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CIGRE-IEC 2019 Conference
on EHV and UHV (AC & DC)
April 23-26, 2019
Hakodate, Hokkaido, Japan

Study Committee B2: Overhead Lines

Use cases of dynamic line rating for optimized operation and planning of power transmission network

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SUMMARY

Dynamic Line Rating (DLR) is increasingly being used by Transmission System Operators (TSOs) around the world as an option in system operation, maintenance and investment planning to optimize the use of assets and system design, while ensuring security. This paper presents practices of DLR focusing on applications that reduce the burden of renewable energy (RE) integration. DLR eases the management of power flows by allowing accurate and efficient assessment of maximum transmission capacities. It enables secure and efficient line limits to be used in system operation, safely increasing N-1 limits and therefore the need for RE curtailment. Combined with forecasting, DLR contributes to optimizing system maintenance schedules with production schedules without being compromised by RE infeed. Using statistics and probability of DLR for future scenarios it is useful in efficient investment planning of RE interconnections and grid reinforcements for RE integration.

KEYWORDS

Dynamic Line Rating, Thermal rating, Ampacity, Smart grids, Sensors, Real time monitoring, Forecasting, Planning, Network, Market, Renewables

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INTRODUCTION

This paper presents practices in optimum transmission line operation that "at the same time" reduce the burden of renewable energy (RE) integration.

Transmission System Operators (TSOs) around the world are increasingly using Dynamic Line Rating (DLR) as an option in system operation, maintenance and investment planning for efficient asset use and system design, while ensuring security. This trend is compatible with that of the "energy transition", characterized by rapid increase in RE installations in resource-rich areas, maintenance of an aging infrastructure, and accelerated exit of conventional power fleet like nuclear and coal. Especially wind power, tends to be interconnected to areas in the grid remote from demand centers. Compounded with decreasing supply from conventional power plants, this causes locational change in supply infeed, and hence changes in power flow trends (horizontal and vertical). Transmission system operation and planning that has been optimized for "traditional" power flow trends becomes inadequate for the new paradigm. This may be considered a "burden" on the power transmission network, since the "new" power flows caused by the potential maximum infeed of the newly connected wind power plants may be incompatible with the maximum rated capacities of transmission lines and substations, or the limits of voltage control mechanisms and protection systems in place. This means that the grid must be upgraded and/or adapted and optimized towards the "new" power flow trends. Conventional practice in considering limits of the system no longer guarantees the most secure and efficient delivery of electricity. However, when the commissioning of transmission projects is prohibitively expensive and slow, and system operation procedures are typically developed based on years of accumulated experience, the fast growth of RE, especially spurred by growth policies, is an additional complication: The pace of adaptation is simply not accustomed by the traditional transmission system paradigm.

DLR eases the management of new power flows by allowing accurate and efficient assessment of maximum transmission capacities. It is useful in this context for adapting to changes in grid asset usage, as it can be deployed quickly and safely. It is ideal as an option in system operation, especially if real-time monitoring and forecast are enabled with sensors. Making use of information on actual asset conditions enables secure and efficient line limits to be used. This paper shows use cases how the security of temporary loading can be guaranteed, and N-1 limits can be safely increased. This allows a reduction of redispatch measures, like RE curtailment. Especially in extraordinary situations (unusual weather, unusual power flows), DLR can be more secure than static ratings.
The same setup is useful for system maintenance. The example from Belgium shows how the maintenance of a critical 220kV line could be scheduled and implemented during times when the system impact is known to be less, without being affected by the infeed of wind power.
Using statistics and probability of DLR is useful in investment planning for efficient design while ensuring security. The examples from France and Germany show how the design parameters of a new transmission line to interconnect a wind power plant can be optimized while reducing the possibility of curtailment.
The optimal way is to address system operation first, in short-term. Then there is the opportunity to optimize development of grid, since aging asset can be: replaced to prolong life; retired or uprated to adapt to new power flow patterns.

DESCRIPTION OF DLR

The primary concern with electrical loading of overhead lines is to respect the "ground clearance" [1]. As illustrated in Figure 1, the distance between the point of suspension of the conductor from the tower and the mid-point of the conductor is the Sag (marked "S"). While the distance from the conductor to ground, or (permanent or transient) objects below the line, is the Clearance (marked "C"). Usually, a **minimum clearance** is mandated by law to ensure public safety.

