ANALYSIS OF DIFFERENT DYNAMIC LINE RATING SYSTEM CONFIGURATIONS IN A DISTRIBUTION LINE

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ABSTRACT

Different dynamic line rating systems have been developed for monitoring overhead lines. The aim of these systems is to estimate the actual rating of electric lines and use all the available capacity to achieve a more efficient use of the existing lines. Some systems have been installed in a distribution pilot line to evaluate the different uncertainty levels. Systems that measure weather parameters, conductor temperature and tension are assessed. The results show that in conductor temperature and tension based systems the uncertainty decreases as the conductor temperature increases.

INTRODUCTION

The static ratings of the distribution overhead lines are calculated with conservative weather condition values (low wind speed, high ambient temperature, high solar radiation). Dynamic line rating (DLR) systems provide the system operators with information about the actual rating of the lines. There are several DLR system technologies. Some systems are based on weather measurement: standard commercial sensors for ambient temperature, wind speed and solar radiation are located close to the line or existing weather stations are used. Other systems are based on direct measurements of the conductor temperature, tension and sag. Furthermore, the DLR systems are usually a combination of direct measurements and weather measurements.

When a DLR system is chosen both the cost and the uncertainty are taken into account. The aim of this paper is to evaluate the uncertainty of different DLR systems, including direct tension and conductor temperature measurement based DLR systems and weather based DLR systems. For this purpose, some systems have been installed in a distribution line.

DYNAMIC LINE RATING AND OVERHEAD CONDUCTOR THERMAL AND MECHANICAL BEHAVIOUR

The rating of a line is limited by a maximum allowable temperature and a sag limit that ensure safe operation as well as integrity of the conductor material. If the conductor reaches a higher temperature than the thermal limit, the involved risks are the loss of the properties of the conductor and a sag increase.

Nowadays, ratings are fixed by conservative static values. Depending on the country and the technical rules, the ratings are seasonal or remain equal for a year. In all those cases the rating is calculated with heat balance equations. In these equations the influential parameters are the meteorological ones, due to the cooling and/or heating effect of the weather.

Overhead conductor thermal model

The CIGRÉ [1] and IEEE [2] thermal models are used to calculate the actual rating (also called dynamic line rating or ampacity) of overhead conductors. In the overhead lines, the weather influences the actual rating, thus, ampacities vary steadily. The common practice is to monitor the influential parameters and to use the measured values to calculate the ampacity with the model. Then, the rating is calculated by a heat balance equation, as shown in equation (1).

$$I = \sqrt{\frac{P_c + P_r - P_s}{R_{ac}(Tc_{max})}} \qquad (1)$$

Where P_c is the convective cooling of the conductor, P_r the radiative cooling, P_s the solar heating and R_{ac} the conductor resistance at its maximum allowable temperature.

When the line is carrying a current equal to its actual rating, the joule heating and the convection cooling are the most influential. On the contrary, the radiative cooling effect is low compared to convective losses. The solar heating is low as well, especially in cloudy days and does not have influence during night.

Conductor mechanical model

The conductor mechanical model [3] is defined by the catenary equations of the span. Thereby, there is a relationship between tension, sag and temperature of a conductor. One of the equations used in the mechanical models and in this work is equation (2).

$$L = L_0 + L_0\left(\alpha(T - T_0) + \frac{H - H_0}{E \cdot A}\right) \qquad (2)$$

Where L is the conductor lenght, L_0 is the initial lenght, T_0 and H_0 are the stringing temperature and tension respectively, α the coefficient of linear expansion of the conductor, E is the elastic modulus and A the cross-sectional area.

INSTALLED MONITORING SYSTEMS

The DLR systems have been installed in a 30 kV distribution line and measurements have been recorded with a sampling period of one minute. As it is shown in Figure 1, the installed monitoring system consists of:

1. System for measuring the conductor surface temperature and current (SMT, Arteche).
2. Ultrasonic anemometer for measuring the speed and the direction of the wind.
3. Solar radiation and ambient temperature sensors.
4. Load cell for measuring the value of the mechanical tension of the conductor.

