Dynamic Management in Overhead Lines: A Successful Case of Reducing Restrictions in Renewable Energy Sources Integration

R. Mínguez(1), R. Martínez(2), M. Manana(2), A. Arroyo(2), R. Domingo(2), and A. Laso(2)

(1) Viesgo Distribución Electrica S.L
(2) University of Cantabria

Abstract. The total renewable wind energy capacity of Spain currently accounts for more than 20 % of the total installed energy capacity, which makes integration into the grid challenging for wind farm owners as well as Distribution System Operator (DSO). Electrical companies require new techniques to integrate renewable energies safety and with low investment costs. Dynamic line rating (DLR) is one of these techniques, and is used by DSOs to maximise the capacity of existing infrastructure. This paper presents a successful case of DLR application by a DSO over several years to reduce the time that wind farms were out of service due to an excess of electrical energy generated. Over the period from January 2015 to September 2018, the application of the DLR technique prevented 4,100 hours of out-of-service time, increasing the energy supplied by the wind farms by 70.9 GWh and by extension saving 7,800 tons of CO2.

Keywords: Ampacity · Dynamic Line Rating · Overhead Lines · Renewable Energy Integration · DSO.

1 Introduction

The drastic emission reductions stipulated in the COP21 agreement will only be possible by replacing fossil fuels with renewable generation. These types of energy, however, require a flexible power system, resulting in new ways of operating the electrical system. Electrical companies require new techniques and tools to be able to adapt to these new requirements with balanced investments. Dynamic Line Rating (DLR) is a tool that can be used to maximise the use of existing infrastructure [1–3]. CIGRE TB601 and IEEE 738 [4, 5] are standards that can estimate the DLR using different algorithms. Additionally, the technical brochure CIGRE 498 [6] proposes a guide for real-time monitoring of the system, and the technical brochure CIGRE 299 [7] details a guide for selecting the weather parameters for bare overhead conductor ratings.

In Spain in 2015, the total renewable wind energy capacity exceeded 20 % of the total installed capacity of the country [8]. However, restrictions arising from the lack of transmission or distribution network capacity was 0.3 % of the wind resource [9], effectively replacing the renewable energy available by non-renewable sources. The integration of renewable energies, particularly wind energy, into existing infrastructure, is an important undertaking that would allow flexibility in the operation of the grid [10]. The main problems affecting wind power integration are that backup power plants are needed to ensure consistent electricity availability, and that the wind is significantly variable. The construction of new electrical lines or the adaptation of existing ones to connect consumers to new renewable energy sources presents a challenge [11]. Further, certain legal and environmental issues make it even more difficult to build new lines or re-power existing ones [12, 13].

There are several options for increasing the integration of renewable energies and reducing the restrictions preventing their full potential: new infrastructure; increase in the voltage level of existing infrastructure; use of low-loss or high-capacity conductors [14]; changes in tower design [15]; and dynamic management [16, 17].

Viesgo is a distribution system operator (DSOs) of the Spanish energy system. The company distributes and supplies electricity to more than 745,000 customers over a distribution network spanning 31,150 kilometres across the North of Spain. Current efforts of Viesgo are focused on supplying excellent service and network availability, involving sizeable investments in new infrastructure and intense network maintenance.

Wind farms have better public acceptance than high-voltage overhead lines, and the licensing process necessary to build a new wind farm is typically simpler than the process of building a new high-voltage line. As a result, often the infrastructure necessary to evacuate the renewable wind energy is not ready within the time requested. Due to this fact, and although the creation of a new line is planned, a more immediate solution (in this case DLR management) was necessary.

Viesgo has implemented a DLR management system that allows the operation of overhead lines above their static rate, and consequently the safe integration of more energy into the grid network. The implementation of this system has gone through different stages, from the pilot system to the final system, all with 132 kV network monitoring. Previous experience [18] has shown the advantages of moving from static thermal rating operation to seasonal static thermal ratings. Dynamic operation is a step further in the optimisation of the use of existing infrastructure. In Spain, the Royal Decree 223/2008 of February 15, 2008 set forth regulations on technical conditions and safety guarantees in overhead line (OHL). Its ITC-LAT 07, section 4.2.1, establishes the calculation conditions for obtaining the static rate of conductors from the maximum current density in the permanent regime, applying a correction factor according to the geometry of the conductor. Before implementing the plan, a Monte Carlo analysis was performed. It showed that eleven lines were most likely to operate over their static rate. As consequence of additional benefits of this technology, all 49 lines were monitored and operated dynamically. Besides increasing the line capacity, monitoring for DLR has other benefits, providing information on conductor temperature which allows better asset management, and improving operation efficiency which allows better work scheduling. Finally, it supports enhanced operational security in emergencies and line failures.

