21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

C2-103

CIGRE 2014

Operational experience with Dynamic Line Rating forecast-based solutions to increase usable network transfer capacity

H.-M. NGUYEN*[1], J.-J. LAMBIN[2], F. VASSORT[3], J.-L. LILIEN[1]
Université de Liège[1], ELIA[2] , Ampacimon SA[3]
Belgium

SUMMARY

This proposed paper focuses on the criteria that need to be met to allow network operators to effectively use Dynamic Line Ratings in real-life operations. Today DLR has reached a point where the focus of research & testing has moved on from how to determine the most reliable & accurate rating to how to effectively integrate DLR in the processes of the network operators and maximize the use of the network. Different pilot projects in Europe and around the world have proven the DLR technology works in the field and many papers within CIGRE and other organizations highlight those results, but now the focus is shifting to how this technology can be put to best use: where it makes sense and how the results should be used to maximize the benefits while reducing the operational risks. The paper will highlight the experience the Belgian TSO, Elia, has had regarding those questions.

The specific aspects detailed here is the usability of day-ahead forecasting of DLR. Indeed, most decisions regarding network operation and Electricity Market are taken many hours/days in advance; therefore if DLR is to influence these decisions, a reliable forecast of the dynamic rating values is required. This is very similar to the need for the forecast of wind & sun production that allows the safe integration of those intermittent energy sources into the power system. Within the EU-funded FP7 Twenties project, the University of Liège, Belgium, together with Ampacimon has developed such a capability. Elia and Coreso have evaluated the usability of such a DLR forecast value to increase the flexibility of the network, to allow more exchange capacities for the market, and help solve pan-european congestion issues related to the increasing share of intermittent power from RES (Renewable Energy Sources) in the energy mix. Two-day ahead DLR forecast has shown an average capacity improvement of more than 10% over seasonal rating with 98% confidence. The confidence interval may be adjusted to operational needs, as a tradeoff between more gain and more confidence in the forecast has to be set, depending on the risk policy. Different cases may even feature different risk policies, making them flexible as well, e.g. what are the other available options to increase flexibility at that moment? These forecast capacities can then further be used for day-ahead management of PSTs (Phase-Shifting Transformers) in a coordinated way, together

HM.Nguyen@ulg.ac.be

with stability forecast algorithms developed thanks to PMUs (Phasor Measurement Units) measurements.
The paper will further highlight 3 years of operation of two critical lines located near the North Sea and impacted by the connection of off-shore wind resources using intra-day and day-ahead forecasting of DLR. It will answer the following questions: what were the usable operational gains?, what were the lessons learned ?, how was DLR integrated in the operational tools & processes ?

The conclusion of those experiences shows that innovative solutions emerge from two-day ahead ampacity forecast provided by DLR. They release their full operational capabilities when combined with controllable assets (FACTS, PST, curtailment) and stability monitoring (PMUs) within integrated solutions. They hence achieve the objective of increasing the efficiency of the existing network and help integrate intermittent renewable energy sources in a safe and economical way.

KEYWORDS

Transmission lines - Dynamic line rating - Thermal rating - Weather forecast – Ampacity - Smart grids – Sensors – Planning – Network - Market.

INTRODUCTION

Wind farms and PV development have continuously grown over the past years. In Europe only, wind farm installed capacity was 90GW in 2011 with more than 10% annual growth [1]. This change in the production portfolio generates very significant needs for additional transport & distribution capacity at all levels of the network. It is more and more obvious that replacing, uprating and building the required new electrical power lines (50 000 km in Europe) [2] will become the main bottleneck to reach the EU 20-20-20 objectives. Therefore it has become mandatory to develop new approaches to increase the efficiency of the existing network assets in a secure way and deliver the required capacity in a timely and economically viable way.

Intermittent & distributed generation significantly changes the characteristics of the power flows in the various networks, increasing the need for capacity but at the same time reducing the line usage factor (MWh transmitted per MW of transmission/distribution capacity) of the network assets due to the increased volatility and variability of the flow patterns. One of the solutions to adapt the system to these new constraints is Dynamic Line Rating (DLR), which allows TSOs and DSOs to monitor their existing assets in real-time and significantly increase the dynamic line capacity, also known as ampacity, over the traditionally used static/seasonal ratings.