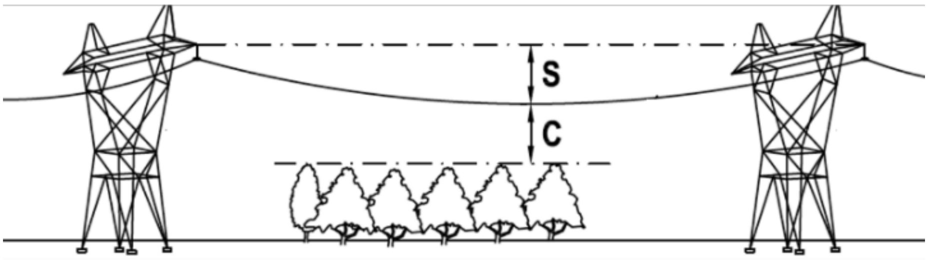

Figure 1 : Line Clearance (C) and Sag (S)

The Sag depends on the material properties of the conductor, and its expansion characteristics (mainly) due to heating from line loading, ambient temperature, solar irradiance, and wind. Traditionally, the difficulty in predicting weather parameters and line loading resulted in conservative assumptions, and therefore it became common practice to set a static maximum line loading (in Ampers) based on fixed ambient conditions: typically 0.5 m/s wind speed; 1000 W/m^2 solar irradiation; and the average temperature of the year.

However, if grid operators want to better utilize their overhead lines while ensuring that the regulatory clearances above ground are always met, they need a system which determines the line sag in a span by direct measurement. By measuring the actual sag, the remaining distance until the minimum clearance (aka. the limit) can be calculated, which then indicates how much the line loading can be increased until the limit is reached. The sag is constantly changing, which means that the maximum line loading is also changing. This is why it is termed “Dynamic Line Rating”.

Dynamic Line Rating (DLR) technology based on sensors directly measuring the sag is provided by Ampacimon. It is a line-mounted sensor which measures vibration and sag, wind speed and ambient temperature, and a software that combines these real-time measurements with information about the physical properties of the conductor, installation conditions, grid operation data from SCADA/EMS, and weather observations and forecasts from weather service providers (like bureau of meteorology), to provide real-time utilization rate and remaining capacity of the transmission line, as well as forecast capacity, until the maximum line sag is reached.

DLR technology that measures sag, are superior in accuracy compared to indirect methods and those that monitor only conductor temperature. Examples of indirect methods are weather station based or weather model based calculation techniques. These monitor ambient weather conditions and theoretically calculate the conductor temperature. Such techniques work well if the system behaves exactly in accordance with the mathematical model. However, physical world systems are not as ideal as the models used to describe them. This means it carries risk of inaccuracy which must be taken into account in application.

These methods consider the line rating from a thermal point of view only. It assumes a relationship between conductor temperature and sag. For example, the estimation of the conductor average temperature is not trivial. There are significant temperature gradients along the conductor length, mainly caused by wind velocity gradients along the span. According to some tests results [2], substantial temperature variability within a single span and between adjacent spans can exist. Longitudinal variation of about 10°C-25°C had been observed in a single span [2]. At high conductor temperature, higher variation (up to 50°C) can be observed [2]. Considering the secure operation of the line, taking into account a single conductor temperature measurement should not be enough in order to apply dynamic line rating models to real time operation [2]. Furthermore, the relationship between sag and conductor average temperature vary with time because of creeping or exceptional events (like icing or high winds). This means that, if only temperature is monitored, sag may well be violated, thus exposing the line to serious safety issues, like arcing. Measurement of conductor temperature or of wind speeds along the line requires an assumed relationship between conductor temperature and sag and is thus inherently less accurate than the direct measurement of sag or tension.

Since the rating of most lines is determined by sag clearance, the monitoring of sag or tension is the most accurate method. Direct real-time monitoring systems (except temperature sensor) may detect any excessive sagging. Where the first condition to be met is to ensure that minimum clearance is never violated, direct methods monitoring the line characteristics that have strong dependency with the sag give most accurate DLR.

USE CASES DEMONSTRATING BENEFIT OF DLR

The Transmission System Operator (TSO) in Belgium implements sensor-based DLR on several critical lines in its transmission grid already since 2008. Therefore it has accumulated experience and a databank of measurements to capitalize from learnings. Furthermore, new methods have been tested for considering DLR in planning studies in Germany and France. The benefits underpinned by empirical evidence are presented in this paper for different use cases.

