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# DLR use for optimization of network design with very large wind (and VRE) penetration

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***Abstract* – Due to the stochastic nature of wind and clouds, the integration of wind and PV generation in the power system poses serious challenges to the long-term planning of transmission systems. Grid reinforcements always involve relevant direct costs while the average load factor of the wind and solar PV dedicated transmission lines is usually low. Additionally, in very windy sites, the same high wind resource that produces large amounts of wind generation and may congest the transmission lines transporting it to distant consumption centres may also have a beneficial effect in increasing the transmission capacity of those lines. In fact, the occurrence of wind not only contributes to the loading of the connecting line, but also increases the line capacity, via the convective cooling of the cables - one of the main heat transfer mechanisms in conductor heat balance; in other words, higher winds speeds contribute to faster cooling of conductor and therefore higher conductor's capacity potential. In this paper the existing methodologies to characterize those thermal effects in electrical cables - usually referred as dynamic line rating (DLR) - are applied to several IEA Task 25 countries case studies to characterize the technical value of the dynamic operation of thermally congested lines, as well as its potential economic benefits.**

***Keywords* - Wind power integration, DLR, VRE, Cable thermal balance, smart grids.**

## 1. INTRODUCTION

Electric grid capacity is a very scarce "product" whereas the construction of supporting transmission and distribution network is highly time and resource consuming. The purpose of using the "in real-time methodology" usually referred as *dynamic line rating* (DLR) is to enable power system operations with higher thermal ratings than the ones specified by nominal conditions without compromising the physical operating limits of overhead lines on existing transmission and distribution networks.

The use of DLR in conjunction with the integration of variable renewable energies (VRE) mainly wind and PV systems, is especially relevant due to the lower capacity factor (and high investments) associated with the transmission lines serving these renewable power plants. DLR provides the possibility of using "hidden" capacity of existing transmission lines to accommodate additional wind (PV or other VRE) power generation.

The physical and operational limits of electrical lines hinge on two main criteria: maximum conductor temperature, and minimum distance above ground – or *clearance*. Using a dynamic line rating (DLR) approach one may compute a realistic set of values for the line capacity, thus it can be used as a cost-effective solution to alleviate line congestion problems and achieve both an optimal loading of the grid for different weather conditions, while minimizing the cost of new VRE connection to the grid.

A few operational DLR analysis systems were recently developed and applied by research and academic organizations - e.g. LNEG [1], [2]; KTH [3], [4] and INL [5], [6], among others - all based on CIGRE and/or IEEE methods for thermal rating calculation of overhead lines [7]–[9]. Some of the tools also associate the DLR analysis to the calculation of an optimized power flow with variable renewable generation, e.g. [2], while others are focused on reliability aspects and risk analysis of the electrical network [10]. Presently, a common objective of these R&D groups is the analysis of the benefits of DLR use and the identification of risks and constraints.

The present paper compares static line ratings (SLR) and Dynamic Line Ratings (DLR) results, demonstrates the value of using DLR at the planning phase of new transmission lines (in areas with high wind probability) and implements DLR operational real time tools with wind forecast systems. It allows to assess the lines' added ampacity available (or not) given the meteorological conditions present, and to estimate the lines capacity values, thus showing the value added by using a DLR approach when operating transmission lines in different regions.

This work presents the DLR case studies for four IEA Task 25 countries: Portugal, Sweden, Germany and United States, makes a brief description of the methodologies and approaches used, mostly previously published. The case studies addressed demonstrate the potential of DLR on different scales and highlight the precautions when using it.

Section 2 presents the DLR methodologies used by the different R&D groups and Section 3 provides a brief description of the selected case studies. Section 4 presents the results obtained, that are discussed and analysed in detail in section 5. Some final remarks are provided on the applicability and value of DLR in Section 6.