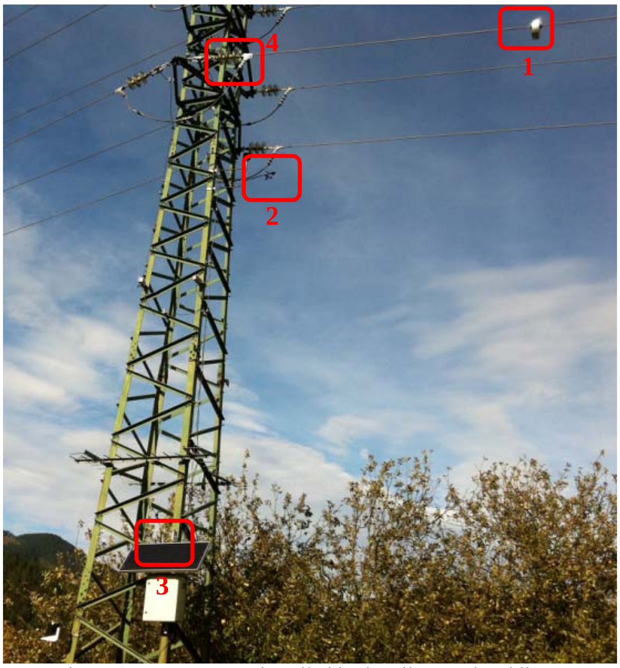

Figure 1: DLR systems installed in the pilot overhead line.

During the monitoring period, the average ambient temperature was 9.5 ºC and the line carried an average intensity of 165 A. The measured mean wind speed is 1.51 m/s and the maximums 14 m/s. In most days wind speed increased in the afternoons reaching between 2 and 5 m/s. Although it is not a windy place, conductor temperatures were low (13.4 ºC average) due to the low temperature and low load. In the registered data, the solar heating has contributed a 15 % to the heating of the conductor, whereas the other 85 % has been due to the joule and magnetic heating of the conductor. The wind cooling was of 85 % and the radiative ones of 15 %.

ANALYSED SYSTEMS

The evaluated systems are the weather parameter based system, conductor temperature based system and tension based system. In the next paragraphs the calculations made in each step and the measured parameters are explained.

Weather parameters based system

These systems are cheap and cost-effective and have been used in several pilot projects [4,5]. The parameters measured are the wind speed and direction, ambient temperature and solar radiation. The actual rating is calculated directly, solving equation (1) (see Figure 2).

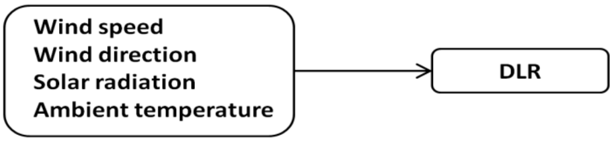

Figure 2: DLR calculation process in weather system.

Conductor temperature system

There are several commercial devices to measure the conductor temperature [6,7]. This system does not record wind measurements, instead, the effective wind of the line is calculated with the thermal model. Conductor temperature, intensity, solar radiation and ambient temperature measurements are required to calculate the actual rating in two steps (Figure 3). In a first step, the effective wind is calculated with the thermal model. In a second step, the calculated wind and measurements of ambient temperature, and solar radiation are used to solve equation (1) and obtain the rating.

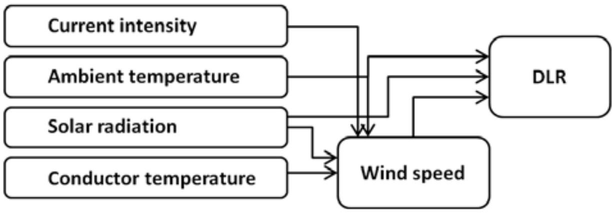

Figure 3: DLR calculation process in conductor temperature system.