Use case 1: Reduction of redispatch measures, like RE curtailment

Wind power plants are installed offshore and as distributed generation in the Belgian grid. New power flows caused by infeed from wind power plants appear as congestions in the main corridors of the transmission grid (Figure 2). Both power infeed from wind power plants and DLR increase correlate with higher wind speeds (Figure 3). This evidence shows that twice the capacity can be gained when subject to wind speeds of 5 m/s. In other words, while congestions are caused by wind power, infeed is higher when DLR is also higher. Figure 4 shows the result from an Ampacimon device installed on a 150 kV line to minimize the curtailment of the wind power plants. The sensor was installed in 3 months, as opposed to building a new High Voltage (HV) line costing 24 mEUR with a 5-year delivery time. The sensor allows up to 50% increase in capacity when it is needed, thus avoiding line congestion. The saved congestion includes the otherwise curtailed wind power. It is also interesting to note that a relatively low perpendicular wind speed (near 2 m/s) can already achieve significant (>150%) capacity gain.

In a similar approach, the TSO equipped a 70 kV line with the DLR sensor to reduce the amount of curtailment required to the very strict minimum. This solution allows the TSO to use the full available capacity of the line and curtail only when incidents occur, instead of statically adhering to the N-1 principle. This approach alone already increases the available connection capacity by nearly 75%. This approach maximizes the use of the existing 70 kV network and at the same time minimize the total cost towards the energy consumers.