## 2. THE DLR METHODOLOGY

TSOs commonly use numerical models to assess the cables "steady-state" thermal equilibrium for a predetermined set of local extreme meteorological conditions, which define the maximum ampacity of the overhead power lines. In recent years a set of measured or forecasted meteorological conditions have been used instead, to obtain more realistic "in-time" values for the cable's ampacity[1]–[6]. The inclusion of the cables thermal inertia in the thermal analysis approach imposes a dynamical thermal balance.
That approach lead to the development of detailed numerical thermal models such as the IEEE Std 738-2012 [7] and CIGRÉ [8] similar approaches, compared by Arroyo et al in [9]. The DLR physical models used in the IEA Task 25 countries and presented in this paper are analogous and based in those two main standard methodological approaches.
For ***Portugal***, LNEG built and applied a DLR analysis methodology [1], [2] using GICRÉ's model, later integrated with an optimal power flow (OPF) model using an ArgGIS interface for grid layout and geo-referencing of the lines. Weather input uses historic and forecasted meteorological series (wind/solar) from mesoscale models coupled with data mining approaches [11].
The method used by the Idaho National Laboratory (INL) to study the dynamic line rating calculation in the ***United States*** case studies requires the coupling of historically collected weather data with a computational fluid dynamic (CFD) model. To calculate the wind field in the CFD model, the steady-state Reynolds-Averaged Navier-Stokes (RANS) approach is used for the large scale turbulent modeling. This approach allows for a model that can be run on a workstation computer. The software used for the weather modeling, WindSim, allows for easy coupling of the weather station locations to the transmission line locations for calculating the wind speed. The use of this CFD software has been validated in several past studies for wind flows [5], [6], [12], [13] .
The use of CFD in DLR calculations has several major advantages. The first is that the CFD can be calibrated against known weather data using the assumption of similarity of boundary layer flow for accuracy. The interpolation of the CFD wind speeds allows for the calculation of a wind speed at specific locations of the transmission lines with only sparsely populated locations for weather data collection. This allows for accounting for slow wind speeds occurring due to terrain effects away from the weather station locations, which in turn gives a more conservative estimate of the total DLR calculation for the line. With a coupled CFD-weather station approach, no outage of the line is needed for installation devices, such as direct techniques using temperature or sag measurements. The adaptability of the method allows for the use of weather data from any input – which allows for historical analysis as done here, but also allows for an analysis to be done by importing forecasted data sets instead. If direct measurement devices are still wanted by the utility, CFD can be used to identify limiting transmission line midpoints for its installation.
For ***Germany***, in the case study build by Fraunhofer IEE, the conversion of weather data to ampacity is also based on the CIGRÉ approach. It was expanded by using the air pressure and the humidity as further inputs to determine the thermal cooling. For ***Sweden,*** the methodology is presented in detail in [3], [4].

## 3. FOUR IEA TASK 25 DLR CASE STUDIES

### 3.1 *Portugal*

The case study for the DLR analysis tool uses real data for a Portuguese central and interior region (Pinhal Interior) where a large renewable capacity is installed and operating. Pinhal Interior has 45 wind power plants totalling 1480 MW and 14 hydroelectric power plants with 1060 MW of nominal capacity. The location of the renewable power plants and the grid layout is generally depicted in Fig. 1. The characteristic parameters used for the overhead power transmission lines are published by the Portuguese TSO along with real georeferenced meteorological data used for the static rating (irradiance, temperature and wind velocity), calculated for December 23, 2009 at 1:00 p.m. The DLR scenario constructed and presented in this paper introduces a strong rise in the loads located region southern to Pinhal Interior (Alentejo) due to its envisaged general development through wind and PV distributed generation, along with the rise on the energy exported to Spain. To obtain the additional wind power generation, the wind speed data for 80 m a.g.l. were obtained using mesoscale numerical models for each wind park in the region. Then, based on the number of wind turbines of each park and the manufacturer guaranteed power curve, the wind power for each hour was computed and the ampacity of the lines calculated accordingly.

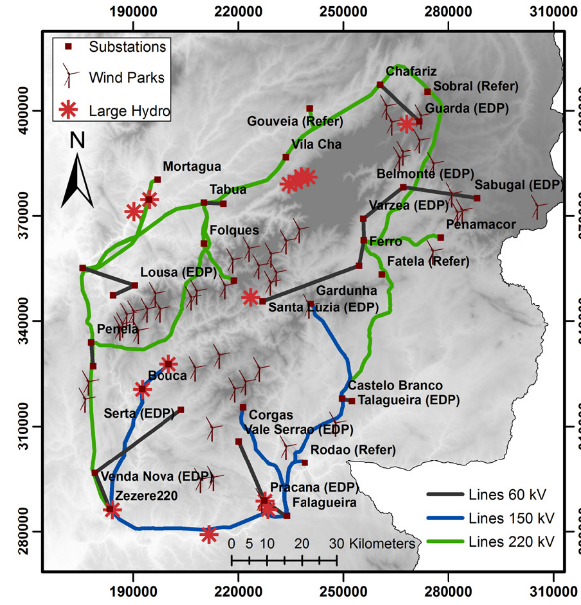

Fig. 1 DLR case study: transmission grid and power plants in the region of Pinhal Interior, Portugal.

### 3.2 *Sweden*

Climate in Sweden has advantages for DLR application, specifically in wind energy field, due to low ambient temperatures and high wind probability [3], [4], [10].

While a lot of research was done on the development of indirect/numerical DLR applications methods, Swedish DSO E.On has positive experience in using both direct measuring devices and indirect methods for DLR systems. In Sweden, E.ON has over 4 years of experience in connecting wind parks to the grid by using DLR monitoring devices.