Tension system

Tension systems are based on the conductor tension measurements of load cells [8]. As the conductor temperature is related to tension and sag, it is possible to calculate the conductor mean temperature along the span solving equation (2). In a second step, the effective wind is calculated with the thermal model, as it is done in conductor temperature system. With the calculated wind and other measurements, the DLR is calculated with equation (1). A diagram of the calculation process can be seen in Figure 4.

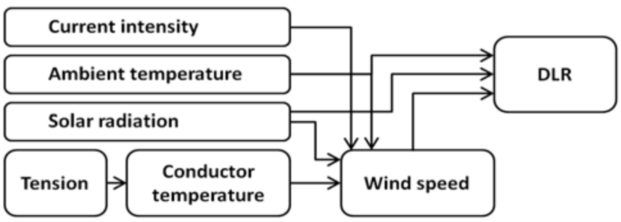

Figure 4: DLR calculation process in conductor tension system.

DLR UNCERTAINTY RESULTS

The ampacity uncertainty due to the instrument measurement inaccuracy has been evaluated for each system mentioned before. The DLR rating uncertainty level has been calculated as the difference between the maximum ampacity and the minimum ampacity. The accuracy of the instrumentation is summarized in Table 1.

Table 1: Measurement sensor errors.

Measured parameter	Measurement error
Wind speed	2%
Wind direction	3º
Ambient temperature	1ºC
Solar radiation	5 %
Conductor surface temperature	1ºC
Intensity	2%
Tension	2%

Weather system uncertainty

With weather parameter based system, the highest uncertainty in absolute terms is low, always under 40 A and with a mean value of 7,5 A (see Figure 5). In relative values, it does not exceed 10 % of the lowest DLR. The thermal model shows low sensitivity to instrumentation measurement errors.

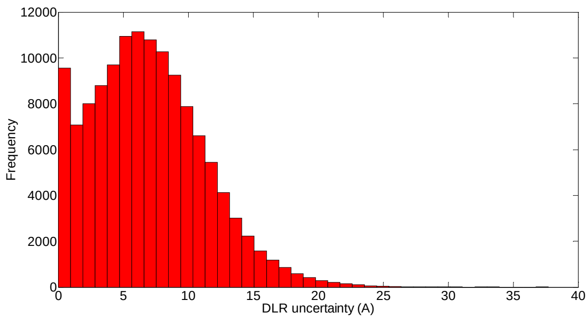

Figure 5: Histogram of the DLR uncertainty in the weather system.

The highest cooling type in a conductor is the convective cooling, and in this line, the computed convective losses represent the 85 % of the total refrigeration. The importance of wind in the refrigeration of an overhead conductor is evident and this can also be noticed in the uncertainty. In Figure 6, DLR with positive and negative wind measurement errors can be seen. The wind in the graphics has been calculated from the speed and direction measurements and it has been converted to an equivalent perpendicular wind speed. Although the ambient temperature and solar radiation uncertainties have been computed as well, the DLR uncertainty follows exactly the effective wind uncertainty.

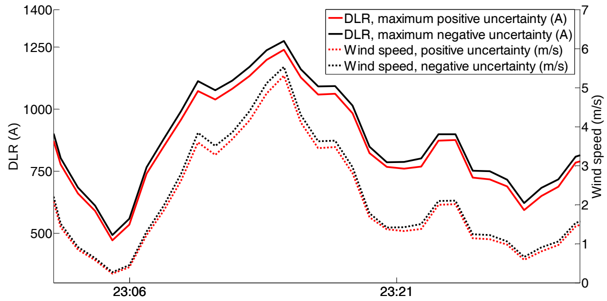

Figure 6: maximum and minimum DLR and measured wind speed with uncertainty.

Conductor temperature system uncertainty

In conductor temperature system, the uncertainty values show a high dependence on the difference between the measured conductor surface temperature and the ambient temperature. The lower the difference between both temperatures the higher the uncertainty will be [9]. The wind is calculated with the thermal model and the error made in calculating the wind when the conductor temperature is similar to the ambient temperature can be high and this implies a high DLR uncertainty. For this reason and the fact that in the measured data the difference between conductor and ambient temperatures are low, the uncertainties obtained in the calculations are high (see Figure 7).