Moreover, Dynamic Line Rating of overhead lines combined with Active Network Management have proven to be very promising in this frame [3], as a strong positive correlation between wind farm generation and an increase of nearby transmission & distribution lines ampacity have been shown. Extra line capacity is thus available when required, and this without waiting for infrastructure reinforcements/extensions that often lead to both long delays and cumbersome costs. The optimum efficiency is obtained when DLR is combined with the possibility to adapt/curtail generation. When DLR is used, allowing a small percentage of curtailment significantly increases the amount of renewable generation that can be connected to the existing network, and thus gives an optimal solution for all the concerned actors: TSO, DSO and wind farm owners and investors.

However, up to now, few experiments addressed ampacity forecasting, which is of prime interest for TSOs, DSOs and the whole electricity market. Indeed most decisions regarding the operation of the network are taken either one day ahead or 2 days ahead, such as the capacity nominations (NTC) for the cross-border energy markets [5].
The University of Liège (ULg), Belgium, successfully developed an algorithm based on real-time DLR measurements and weather forecasts within the EU Twenties project to provide two-day ahead ampacity forecasts with controllable prediction interval, despite high sensitivity of dynamic rating w.r.t. low wind speeds, typically hard to measure and forecast [4].

However, even though very conclusive results have come out of those experiments, system operators are still somehow reluctant to undertake large deployment of DLR systems on their network.

This paper deals with decision making issues TSO's are facing today, including change in present processes, investment strategies, risk management, complementarity with other available technologies, line installation and operation.
Those issues being extremely vast, only the most prominent ones, gathered in-the-field, will be presented and discussed here.

MAIN ISSUES PREVENTING LARGE DEPLOYMENT OF DLR TECHNOLOGY

Even though DLR is today a robust and reliable technology, system operators are still baulking at adopting it massively. The reasons are manifold [10], and are investigated below.

First, TSOs need to believe in the technology. That's the reason why many pilot installations have been driven with successful outcomes these last years. This point can be considered overcome today with collaborating TSOs. Independent measurements have shown that a reliable measurement of the sag (±20cm) could be achieved with the studied DLR sensor. New TSOs wanting to adopt the technology still systematically require a pilot phase, that may be long for the reasons explained below, which has been postponing large deployments. That delay shall however narrows as more and more TSOs adopt DLR to operate their network, particularly when figures can be put on the benefits brought by this technology.

Second, TSOs have to ensure a smooth and global integration of this technology in their IT system, in particular implementing DLR information in their EMS (Energy Management System), preferably through their SCADA. This enables operators to practically make use of the technology, by including DLR data in network security analyses (e.g. N-1 situations), and by keeping the information up-to-date continuously. In this regard, reliability in communication systems has become a major concern for smart grids technologies. In the case of communication failures, safe fallback modes have to be well thought up beforehand, to be able to maintain the system's security — though functioning in a degraded mode —, until complete restoration.

Third, new processes have to be defined to adapt system operation to DLR. Indeed, highly regulated entities like TSOs follow very strict operating rules and processes. A large-scale deployment of DLR brings a lot of information, which has to be gathered, processed, and managed to come up with decision rules to apply on the field in due time. This thought process is somewhat heuristic, as those processes may vary from one TSO to another, depending on the availability of control tools (FACTS, PSTs, HVDC, ANM, etc.), the particular topology and regulation rules. System operators have to define the most efficient way to deal with this new piece of information and bring it in line with present operator's procedures: how to gather relevant information in real-time?, how to deal with alerts?, and what are the actions to take in those cases?
Beyond operating processes, installation processes have to be defined as well to speed up the technology deployment. Today, there are no generalised written procedures featuring criteria to determine what kind of line should be installed with DLR, nor which the critical spans to monitor are (including the probability of low wind speed occurrences, and the presence of obstacles below the span).