This paper presents a real, successful case of DLR application by a DSO over several years to reduce wind power curtailment. The line selected for this study is a 132 kV line, located in the north of Spain (see Figure 1) its conductor is 94-AL1 / 22-ST1A (according to Regulation EN 50182 [19]). According to the manufacturer (General Cable Company), this type of conductor consists of two outer layers of aluminium (18 + 12) and two inner layers of galvanised steel (6 + 1). Its total cross-sectional area is 116.2 mm^2 and its electric resistance in DC at 20 C is 0.3067 Ω/km. Taking these properties into account, the maximum current of the line in static conditions is 314 A. This line has been selected as it exhibits the optimal conditions for DLR: restrictions (a high number of hours of curtailment) and a high share of the total wind energy generated. Further, it was the first line in which DLR was implemented, and thus more reliable data is available.

L.A.T.	132 kV
Conductor	LA-110
Diameter	14.0 mm
Maximum Tª	80 ºC
Static Rate	314 A
Length	15 km

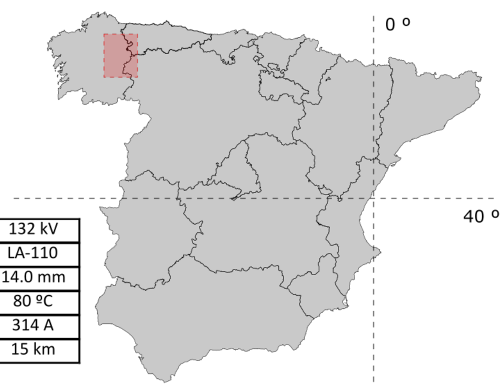

Fig. 1. Characteristics and location of the studied line in Spain.

This paper presents the successful case of implementation of a DLR system. The evolution of the DLR system developed and implemented is provided in Section 2. The results of the DLR application is proposed in Section 3. Finally, Section 4 summarizes the conclusions of the application of the methodology.

2 System evolution

The dynamic management system implemented by Viesgo began with the development of the project DYNELEC: Dynamic Management in Lines (INNPACTO IPT-2011-1447-920000) partially supported by the Spanish Ministry of Economics and developed by Viesgo, University of Cantabria, and Arteche Smart-Grid.

The implementation of the current dynamic management system of Viesgo has moved through two main phases: the pilot phase from 2011 to 2015, and the industrialisation phase since 2016. In each of these two main phases, the system moved through several stages. The first stage was a dynamic system monitored through one weather station for each line, located in the least-refrigerated point as determined through a micro-climatic study. This system used a steady-state algorithm, based in CIGRE TB601 [4] and IEEE 738 [5] equations for ampacity and temperature calculation, adapting them for the real operation. The adaptation made it for real operation were:

1. **Solar radiation.** Both, CIGRE and IEEE, in their first versions of the standards for calculating the ampacity and the temperature in overhead lines, obtained the solar heating through theoretical values.In the last versions, CIGRE TB601 [4] and IEEE 738 [5], the use of the solar radiation monitoring systems is treated in a superficial way. In the case of the studied system with CIGRE equation, the solar radiation monitoring system measures the direct radiation and for the calculation, the diffuse sky radiation and albedo are considered negligible.

$$P_s = \alpha_s.D.\left[I_B.\left(sin(\nu) + \frac{\pi}{2}.F.sin(H_s)\right) + I_d.\left(1 + \frac{\pi}{2}.F\right)\right] \quad (1)$$

   Being P_s the solar heating, α_s absorptivity of conductor surface, D conductor diameter, I_B direct radiation, ν solar beam angle, F the albedo, H_s solar altitude and I_d diffuse radiation. If I_d and F are negligible:

$$P_s = \alpha_s.D.I_B.sin(\nu) \quad (2)$$

2. **Safety coefficient.** Conductor manufacturers provide the maximum permissible conductor temperature. This value is used to calculate the ampacity of the conductor. In the studied system the value of the maximum temperature is reduced in around a 20 % to use it as a safety coefficient.
3. **Operational maximum conductor temperature.** As pointed out above, overhead lines are usually operated with the maximum conductor temperature value with a safety coefficient but there are some situations in which lines have to be operated with a lower maximum temperatures. This situations are lines with sag limitations or hot spots.