The installation (and case study) in Sweden is located at the island Öland at the east coast in southern Sweden. The case was to install 50 MW of wind power on the northern part of the island. The connection to the mainland was made by two 50 kV transmission lines.

Calculations showed that the grid had capacity for 30 MW at its maximum with static temperature ratings. The solution was to install a DLR operational system and to measure the temperature on the overhead lines as well as a control system that could curtail the wind farm when overriding 50 °C. The overhead lines are located close to the shore so the wind effect was very good. The calculations showed that the wind farm should not be curtailed more than 8 h per year. Two different types of DLR equipment were tested in three different places.

The DLR system is integrated in the network protection system on the island and also integrated in the SCADA-system (see Fig. 2 and 3). The signals from the DLR control the wind farm in normal conditions and during faults and hazardous events the relay protection system will take over.

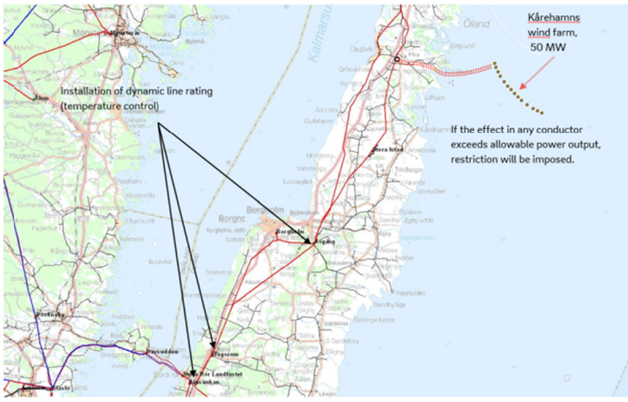


Fig. 2 - The DLR installation on Öland in Sweden.

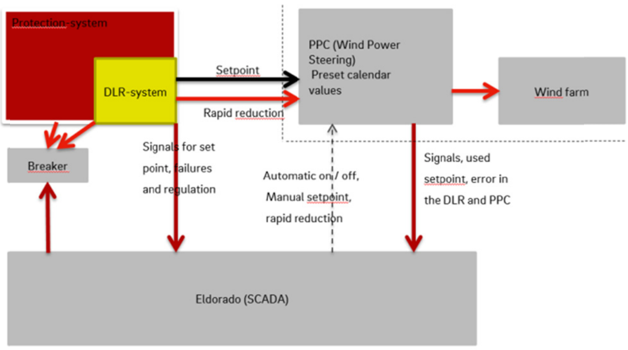


Fig. 3 - DLR integration with the SCADA system (Sweden).

### 3.3 *Germany*

For the case study in Germany two different transmission lines are investigated. One is comparably long and goes through mainly complex terrain. The other is a short line situated in almost flat terrain. They were picked to identify if the DLR method developed shows a benefit under different general set-ups. Three scenarios will be compared in the results. First, the nominal capacity using a SLR approach is shown. Second, the mean ampacity using DLR at all times is calculated. And third the mean ampacity using DLR in windy times, i.e. of all time steps the 20 % with the highest wind speeds, is derived.

Five years of high resolution reanalysis data (REA6 and REA2, [14]) are used within this study as well as four years of satellite data for the irradiance. To increase the horizontal resolution of 6 and 2 km, respectively, the German Windatlas [15] with a resolution of 200 m was taken to adapt the statistical behaviour of the wind speed to local effects. To calculate the ampacity, the weather data was interpolated for each of the sags of the transmission lines.

The maximum ampacity was limited in a way that the conductor temperature had to be always below 80°C for security reasons. At each time step the limiting sag was picked. The sags with the most limiting times within the five investigated years were defined as "hot-spots". This outcome was combined with GIS-data to finally select the masts where meteorological measurement equipment should be installed. As the current weather is monitored in operations only for some points of the transmission lines buffer values are necessary to keep security levels. The final possible ampacity is obtained by calculating the maximum possible ampacity and subtracting the buffer.

### 3.4 *United States*

The area studied in North America is Hells Canyon which is a complex terrain in the state of Idaho. The canyon is the deepest river gorge in North America with terrain variations from 1600 meters above the river on the west rim to 2300 meters on the east side. This region is of interest due a number of hydroelectric dams in the area. Congestion of the power out of the region is of concern due to the possibility of the high mountains blocking the wind and preventing convective cooling currents on the transmission lines. The data here is analyzed over a 1 year period of data collection from 5 weather stations placed along the transmission line.