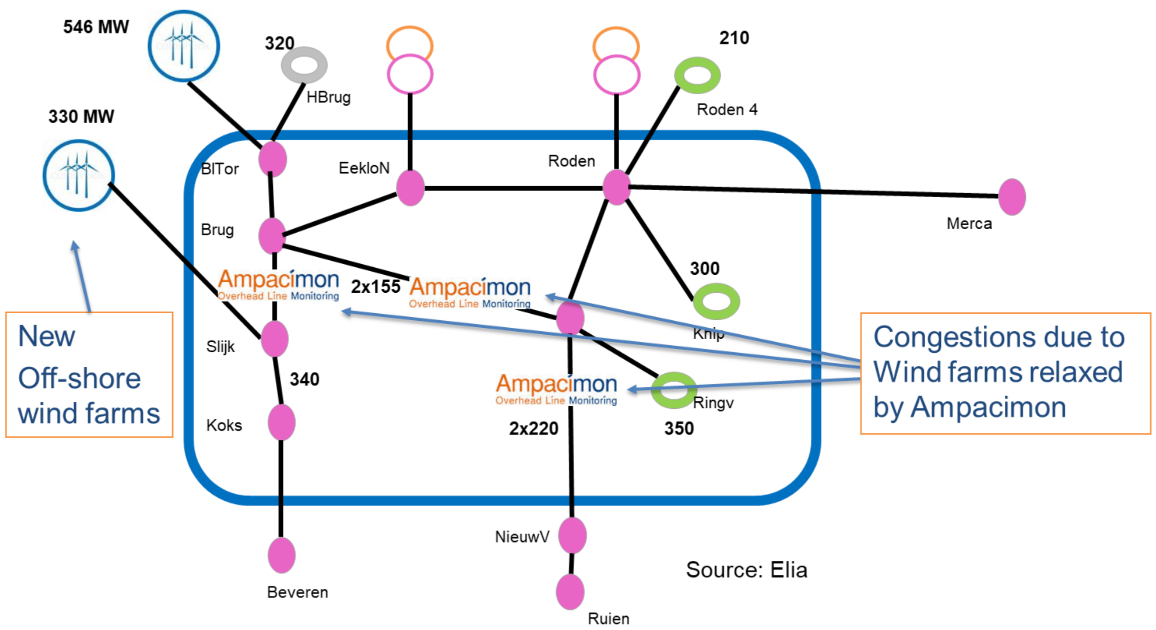

Figure 2 : Wind power integration in the Belgian grid

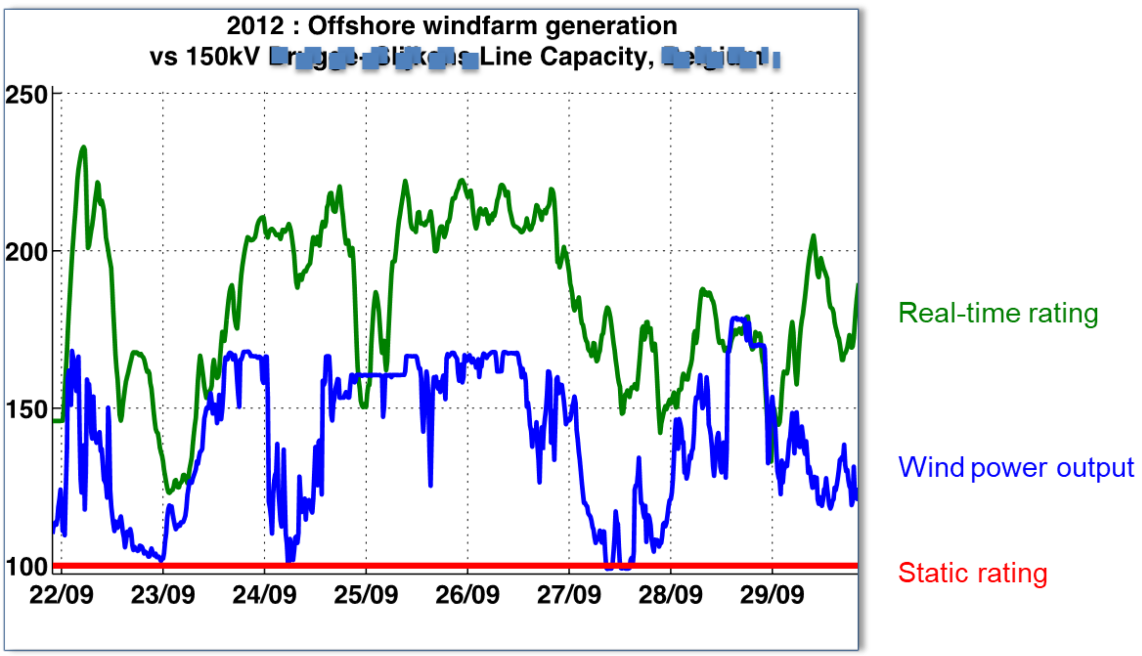

Figure 3 : Wind-DLR correlation

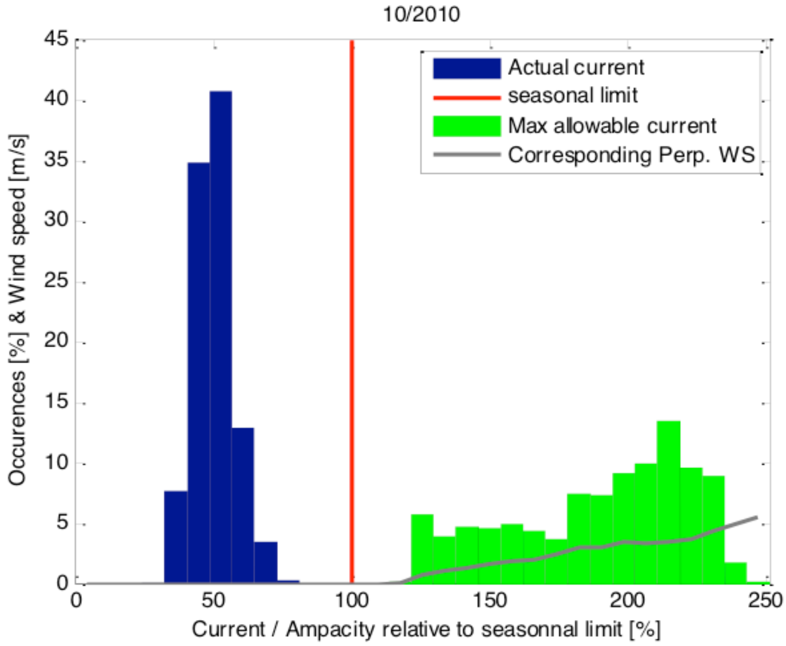

Figure 4: Histogram of available dynamic capacity (green) as percentage of static rating for October 2010.

Use case 2: Security of temporary loading can be guaranteed

The Belgian grid complies with operational risk of less than 0.1%. The risk cannot be compromised by using DLR. This means that forecast DLR values cannot exceed those used for real-time operation with a guarantee of 99.9%. Therefore, a methodology was developed by the TSO together with Ampacimon, which is outlined in [3]. As described in the document, "The basic principle is that by applying a methodology to integrate DLR in the [grid] capacity calculations processes for any timeframe, one should aim to maximize the average gain of the capacity increase without going beyond predefined levels of a risk increase for operating the grid in a secure manner." This means, in the process of ensuring grid security (e.g., N-1 calculations) for real-time operation (1-hour ahead until real-time), **DLR can be used as reliable capacity complying with the regulatory requirements**. Typical ways to do this are to apply a capping method, or a derating method. Both were investigated using Ampacimon sensor data by the Belgian TSO and compared as depicted in Figure 5. Here, the operational risks is shown as a function of the average gain of the DLR. The DLR values used in this analysis are sensor measurement based values accumulated from field application of Ampacimon sensors in the Belgian TSO's network. Clearly it is shown that for similar average gains, the risk level is much lower for a capping rule in comparison with a derating rule.