During the development of the pilot, several algorithm improvements were made to obtain temperature estimation results closer to the measured conductor temperatures:

1. **Systematic error correction.** A deep study of the correlation between the input variables of the conductor temperature calculation algorithm (wind speed, wind direction, ambient temperature, solar radiation and current) with the error in conductor temperature calculation showed that there were

several systematic errors due to the ambient conditions and the current of the system. Consequently, several fitting curves of the relationship of each input parameter with the error in temperature calculation are created. For some input parameters, the parameter is divided in ranges producing several fitting curves. Finally, the fitting curves are applied in real time to estimate the error depend on the input variables. This error is subtracted from the conductor temperature calculation obtaining a performance enhancement .

2. **Unsteady- state calculation.** The implementation of the unsteady-state algorithm to calculate the conductor temperature allowed obtaining a improvement in the results with lower errors than the previous system. This procedure uses the thermal balance equation but adding a thermal inertia term. This term calculates the conductor temperature taking into account the resistance to the temperature change in the conductor.

The location of the weather station in the least-refrigerated point resulted in some difficulties with mobile card durability and signal power level. Due to this fact, the upgrading to two weather stations per line of the pilot (the second located in the substation) allowed avoidance of the problems arising from using only one weather station and creation of a multi-monitoring system.

At the weather stations sensor data, excluding the wind, is taken every second. The ultrasonic anemometer only allows a ten-second request and returns a self-calculated average for that time to the weather station core. Mechanical anemometers are not recommended, as stated in standard IEEE 738 [5], due to the high errors they produce at very low wind speeds.

The margins of error of the sensors are shown in Table 1. The frequency of ampacity and conductor temperature calculation was every 4 minutes during the pilot phase, but was increased to 1 minute in the industrialisation phase. The weather stations had a Modbus table, with the average for every variable value over the previous minute ready at any time.

The server is queried every minute for new data to process new calculations. The data from the different sources was requested from the same software that performs all the calculations, so that everything is managed together via different developed communication connectors.

Therefore, if the integration of new sensors is required, only new connectors must be developed The resulting data was stored in a non-relational database to allow a fast response from user queries when analysing long periods of data. Figure 2 shows the architecture of the system.

This system determined the ampacity and conductor temperature corresponding to the most restrictive weather conditions. In case of weather stations failures, the ampacity and temperature could be estimated by a weather station close to the line. Once the pilot was finished, the industrialisation phase started. The aim of this phase was to spread the dynamic management system to all of the 132 kV network. During this phase, the implementation of an unsteady-state algorithm for ampacity and temperature was an important point.In Figure 3, the on-field infrastructure layout is shown: the weather stations ($WS1$ and $WS2$) and the power quality analysers ($PQA1$ and $PQA2$) were placed inside

Table 1. Resolution and error of WS magnitudes.

	Resolution	Error
Wind speed	0.03 m/s	3 %
Wind direction	0.2 °	3 °
Ambient temperature	0.1 $°C$	3 $°C$
Humidity	0.01 %	2 %
Solar radiation	1 W/m^2	5 %
Rain	0.001 mm	0.05 mm/h
Pressure	0.1 hPa	1 hPa

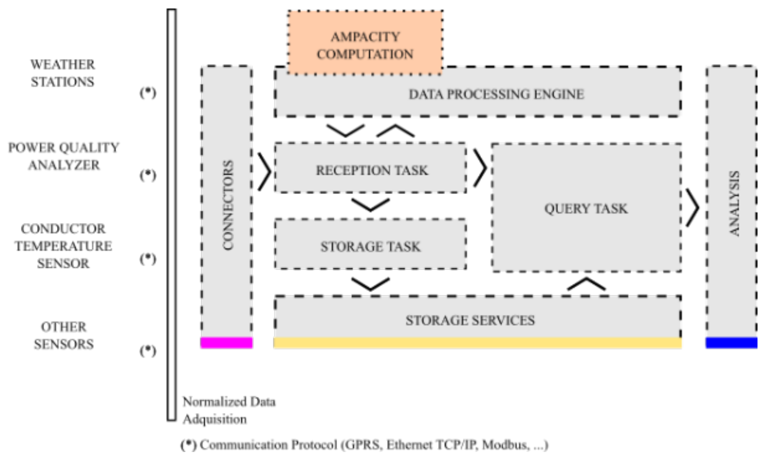

Fig. 2. Architecture of the ampacity control system developed by Viesgo.

of the electric substations, and communication was via Modbus over TCP-IP. The communication was sent over UTP cable communications, and with optical fibres for communication between the substation and the data centre. There were also two gateways ($SNG1$ and $SNG2$), each of which was able to connect up to 6 different temperature sensors (TS) via short-range radio (less than 100 m) and transmit temperature data through a private APN to the data centre.