The exact region of interest in this study is sized 30 kilometers east-west and 60 kilometers north-south. The map of this terrain is shown in Fig 4, for both the roughness layer and the elevation layer with the transmission line structures shown. The roughness layer is scaled from 0 to 1 to model subgrid effects such as shrubs, trees and buildings, this roughness value is used in the boundary condition in the CFD model. White regions represent smooth areas – river or plains, while red regions represent dense vegetation or forests. The terrain layer shown next to it highlights the steepness of the terrain within this small section varying form the peaks to the river level. The terrain is implemented into the CFD simulations using the digital elevation model (DEM) data at a horizontal spatial resolution of 30 m. The DEM data was converted from lat-long into a UTM

11 projection. There are 160 structure locations along the length of the transmission line. The transmission line structures are divided into 5 different line segments for the sake of this study, these segments are circled in the map and correspond to the nearest weather station locations.

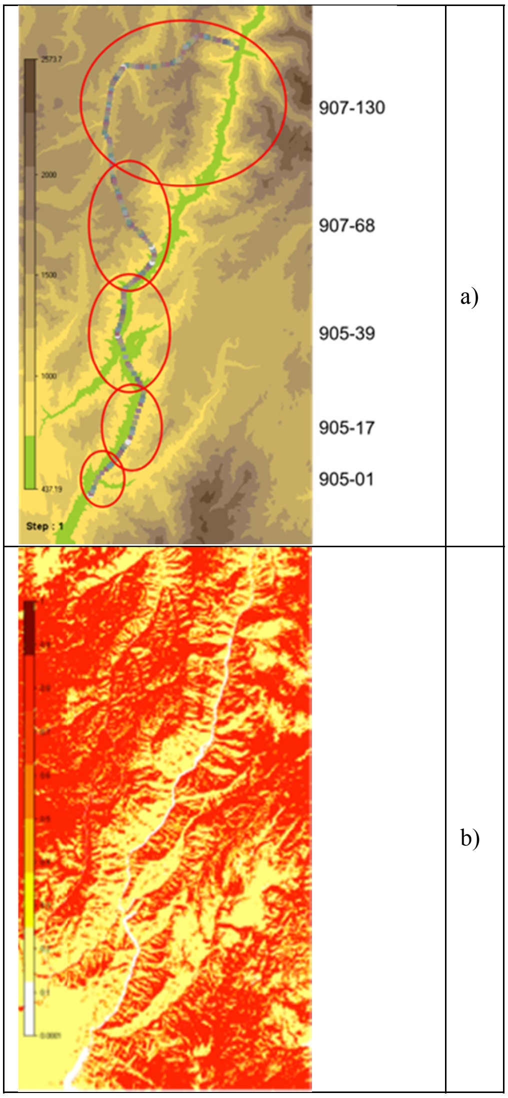


Fig. 4 – Hells Canyon a) terrain layer map, and; b) roughness layer map.

## 4. Results of DLR application to potentially congested lines

### 4.1 *Portugal*

The Portuguese case study was designed to study and analyze the benefits of using a DLR approach in scenarios where a strong increase in the load's factor occurs and eventually approaches the network's congestion in some regional lines. The region under study is characterized by the existence of a large number of hydro power plants and many other distributed renewable power plants - mainly wind for the time being, but the planning for future PV plants is underway (at the licensing stage).

The study computes the network's optimal power flow using a static rate approach to assess the lines capacities (TSO's nominal operation values) and the results are compared to the DLR ones. Meanwhile, the development perspectives of the Southern region of Alentejo will risk the load demand at Falagueira's bus. A contribution for the additional power generation may be supplied by upgrading the three wind farms connected to Corgas from 16, 144 and 8 MW to 36, 144 and 80MW, respectively. That power increase brings the 150kV Corgas-Falagueira line close to the TSOs rated congestion as showed in figure 5 below.