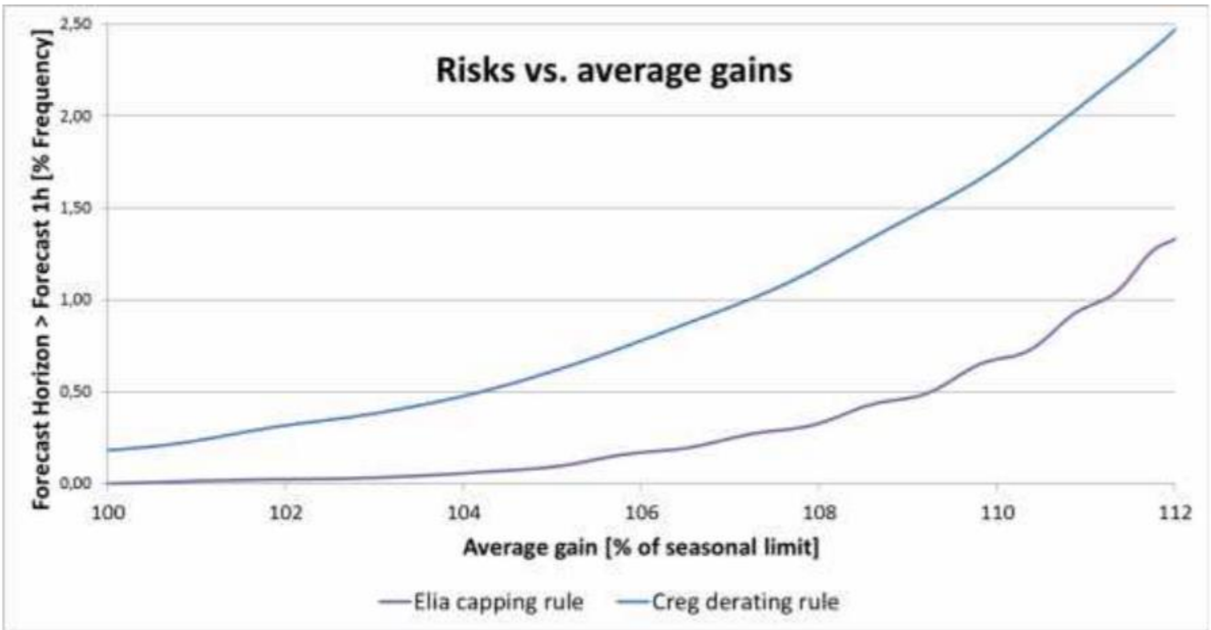

Figure 5 : Comparison of the operational risks (y-axis) in function of the average ampacity gains (x-axis) for both pre-treatment (capping and derating) approaches. Source: [3]

Furthermore, it was discovered that for the same capping level, the associated operational risks are systematically higher during the day than during the night. Therefore, the capping rule was extended, making use of two different upper capping rules that differentiates between night and day (these correspond with peak hours and off-peak hours during market coupling). For each cross-border line, the accumulated historical sensor data was used to perform the following analysis: for each hour in the peak and off-peak time, the forecast DLR value was capped where it exceeded the capping level. This value was then compared to the DLR value used in real-time operation. The number of hours where the capped forecast value exceeded the real-time value as a percentage of all the hours evaluated, is considered the operational risk. The results of this evaluation are shown in Table 1.

Therefore the final recommendation by the TSO was: to apply an upper cap at maximum 105% of seasonal rating for peak hours; and an upper cap at maximum 10% of seasonal rating for off-peak hours, while maintaining the values of the of seasonal rating as the lower limit.

Table 1 : Average Ampacity gains with respect to seasonal ratings and associated operational risks in function of the capping levels.

Cap (%)	All hours		Peak hours		Off-peak hours	
	Av. Gain	Risk	Av. Gain	Risk	Av. Gain	Risk
100	100,0	0,00	100,0	0,00	100,0	0,00
101	100,9	0,01	100,8	0,03	101,0	0,00
102	101,8	0,02	101,6	0,05	102,0	0,00
103	102,6	0,03	102,3	0,05	103,0	0,00
104	103,4	0,04	103,0	0,08	103,9	0,00
105	104,3	0,07	103,7	0,12	104,9	0,01
106	105,0	0,09	104,3	0,16	105,9	0,02
107	105,8	0,16	104,9	0,27	106,8	0,04
108	106,5	0,20	105,4	0,30	107,8	0,08
109	107,2	0,27	106,0	0,43	108,7	0,10
110	107,9	0,32	106,4	0,47	109,6	0,15
111	108,6	0,43	106,9	0,61	110,5	0,23
112	109,2	0,49	107,3	0,71	111,4	0,25
113	109,8	0,65	107,7	0,86	112,2	0,42
114	110,4	0,73	108,1	0,96	113,0	0,47
115	110,9	0,93	108,4	1,09	113,7	0,75