Figure 4 represents the block diagram of the DLR methodology. The system estimated the ampacity (A) and the conductor temperature (T_c) for the two substations. The ampacity was estimated with the weather station ($WS1$ and $WS2$) values and the conductor temperature (T_c) was estimated using the weather station ($PQA1$ and $PQA2$) values and current from the power quality analysers ($PQA1$ and $PQA2$).

The line was operated by the control centre taking in consideration the minimum value of ampacity and the maximum value of conductor temperature. In addition, the measured conductor temperature (T_m) was monitored to provide redundant data in case of weather station failure and to check the ampacity and temperature algorithms.

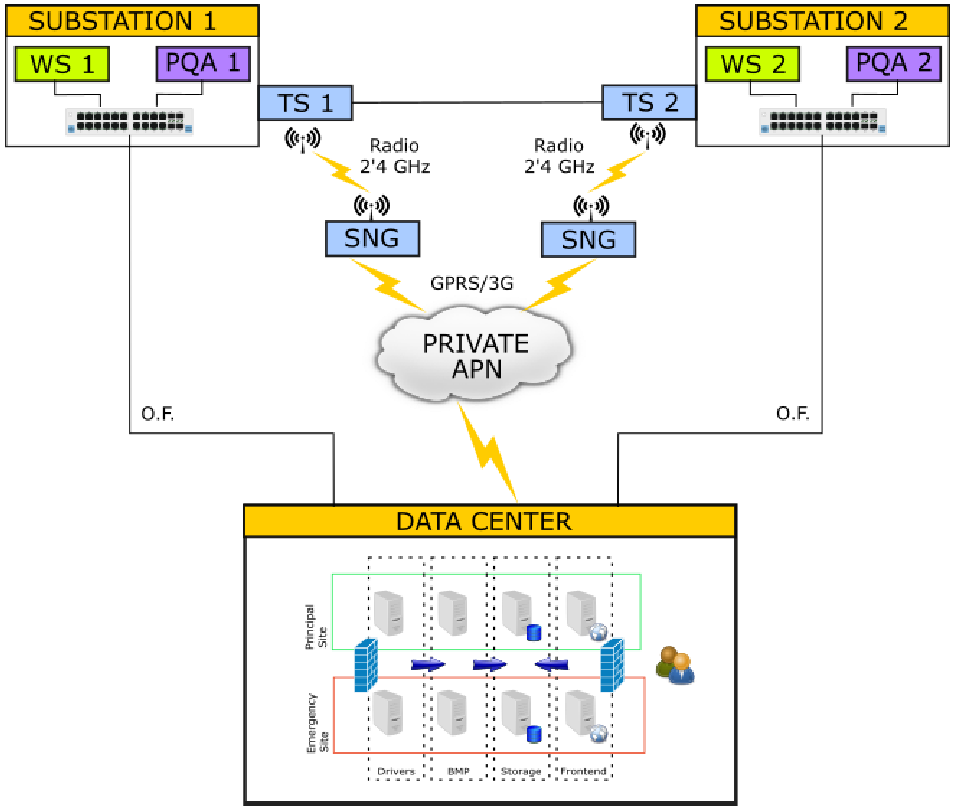

Fig. 3. Block diagram of the on-field infrastructure

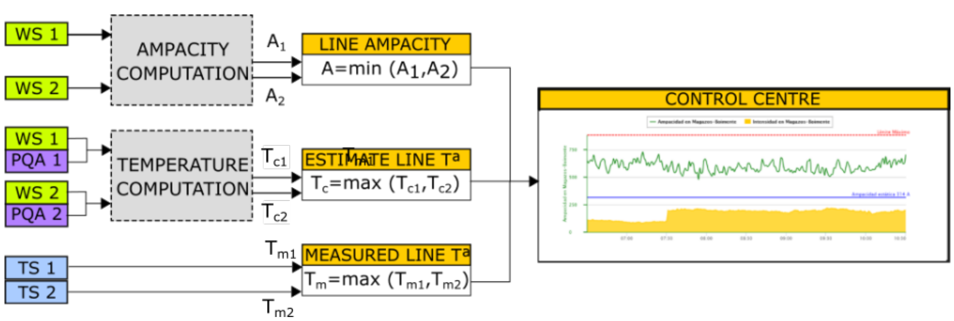

Fig. 4. Block diagram of the DLR methodology

As a new technology, fulfilling all the legal requirements to obtain the necessary permits required meetings with local and regional authorities. The theoretical and practical aspects of DLR we explained to obtain the permits to dynamically operate the overhead lines. In Figure 5, the evolution of the system over time is shown.