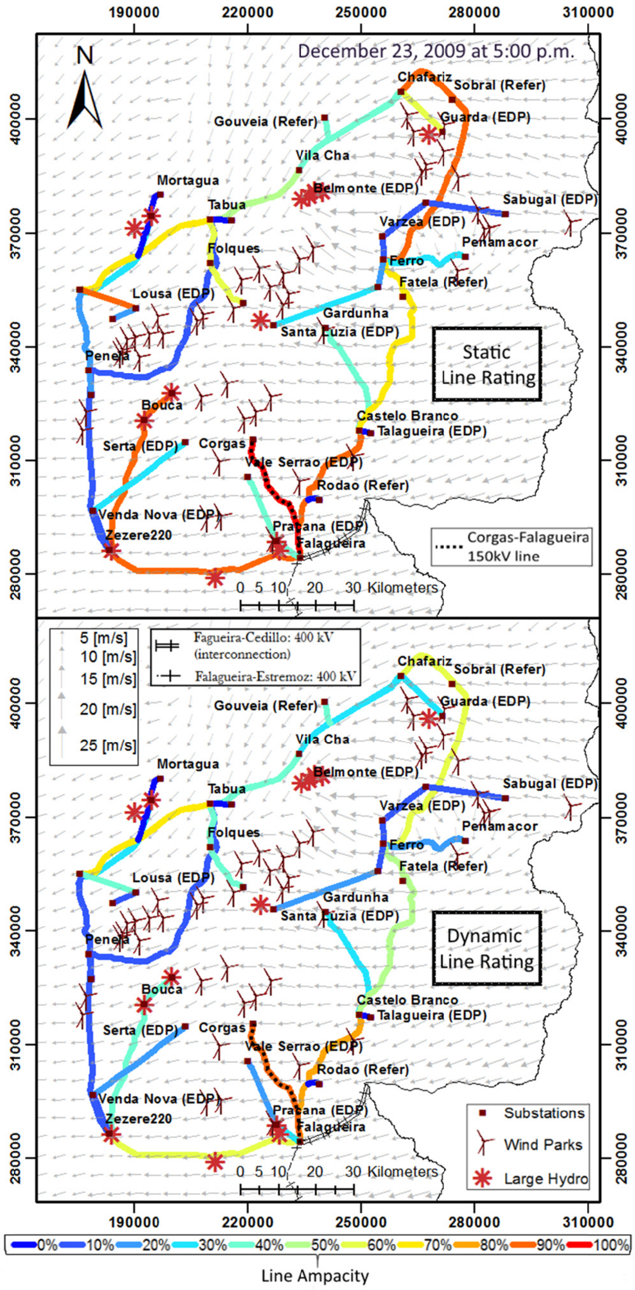


Fig. 5 – Line ampacity results for a SLR versus a DLR approach (worst-case scenario: December 23, 2009 at 5 p.m.).

The figures above show that DLR analysis presents higher ampacity values not only for the Corgas-Falagueira line but also along the lines connecting Falagueira to Chafariz due to a power flow redistribution, granting a safe operation under the new conditions imposed.

**4.2 *Sweden***

For the Swedish experimental case study, after 4 years of DLR application there was no curtailment due to line ampacity issues. The curtailment due to maintenance has been less hours than expected.

The DLR monitoring devices are installed in 3 locations. In Figures 6-9 the DLR application for the period between 28th of March and 12th of May of 2014 are presented for 2 locations with two different points for each location.

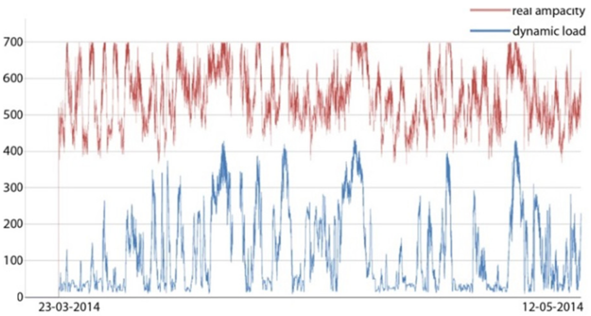


Fig. 6 – Location 1, connection point A – DLR and real line ampacity for the period 23.03.2014 – 12.05.2014

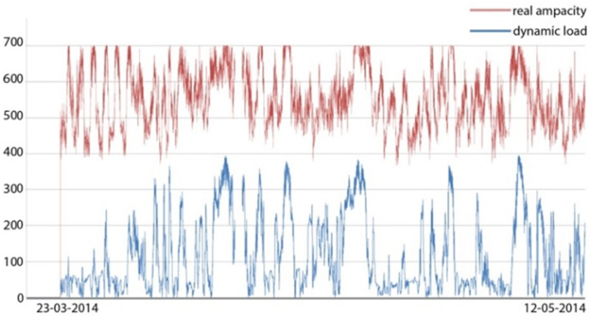


Fig. 7 – Location 1, connection point B – DLR and real line ampacity for the period 23.03.2014 – 12.05.2014

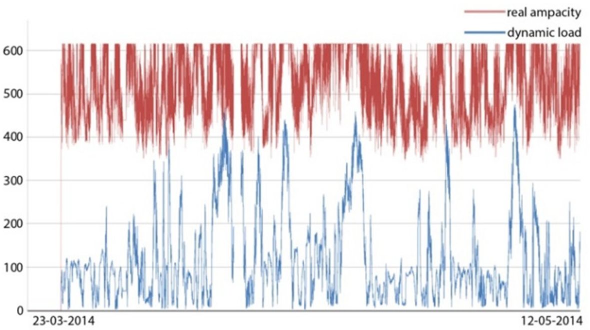


Fig. 8 – Location 2, connection point A – DLR and real line ampacity for the period 23.03.2014 – 12.05.2014

