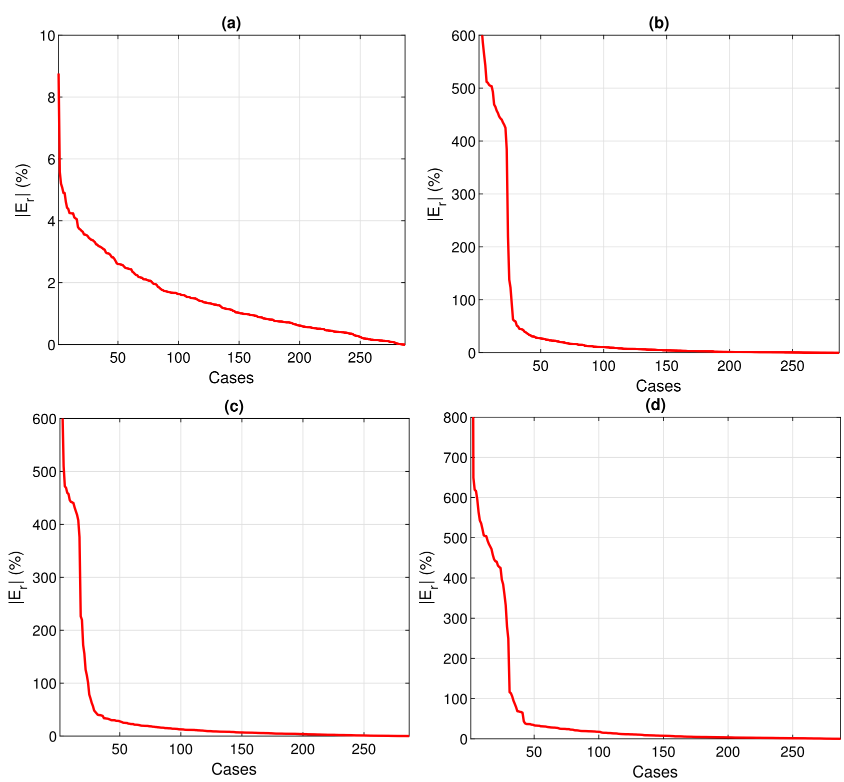

Fig. 5. Errors obtained in the calculation of DLR: (a) Weather station, (b) DTS, (c) Tension monitoring, (d) Sag monitoring.

cases, customary errors are assumed in the measurements taken from the simulations.

First, a typical 24-h profile has been considered for all the variables involved in the calculation of DLR, where it has been observed that CTE-based techniques present unacceptable errors in the resulting ampacity. These errors are caused by the high sensitivity in the calculation of the effective wind speed to small deviations in the estimated conductor temperature.

Then, a Monte Carlo-based analysis has been carried out, where five levels of load in the circuit are considered and random values were assigned to the meteorological variables. The sensitivity to measurement errors resulted to be especially higher for loads under 50% the rated current for all the CTE-based techniques. Particularly for the sag-monitoring method, the mean value of the absolute error reached 158.99% for 10% load level. The presented results prove that typical values of accuracy in the measurements used in CTE-based methods

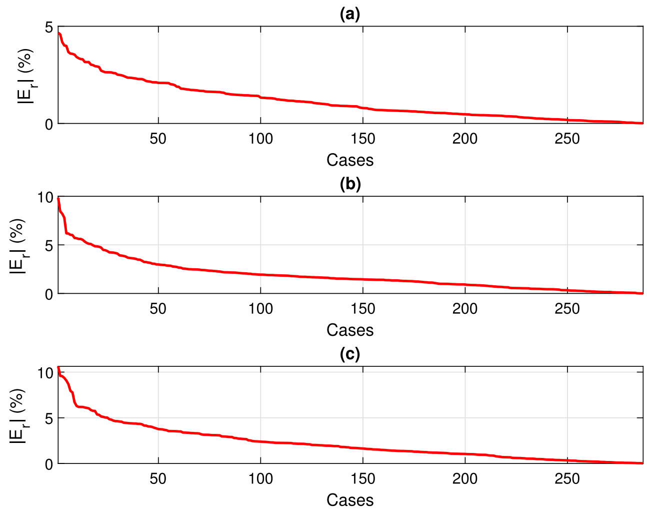

Fig. 6. Errors obtained in the estimated conductor temperature: (a) DTS, (b) Tension monitoring, (c) Sag monitoring.