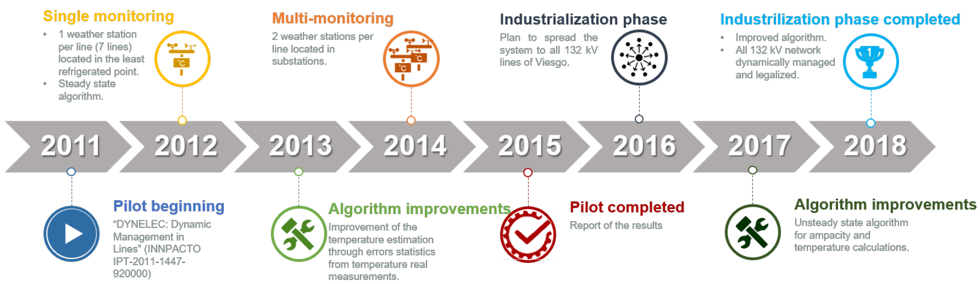

Fig. 5. Diagram of the evolution of the dynamic management system through the years

The control centre monitored the system through an application called "IDbox" (https://idboxrt.com/). "IDbox" is a software which allows supervision of industrial, energetic and smart processes. It integrates all available information sources, processes the captured signals and offers the tools for monitoring and analysis which is extremely helpful in operational decision making. In the case of Viesgo, the software shows the level of ampacity and the temperature of the conductor (both measured and estimated) in real time. This allowed the DSO to know the state of the system in real time and ensure its safe and efficient operation.Figure 6 shows the graphical interface. The upper graph shows the map with the entire network managed in real time. The red dots represent the substations. The state of the lines is represented by colours:

- Green: normal state of load of the line.
- Blue: the load of the line is close to its static limit.
- Yellow: the load of the line exceeds the static limit.
- Red: the load of the line is close to the ampacity of the line.

When the lines is shown in blue, yellow, or red, a bubble is displayed on the screen with the real-time information of the current flowing through the line, the calculated ampacity value, and the calculated temperature of the conductor.

The lower graph shows the statuses of the monitoring variables over the preceding 4 hours. The static limit of the line is represented in blue, the dynamic ampacity in green, the current in yellow, and the maximum security limit in red.

Finally, Viesgo had a dynamic management system that operated approximately 1,000 km of distribution lines with authorisation from the administration.