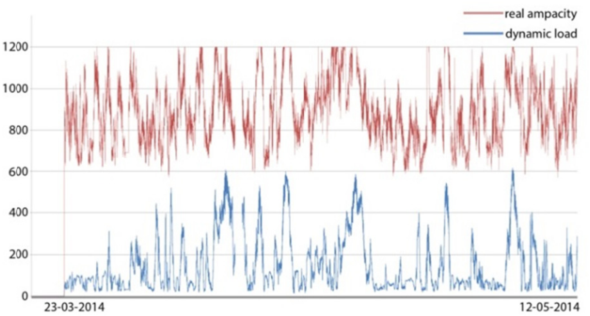


Fig. 9 – Location 2, connection point B – DLR and real line ampacity for the period 23.03.2014 – 12.05.2014

As it can be observed in the Figures 6-9, even for long periods of time the load does not exceed the measured ampacity value. However, in 2018 Sweden experienced the warmest summer in its history. The extreme weather conditions have resulted in several dangerous spikes in the dynamic load. A few times during the period May – September 2018 the load distribution has crossed the real ampacity limit.

**4.3 *Germany***

The use of DLR for the German case study is illustrated in Fig. 10. For both transmission lines under study the mean ampacity over all times increases substantially using DLR: for the long one in complex terrain (A) by more than 20 % and for the short one in flat terrain (B) by almost 40 %. During windy times when the penetration of wind power into the system is high, it rises even more to 145 % (A) and 156 % (B) of the nominal ampacity, respectively.

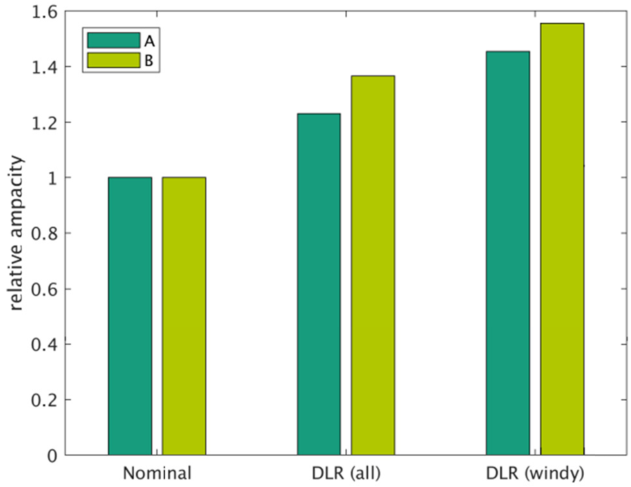


Fig. 10: Ampacities relative to the nominal conditios (SLR) using DLR at all times and in windy times for two transmission lines. A) Long transmission line in complex terrain, B) short one in almost flat terrain.

**4.4 *United States***

The weather data used to run DLR simulations and obtain the results for Hells Canyon case study [16] were collected over a year-long span.

A minimum of the 5 ampacities at each time step was plotted over the yearlong span - this is shown in Figure 11. For the vast majority of the year, the calculations show the DLR ratings are significantly higher than the static rating, represented by the dotted line, with any case below static occurring during brief periods in the summer months.

The ampacity data for each line segment is considered for the amount of time over the static ampacity, this is shown in Figure 12. There the solid lines are the DLR calculations coupled with the CFD wind fields, and the dotted lines are the DLR calculations using only the weather data. Without considered the slow wind fields due to terrain effects in the region, DLR ampacity can be significantly overpredicted without CFD results.

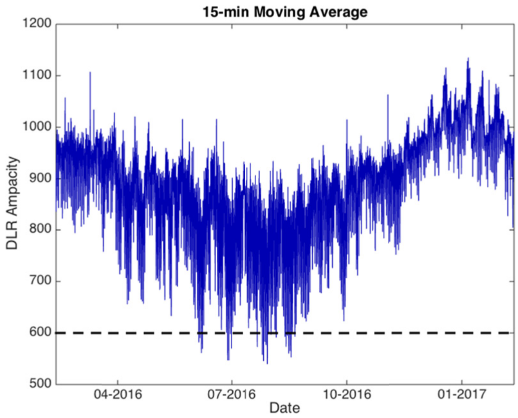

Fig. 11 – DLR ampacity over the yearlong data collection.

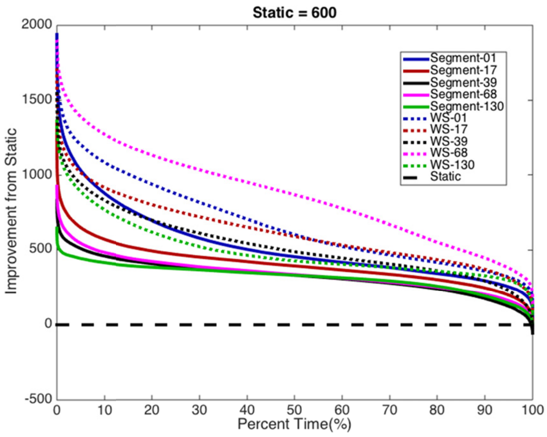

Figure 12 – DLR calculation over static with and without consideration of CFD wind fields.