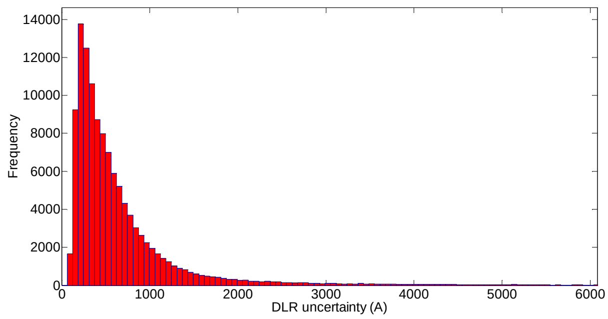

Figure 7: Histogram of the DLR uncertainty with conductor temperature system.

In Figure 8 DLR uncertainty can be seen. The ampacity uncertainty increases when the temperature difference between conductor and ambient temperature decreases.

The available conductor temperature data ranges from -0.5 to 42.4 ºC with an average value of 13.7 ºC, therefore it is not possible to assess the uncertainty at higher temperatures with actual data. However, the uncertainty out of this range can be calculated theoretically, increasing intensity and calculating the equivalent temperature with the thermal model. Then, with the new intensity and temperature, the DLR is calculated. In Figure 9, ampacity uncertainties are shown for different intensities. The curves are smoother than the DLR curves in Figure 8 because the model inputs have been averaged 15 minutes to see better the uncertainty in each case.

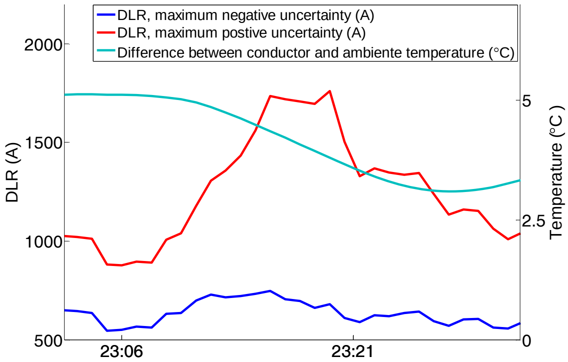

Figure 8: Maximum and minimum DLR and difference between conductor and ambient temperature.

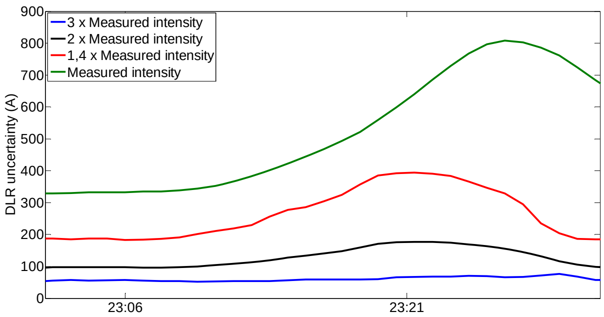

Figure 9: Uncertainty levels for different intensities.

In Figure 10 the histogram of uncertainty for 200 % of the measured intensity is shown. With this current increase the average conductor temperature is 39 ºC and the uncertainty has decreased notoriously, if it is compared to the measured histogram of Figure 7, in which the uncertainties are calculated with the measurements.

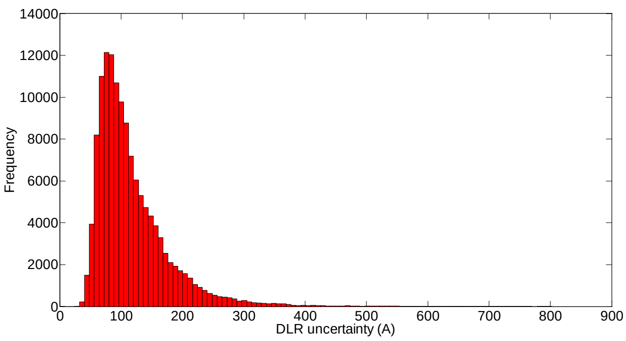

Figure 10: Histogram of the DLR uncertainty for a 200 % of measured intensity.