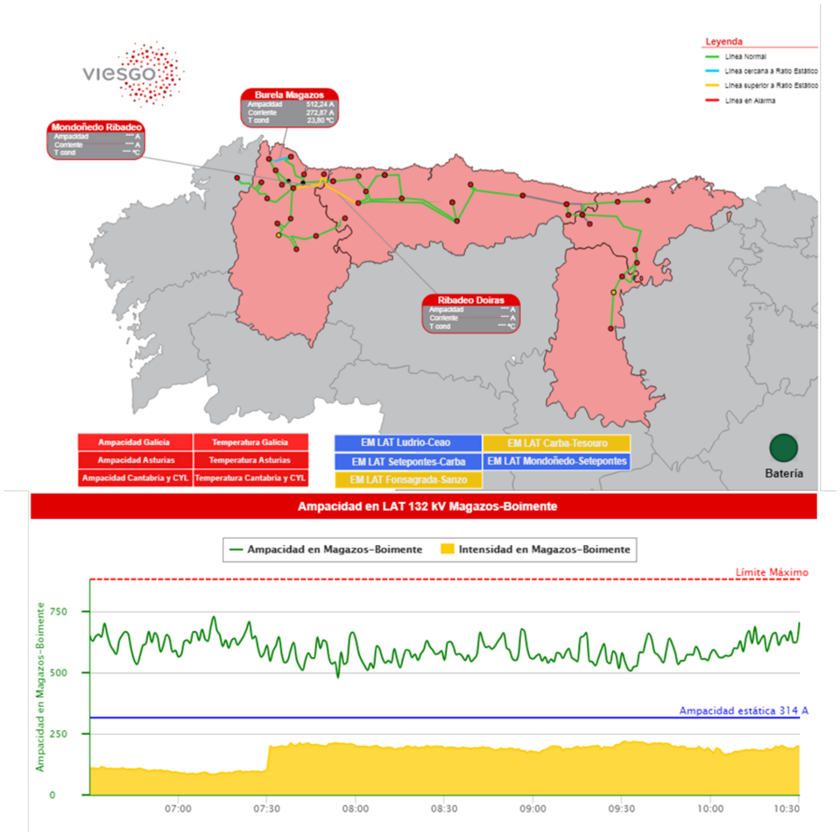

Fig. 6. Capture of the application for DSO operation

3 Dynamic line rating operation results

Dynamic operation is a powerful and useful tool to drastically reduce curtailments in wind energy, even nearly eliminating them, especially in distribution networks with high levels of integration with renewable energies.

The selected line had a huge potential for dynamic operation due to the problems caused by restrictions for the renewable energy producers and the high correlation between power transmission and wind generation.

Additionally, continuous monitoring of parameters such as temperature supports better knowledge of the OHL.

In this section, we will review the main results, including the number of curtailed hours avoided, additional energy transported, ampacity, current, and both measured and calculated conductor temperature, obtained over the period from January 2015 to September 2018. As a first result, table 2 shows the results of the additional energy managed and the number of curtailed hours avoided due to the use of the dynamic system, considering scenarios of 100 % and 80 % of the static rate. In the operation of mesh networks, the 80 % limit is considered to be a safety coefficient, as in case of contingencies, the redistribution of the energy can increase the current of the lines unexpectedly.

Table 2. Dynamic systems results of additional energy produced and number of curtailed hours avoided

Year	Additional Energy (GWh)		Hours (h)	
	100 %	80 %	100 %	80 %
2015	5.6	17.1	516	1115
2016	8.8	22.7	572	1335
2017	6.0	15.3	430	948
2018	7.7	15.7	435	702

The monotonous curves of ampacity and current are represented in Figure 7. From this figure, it can be observed that through dynamic operation of the selected line, 70.9 GWh of additional energy was managed, considering the scenario limited to 80 % of the static rate. This system was operated in dynamic management for 171 days. In the scenario considering 100 % of the static rate, the additional energy managed was 27 GWh over 81 days. The dynamic operation of the DSO allowed the management of an average of 21 % (380 A) and a maximum of 114 % (672 A) increased ampacity over the value corresponding to 100 % of the static rate. These values indicate that the use of dynamic management provides DSOs with greater flexibility in the operation of power lines and reduces the restrictions in renewable energy production.

Considering the yearly medium pool price [20–23], the additional energy transmitted was worth 1.4 Me with respect to operation at 100 % of the static rate, and 3.5 Me with respect to operation at 80 % of the static rate.

Additionally, the use of DLR reduced the CO2 emissions by 7,800 t with respect to operation at 100 % of the static rate, and by 20,300 t with respect to operation at 80 % of the static rate [24].

In terms of ampacity, the system had the capacity to manage 1,025 GWh of additional energy with respect to the energy produced at 100 % of the static rate. In 99 % of total time the ampacity of the line was above the static rate, and higher than 393 A in 80 % of the time. These values indicate an average additional capacity of 490 A, a 56 % increase relative to the static rate.

Another important aspect to analyse is the temperature of the conductor. The conductor temperature during the operation of the conductor allows the DSO to know the real-time state of the conductor and any possible over-heating suffered during its operation. In this way, the DSO will be able to evaluate the ageing of the conductor with greater accuracy. In the case of the line studied, the conductor temperature estimations had an average value of 16.3 $°C$ and a maximum of 80.9 $°C$. Furthermore, during less than 0.22 % of the total time (45 h), the conductor temperature exceeded 50 $°C$ (the hypothesised temperature corresponding to maximum sag according to Regulation EN 50341 [25]. The