Use case 3: N-1 limits can be safely increased to capture market benefits

The following describes an example of incorporating reliable DLR in security constrained dispatch analysis. DLR can be forecasted with Ampacimon devices. A reliable 2-day ahead forecast can improve the results of market coupling which aims at maximizing the day-ahead market welfare. Market coupling methodology is Flow-Based in Central Western Europe since May 2015, which takes in to account the impact of market exchanges on the grid elements and the cross-border constraints. The impact of exchanges between two hubs on one specific grid element is modelled by a factor usually called PTDF (for Power Transfer Distribution Factor).

The key equation of Flow-Based methodology links, for each allocation period (usually 1 hour), the price spread between two different hubs with the PTDFs of the grid element constraining the energy exchanges. For a specific limiting constraint, this ratio is equal to the "shadow price" of the grid element, which is the amount of additional market welfare that would be generated if one extra MW was made available on the constraining grid element.

Flow-Based methodology allows associating to each hour the exact grid element constraining the exchanges in the coupled area. And an average shadow price can then be computed for recurrent bottlenecks in the extra high-voltage and high-voltage grid.

This is particularly useful for prioritizing the installation of dynamic line rating tools. Additionally, Flow-Based methodology allows valuing the gain for the community of the coupled area corresponding to one additional MW of scarce capacity made available for market exchanges.

Flow-Based constraints define a domain in which the market can clear without endangering grid security. If the market clears inside this domain, it means that the energy exchanges are not limited by grid elements and this will result in full price convergence in the between the hubs. On the contrary,

when the grid capacity limits the market, the clearing point will be at the border of the Flow-Based domain, on the constraining grid element.
A few extra MW made available on this specific limiting element can allow significantly higher exchanges between two different hubs (depending on the Power Transmission Distribution Factors (PTDF) of the constraining grid element) as only a part on the energy exchanged between the two hubs loads the limiting element.
To quantify the economic benefit of the 2-days ahead forecast dynamic line rating, we performed a simulation of the “Flow-based market coupling” in the CWE region with and without Ampacimon DLR 2 days-ahead forecasts. For example, on 19/2/2015, the market was limited due to Belgian import capacity. By using the 2-day ahead forecast, this limitation would have been less constraining. During this 4 hours period only, the gain of the forecast on the CWE welfare has been computed to 247.250 €, with an additional import for Belgium of 33MW.