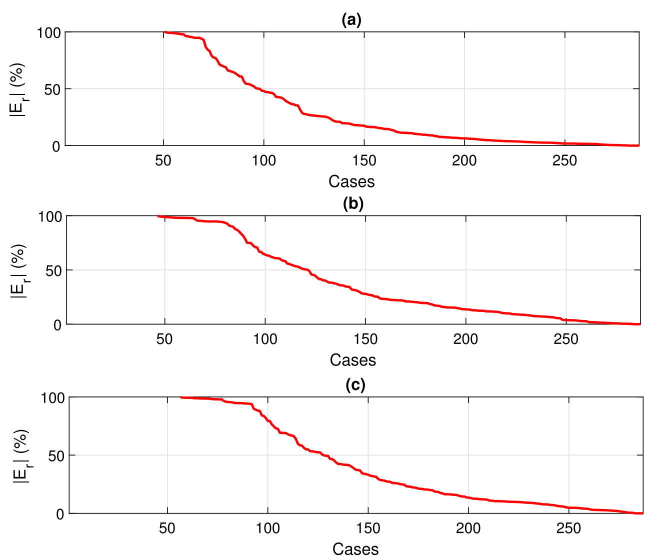

Fig. 7. Errors obtained in the estimated effective wind speed: (a) DTS, (b) Tension monitoring, (c) Sag monitoring.

lead to major issues in the estimation of DLR, so that alternative approaches should be considered, especially for reduced load levels. In this regard, a general recommendation might be to avoid the use of these DLR calculation methods. However, the field measurements involved in these methods, i.e., conductor temperature, maximum sag or tension, offer real-time information about the line condition, which can be used in a complementary manner when taking corrective or planning measures.

With respect to DLR methods that exclusively rely on measurements from weather stations, these techniques fail to consider spatial variations in wind speed and direction. However, the findings presented in this paper demonstrate that these approaches exhibit significantly greater robustness to measurement errors when compared to CTE-based methods.

CRediT authorship contribution statement

M.A. González-Cagigal: Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **José A. Rosendo-Macías:** Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alfonso Bachiller-Soler:** Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Juan Carlos del-Pino-López:** Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization.

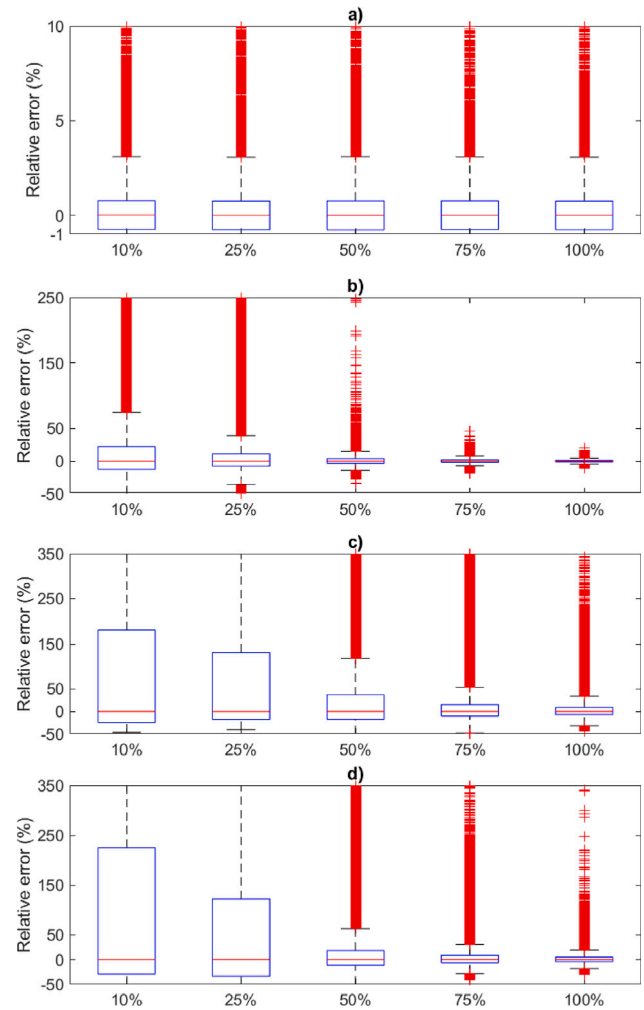

Fig. 8. Box-plot of the obtained relative errors in DLR: (a) Weather station, (b) DTS, (c) Tension monitoring, (d) Sag monitoring.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Share link has been provided

24 h profile for DLR (Original data) (Mendeley Data).

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