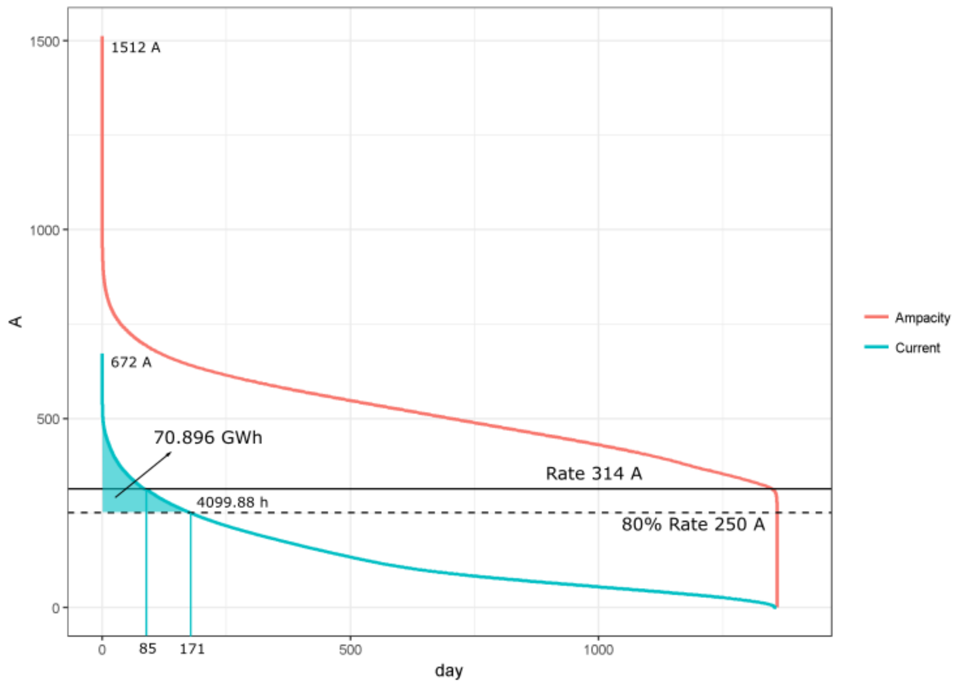

Fig. 7. Monotonous curve of current and ampacity

temperature of the conductor exceeded 70 $°C$ during only 18 h. These values indicate that operation above the static rate will not accelerate ageing of the conductors.

Figure 8 represents the errors in estimation of conductor temperature. In 70 % of the measurements, the estimated temperatures were greater than the measured temperatures due to the overestimation in algorithms. These algorithm works assuming the worst case to calculate the conductor temperature. For this reason, the system was operated in a safer way. The average error in temperature estimation was approximately 1 C, with a maximum error of 20 $°C$. In 80 % of the measurements, the error was between 5 and 5 $°C$.

3.1 Dynamic management utilisation example

As an example of dynamic operation in this line, Figure 9 presents the dynamic ampacity, current, and temperature over one week characterised by high wind power generation.

In Figure 9, it can be observed that high wind translated into high dynamic ampacity. This allows integration of more energy into the line. During the week shown, the DSO needed to operate the line with a high current, above the static rate and very close to the dynamic ampacity. During this period of dynamic

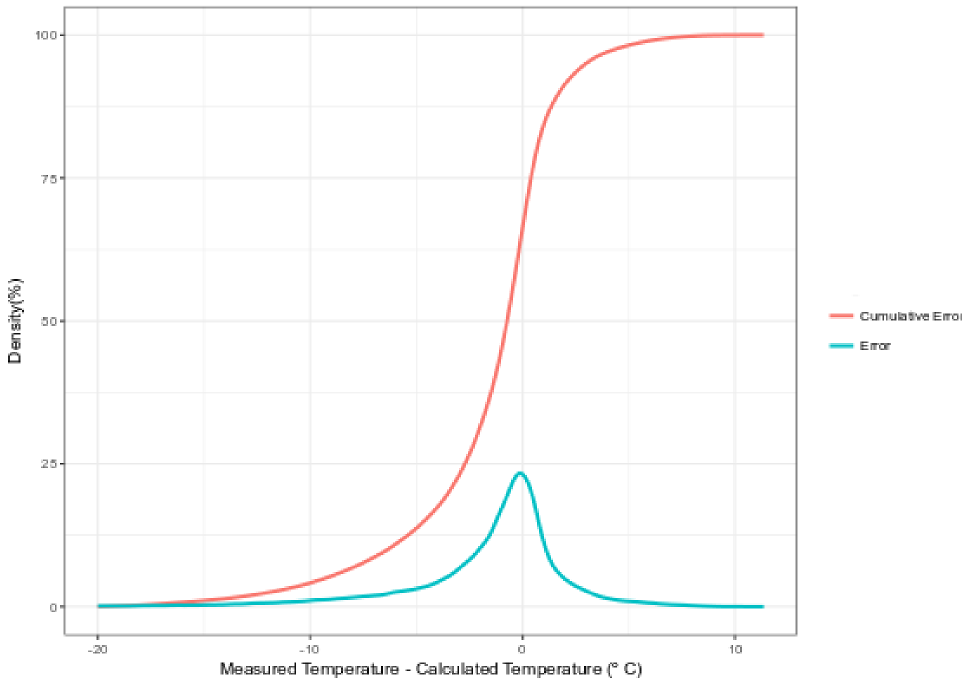

Fig. 8. Absolute and cumulative error in temperature calculations

management, the additional energy managed was 2.97 GWh over 109 h with respect to operation at 80 % of the static rate, or 1.65 GWh over 78 h with respect to operation at 100 % of the static rate. In conclusion, during this week, the system integrated approximately 4 % of the additional energy integrated over the four-year study period. Further, this dynamic system avoided 109 h of restrictions in a single week.