Fourth, DLR has to be considered from a global perspective. Balancing its investment and implementation with other available smart grids or conventional solutions, taking into account several variables like the type of issue to solve (congestion, curtailment, market,…), implementation lead time, return of investment (ROI), reliability, added flexibility, available manpower, investment prioritisation, as well as the regulatory framework. Some uncertainties, and the lack of preceding experience may push utilities to unfortunately opt for unsuited, but more familiar options. On top of that, no clear methodology has been developed yet to assess the ROI, or avoided costs, provided by DLR. This is a central point that determines large-scale deployment of DLR technologies. If investors don't have a clear visibility on their investments, experiments will probably be limited to pilot projects. For that matter, the development of medium-term ampacity forecast at a horizon of 2 days brings a great deal of value to DLR, as forecasting firm extra capacity directly impacts the market in a deregulated environment.

PROPOSED SOLUTIONS AND IN-THE-FIELD RESULTS

Confidence in the developed technology has been built over the last six years with collaborating TSOs. Remarkable reliability of the real-time measurements, significant gain on monitored lines, conclusive results and close cooperation between the product development team and TSOs have proven fruitful (Fig. 1 and 2).

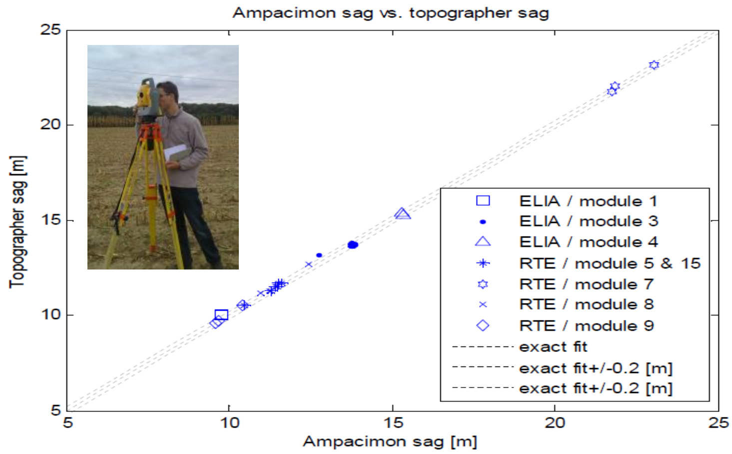

Fig. 1: *Studied DLR's sag measurement vs. independent sag topography measurement showed very good agreement (±20cm).*

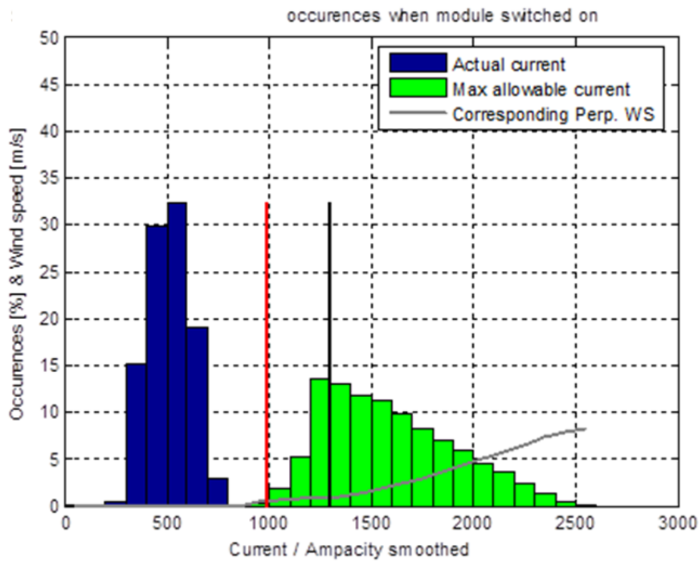

Fig. 2: *typical histogram of power line loading. Static rating is 1000 A. Actual loading on the left hand part (under normal operating conditions) and available ampacity, on the right-hand part, with a trend curve giving the corresponding effective wind speed (same scale as occurrences but in m/s). The black line features other equipment limits as for today.*

Integration into TSO's IT system is the second required stage. Regarding our experiments, a full stand-alone data processing and communication software has been developed, through iterative processes between the University of Liège, the DLR manufacturer, the Belgian TSO (ELIA), and the system integrator as early as 2008. Ampacity and other relevant information are sent in real-time to the EMS, through Electronic Highways (TASE.2 protocol), so that it may be used dynamically for network security calculations (PAS software). A full front-end web-based display has been implemented as well. Safe fallback modes have been implemented, yielding a conservative value for ampacity in case of data inconsistency or communication failure (Fig. 3).
IT operational implementation and integration in TSO's EMS is today up and running, and is used in operation (real-time and 1h-4h forecast) for the 150kV Bruges-Slijkens line experiment with ELIA. Less congestion alerts on the equipped line have been reported since by ELIA. The overall benefits (spared actions, redispatching cost, …) has still to be assessed.