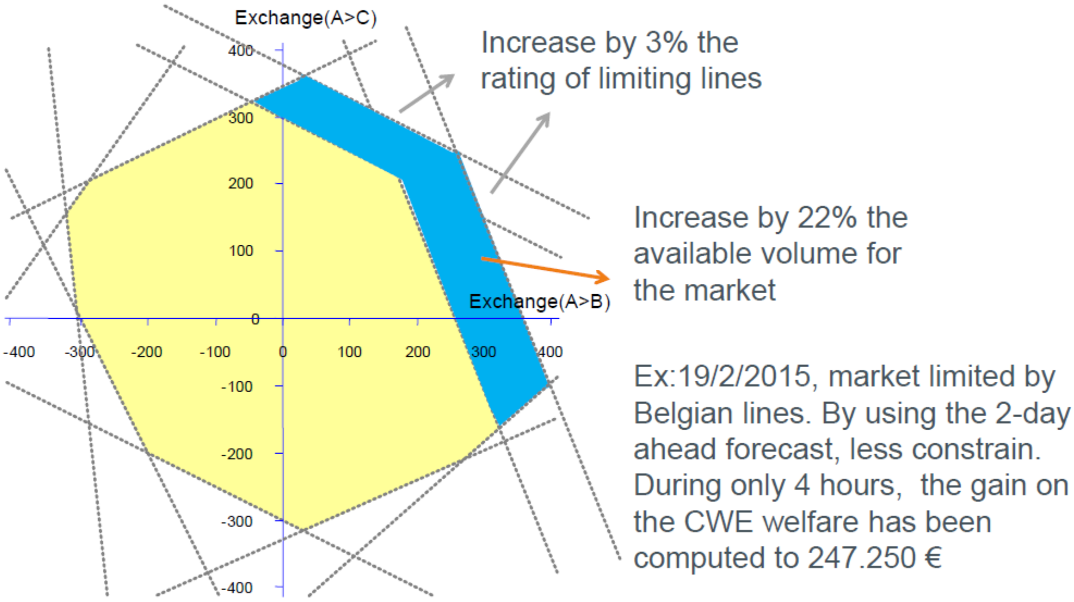

Figure 6 : Increase of welfare on flow-based domain. Source: Elia

Use case 4: Minimize impact during system maintenance
Critical maintenance that requires the outage of backbone transmission lines could be scheduled and implemented during times when the system impact is known to be less, without being affected by the infeed of wind power.
For example, a critical 220 kV line had to be consigned for several months for scheduled maintenance in Belgium. Disconnecting this line entails large costs due to re-dispatch plans. In this case, an adjacent line was equipped with 4 ADR Sense modules and monitored with ADR Operate real-time analysis software. For 3 months, this adjacent line could take in the additional load, namely an average 40% extra capacity. Ampacimon solution make possible for grid operators to set up maintenance plans that are much more flexible, less constraining, less costly, and quickly underway.

Use case 5: CAPEX savings in investment planning
Using statistics and probability of DLR is useful in investment planning for efficient design while ensuring security.

The use of a DLR which makes it possible to know the transit capacity for the next hours should logically reduce the conductive section of the conductors and therefore allow substantial investment gains. Even more so in the case of connection of wind farms, the climatic conditions ensuring good site production (presence of significant winds) are also conditions that promote the cooling of the conductors of overhead lines, which, in turn, ensures a transport capacity often much higher than the reference ampacity. This question of the impact of using a DLR can also be extended to the case of lines existing ones that need to be upgraded. When building a new power line, the question may arise

as to whether the use of a DLR (Dynamic Line Rating) reduces the cost not only of conductors but also pylons and their foundations, since the dimensioning of pylons is essentially dictated by the size of the conductors.
The basic idea of this use case regarding the impact of a DLR on the cost of building a line is to determine the financial gain that we would have for each of the elements of the line by choosing conductors of decreasing sections. The study results for an area of lines with lattice towers at voltage level 90 kV is shown in Figure 7. This line has a length of 14 km and includes 49 pylons (20 anchors and 29 suspensions). The financial savings due to down-sizing that could be achieved with different levels of DLR is shown. Obviously, the higher the potential for DLR, the higher the effect.