## 5. Discussion and Analysis of Results

***Portugal:*** Given the high penetration rate of wind power in the Portuguese case study, the use of DLR allows to take advantage of the high correlation between wind power production and the maximum convective cooling effect of the lines under high wind speeds. That approach rose the ampacity of the 150kV Corgas-Falagueira interconnection by 47% for the worst possible conditions allowing a safe operation of that line far from potential congestion.
Fig. 13 depicts the ampacity increase on the critical sector (maximum sag) of Corgas-Falagueira line showing the high correlation between the transmitted wind power and the line's ampacity increase, as well as the effect of the wind plant disconnection, after 10 PM.

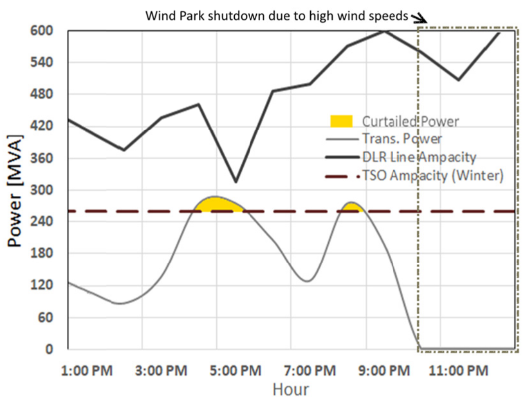

Fig.13 – DLR ampacity increase on the critical sector of Corgas-Falagueira transmission line.

These results illustrate the possibility of integrating additional (and aggregated) VRE generation that typically present low load factors of the interconnection lines, while avoiding a local grid upgrade.
The ampacity results for 4 major transmission lines of the case study's regions are presented in Table II for different local wind speed conditions.

Table II. STR vs DLR ampacity for 4 selected lines

| Line Code | | 1089 | 2164 | 2170 | 2173 |
|---|---|---|---|---|---|
| TSO's STR capacity [MVA] | | 153 | 804 | 434 | 434 |
| DLR capacity [MVA] | Winter (7 PM) | 256 | 1872 | 728 | 535 |
| Increase ampacity [%] | | 67% | 133% | 68% | 23% |
| Wind Speed [m/s] | | 8.2 | 9.1 | 8.6 | 4.1 |
| Angle Direction [°] | | 1 | 79 | 8 | 3 |

In general, the results obtained with DLR for the scenarios used in the Portuguese case study showed a positive and strong increase in the ampacity of the lines, when compared to the nominal SLR approach. However, as highlighted by in the results of Table II, the additional dynamic ampacity varies on wide range and shows a strong dependence of the incident angle of the wind, with the maximum (and atypical) increase experienced by line 2164, which is experiencing an angle of 79º deg, thus almost perpendicular. That strong dependence of the incident angle of the wind - a meteorological parameter very difficult to forecast accurately using both mesoscale and CFD models - recommends great care in its application when applying DLR to complex terrains. To reinforce this statement Fig. 14 represents a daily profile of a line's ampacity together with the wind speed and angle of incidence of the wind on the transmission line.

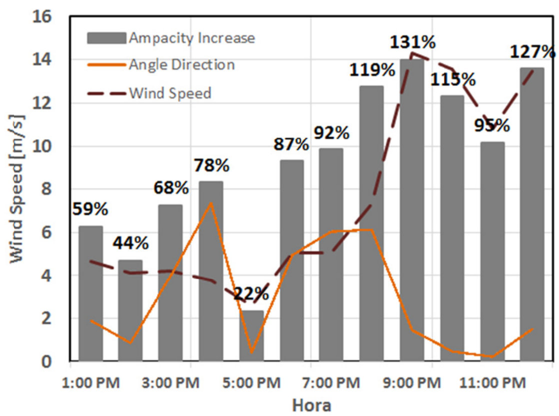

Figure 14 – DLR dependence on the direction of the local wind speed and its angle of incidence to the transmission line.

***Sweden:*** While there were some challenges in the programming of the protection system for DLR, the overall experience in Sweden has showed positive trends. Overall DLR implementation comes with certain challenges, when integrating monitoring devices to the grid, however the economic analysis shows financial benefits for the producer of using DLR for connecting wind parks to the grid. For the grid owner there are benefits, but also disadvantages because of higher losses and more new equipment to maintain. Also these systems are new for the operating staff and can lead to misunderstanding and unplanned outages.