Tension system uncertainty

The theoretical relationship between the tension and temperature of a conductor is given in equation (2). However, the theoretical expansion coefficient does not show a good agreement between the recorded values and the calculated ones. Instead, it has been calculated another coefficient [10].

In Figure 11 the tension-temperature curves for each coefficient and the measured values are shown. The new coefficient estimates better the conductor temperature at high temperatures. Between 0 and 5ºC the calibration curve is more sensitive to measurement errors as can be seen in Figure 12. In that Figure, measured tension and maximum and minimum DLR are shown for the same period of time of Figures 6 and 8. In Figure 13, the histogram of the uncertainties is shown.

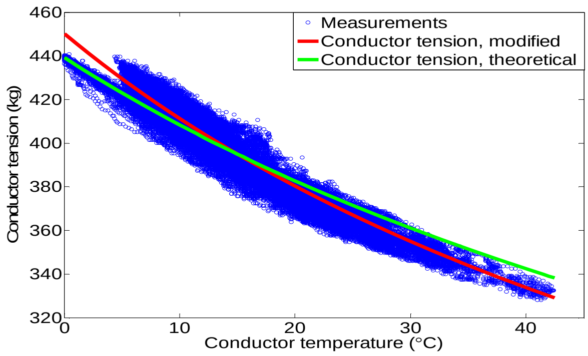

Figure 11: Tension-temperature curves with theoretical and modified linear expansion coefficients.

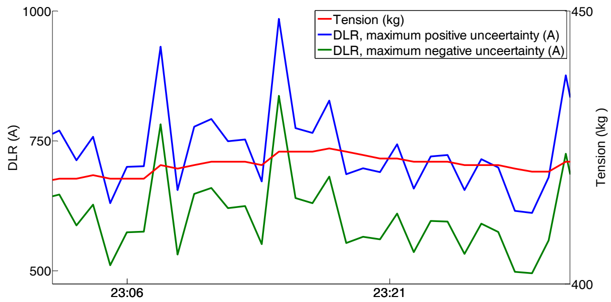

Figure 12: maximum and minimum DLR and tension measurements.

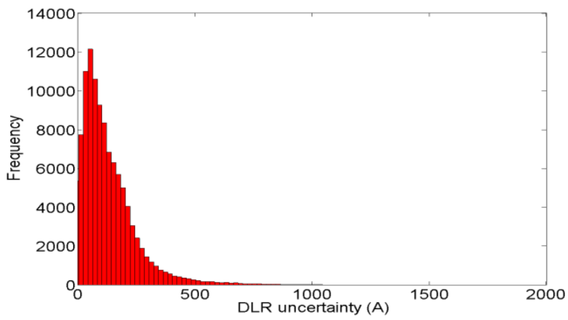

Figure 13: Histogram of the DLR uncertainty of the tension system.

CONCLUSIONS

A distribution pilot line with different DLR systems has been installed to evaluate their uncertainty level. Three different DLR systems have been evaluated. The first system measures weather magnitudes, the second measures conductor temperature and the third system measures conductor tension. The systems that measure conductor temperature and tension calculate the wind speed using the thermal model of the conductor and the measurements of other weather magnitudes and current intensity.

The influence of the measurement instrumentation uncertainties on the ampacity uncertainty has been analysed. The influence depends on the load level of the line. The results show that in conductor temperature and tension based systems the ampacity uncertainty decreases as the conductor temperature increases with high load values. In these systems the ampacity uncertainty is related to the uncertainty of the calculated wind speed. The reason for the high ampacity uncertainty is the high sensitivity of the thermal model in the wind calculation when the differences between the conductor surface temperature and the ambient temperature are low.

Acknowledgments

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