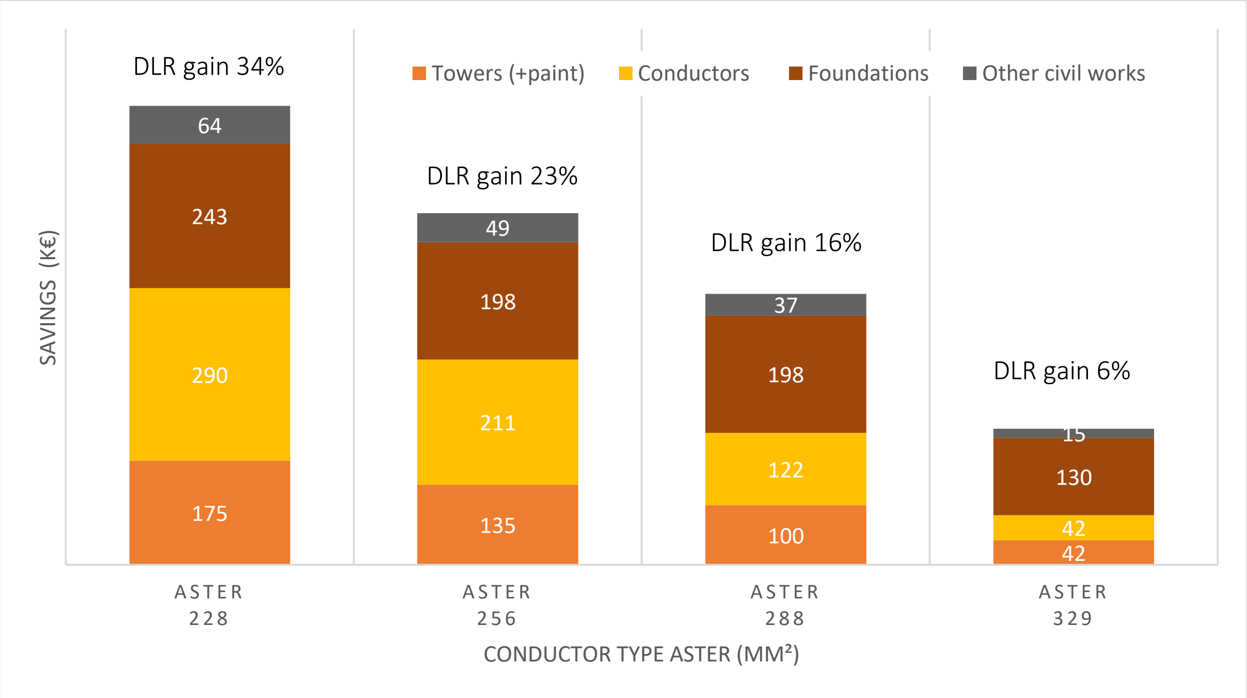

Figure 7: Financial savings for the subject 90 kV line

<u>Use case 6: DLR can be more secure than static ratings</u>.
Figure 8 indicates that sometimes DLR is lower than static rating. This means that if the line is used in full to the static rating limit, the line will drop below its maximum sag, posing a severe security risk. Application of DLR therefore reduces risk inherent in operational standards by introducing accurate measurement-based observations.

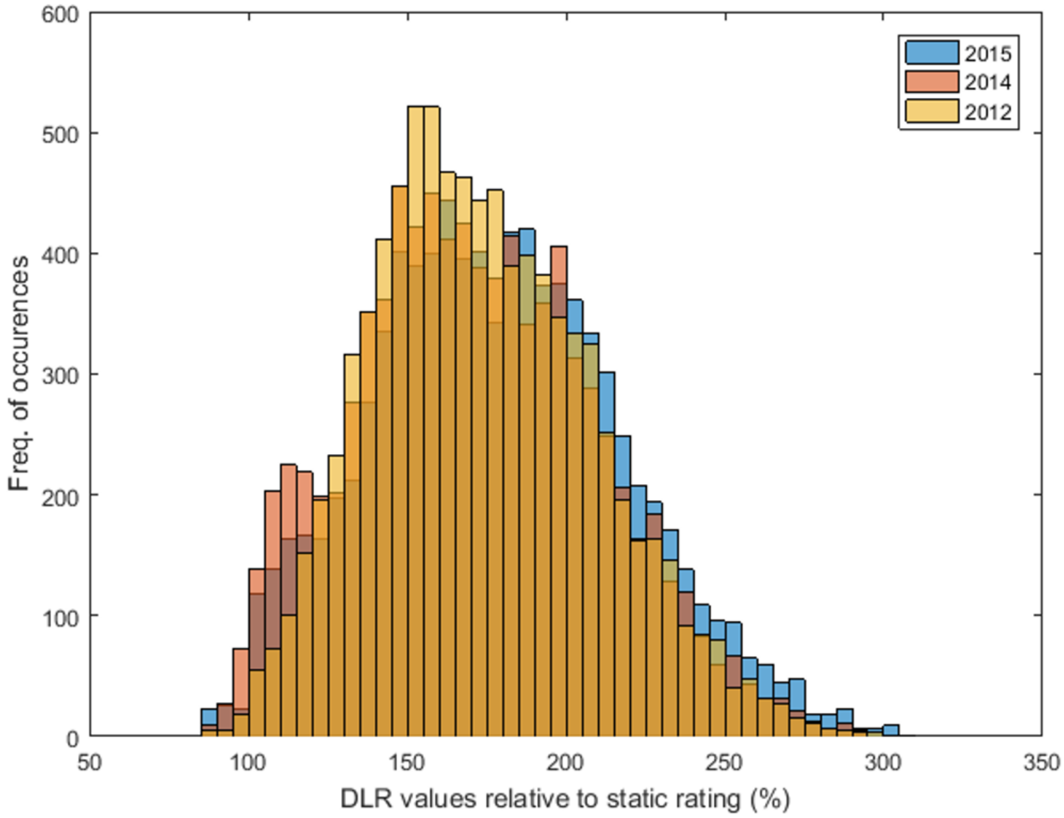

Figure 8 : Distribution of DLR gains compared to static ratings for German grid based on weather years 2012, 2014, 2015 [4]

CONCLUSIONS

The use cases in this paper demonstrates the benefits of DLR for optimized use of transmission systems and reduced burden of RE integration. While some of the use cases reported are strictly speaking in HV and not EHV, the results can be applied also in EHV.
DLR allows accurate thermal capacity assessment and with sensor technology (as opposed to models) additionally allows secure operation and capacity forecasting. It allows reduction of RE curtailment which may be needed if static ratings are applied in N-1 assessment and maintenance planning. It allows accurate emergency overloading, thereby giving more options to system operators. It also allows optimization of new asset build (secure undersizing of lines). Other benefits which could be harvested include grid outage by natural disaster, bridging the gap to recovery, shrinking demand in regional grid: Grid retirement planning, and with Ampacimon devices also possible to combine DLR with ice detection.

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