When implementing DLR and connecting additional DLR devices to the grid it is important to adjust the protection system to the new needs. The DSO experience tells us that the installation challenge often lies not in the installation of the DLR device itself, but in the triggering the control and protection system to communicate with new technology.
On the positive side is the long term investment plan for wind farms. Since building new lines for integration of wind farms is associated with high investment costs, offering additional capacity of the existing lines as the primary grid connection becomes an economically effective solution. In the case of the Swedish DSO, the predicted curtailment of the wind farm was calculated to be only about 8 hours per year, due to line ampacity issues, plus additional hours due to non-DLR related issues, such as maintenance.
***Germany*:** In Germany a lot of expensive down regulations of wind power plants are necessary to keep the electrical grid stable as it is not able to transport the energy [17]. With the results shown it is very likely that using DLR reduces the amount of down regulations. Besides the method discussed here also methods looking at the whole grid at once instead of transmission lines are under investigation in Germany. Another approach called ASTROSE® measures the inclination of the transmission line and determines from that the conductor temperature. The operational use of DLR techniques is increasing.
***United States:*** Weather data was collected over a year-long span and used to calculate the DLR ampacity for a mountainous region. The data was coupled with CFD results to provide corrections to account for terrain effects causing slow wind speeds. It was shown for this particular instance that not account for local wind fields could cause a significant change in the ampacity headroom of the transmission line.
In fact, without accounting for the local slow-down of wind speeds due to the terrain, the DLR calculations can significantly over-predict the headroom available on the transmission line. This effect occurred in US case study for all 5 line segments, with the most dramatic effect occurring with the segment-68 line. This is due to the high wind speed recorded at this location at the top of a ridge, while several associated midpoints are in a valley where much lower wind speeds occur.
To summarize, Table III presents a synthesis of the modelling approaches used by Portugal, Sweden, Germany and United States, to apply the case the four case studies presented and described in this paper IEA Task 25 as well as the maximum added ampacity observed by using a DLR approach.

Table III. Summary of the approaches and results of DLR application for four IEA Task 25 countries case studies.

| | **DLR Method** | **Meteo data** | **Case study tipology** | **Added ampac.** | **Max.added ampacity[%]** |
|---|---|---|---|---|---|
| **Pt** | CIGRE+IEEE | Historic +mesoscale | Numerical | Yes | 68/133 |
| **Se** | CIGRE | Historic +mesoscale | Hybrid | Yes | 40/156 |
| **Ge** | CIGRE | Historic +mesoscale | Experimental | Yes | 56 |
| **US** | IEEE | Historic +CFD | Hybrid | Yes | n.a. |

## 6. FINAL REMARKS

The results presented in this paper are based on independently constructed case studies from four IEA Wind Task 25 countries: Portugal, Sweden, Germany and United States.
These countries have developed and applied similar methodologies - using CIGRE and/or IEEE approaches - to assess the dynamic ampacity of the transmission lines under study. Although there are some differences in the identification of the electric line's critical sectors (or "hot spots") all the results are coherent and in accordance to previous research by indicating an interesting potential (both technical and economic) in the application of the dynamic line rating, especially for operational purposes, when integrating VRE generation, characterized by very low average capacity factors of the connecting electric lines. For the design of new transmission lines, a conventional static approach of the network is still privileged, unless a high penetration of VRE is planned within a region served by constant and strong wind regimes.
It should be highlighted that there are some risks associated with DLR applications. Great care is recommended when assessing the improvement that DLR can bring to specific systems, especially when located in complex terrain regions. Long lines in complex terrains may experience sharp (and fast) variations in the weather conditions that strongly affect its ampacity when in DLR operation. Since the wind velocity parameters (both horizontal speed and direction) are strongly dependent on local surface and orographic conditions, it is likely that in complex terrain some sections of the lines lie in valleys, shadowed from the major convective and cooling effects of the wind and heated by the solar irradiation during the warmer hours of the day, that consequently do not experience improvement of their transmission capacity by weather dynamic effects. That limitation may be addressed by a careful use of CFD detailed models, a deep knowledge of the terrain, both associated with real-time monitoring of the weather conditions and temperature of the electric lines.
Another aspect was pointed out by the Swedish case study: the operation of protections for DLR networks is challenging and needs to be designed with great care.
In overall, hybrid systems, using both numerical and experimental approaches - as the one presented in Fig. 3 appear to be the most encouraging nowadays.
Notwithstanding eventual risks, the approach of dynamically rating the ampacity of overhead transmission lines is a promising area, both economic and technically for optimizing the use of existing overhead transmission lines. Its application may also be considered when designing new electric lines in regions with large penetration of VRE, particularly wind energy.

## ACKNOWLEDGEMENTS

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