The temperature is not directly correlated with the current, as the weather conditions (especially wind speed) play an important role. This effect is shown by the red circles in Figure 9. The conductor reached similar temperatures (36.8 $°C$ and 37.7 $°C$) with very different currents (291.6 A and 372.5 A, respectively). The ampacity value at the first (left-hand) point (402 A) was lower than that of the second (right-hand) point (532 A).

4 Conclusions

Even though DLR has been validated as a powerful tool to reduce curtailments in wind energy generation, the journey to the implementation of this technology in a real application was long and difficult.

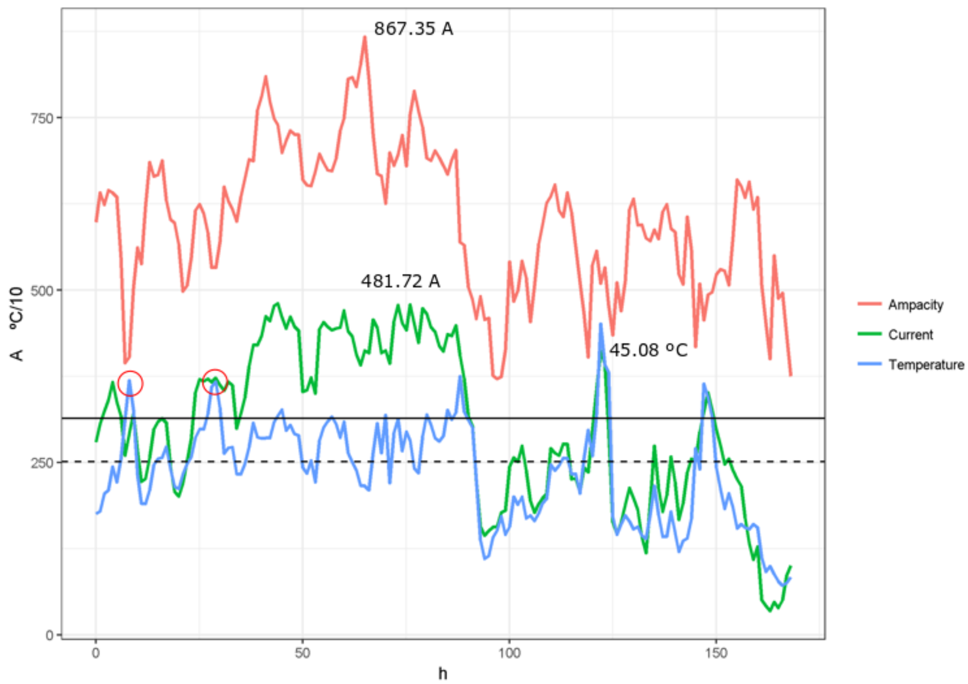

Fig. 9. Example of operational parameters during dynamic management

A major obstacle was gaining the confidence within the company in terms of allowing the operation of this system over their traditional design characteristics. The initial goal was to be able to increase the maximum capacity by 20 %, with significant concerns regarding operation of the line above the static rate safely. As shown, an average increase of 56 % has been achieved.

The control centre considers DLR to be an important tool for control when there is a high level of wind energy in the grid, allowing confident operation of the network close to its dynamic limit.

In emphasis of the real utility of DLR in this line, the most significant achievements were the avoidance of 4,100 hours of wind energy curtailment and the supplementary transport of 70.9 GWh of renewable energy. The main benefits for the DSO provided by the implementation of the DLR system include: reducing the need for new infrastructure, as the capacity of the system increased by an average of 56 %; knowledge regarding the state of the system (ampacity, current and temperature) in real time, allowing safer operation of the network; the confirmation through temperature information that the dynamic system will not exacerbate ageing of the conductor; and a reduction in CO2 emissions of 7,800 t with respect to the alternative scenario characterised by restrictions to the producers of wind energy.

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