Today, those two required stages experience different degrees of completion depending on the DLR system involved.

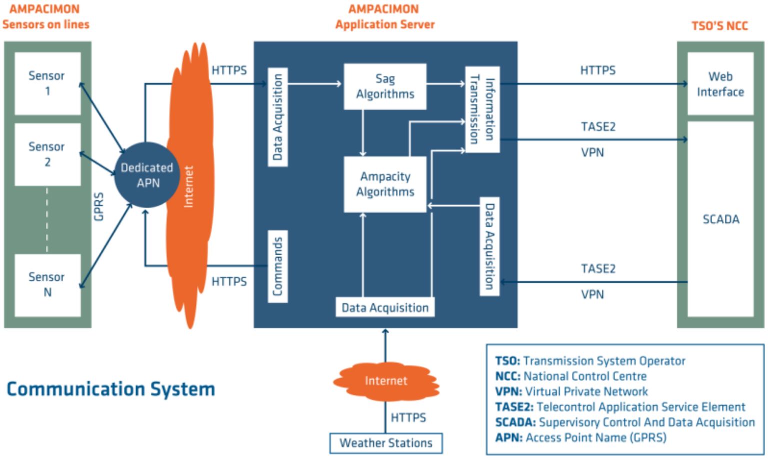

***Fig. 3**: IT platform developed for the studied DLR system providing real-time ampacity and short-term forecast. Those outputs are coupled with TSO's quarter-hourly network security calculation software.*

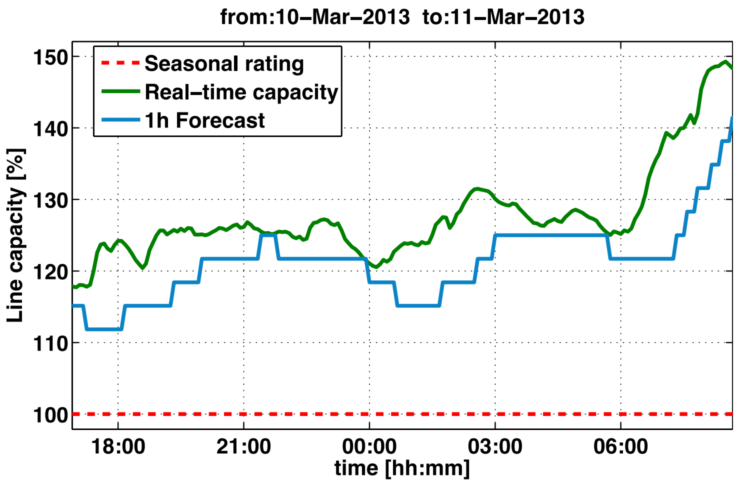

***Fig. 4**: DLR and the corresponding one hour ahead forecast, over 12 hours.*

Regarding processes, even though some line check-up procedures prior to DLR installation have begun to appear [9], adapted operation processes, on the other hand, have not been clearly defined today, as practical use of DLR technology remains occasional.
In fact, knowing dynamic rating in real-time is actually not enough, real added value comes with ampacity forecast. Indeed, transmission network is typically operated on a quarter-hourly basis and unless emergency has to be dealt with, dynamic ratings should be known in advance to operate the network properly.
At least, short-term ampacity forecast (>15min) is required to know the forthcoming dynamic rating, so that appropriate resources be allocated in case of contingency, whether by changing topology or modifying the generation pattern, if necessary. A short-term ampacity forecast algorithm using DLR measurement history has been developed for this purpose (Fig. 4)

However, even if intraday market is developing, it is today still confined to adjusting days ahead procurement. In fact, the essential core security calculations providing the grid's operational limits for the market are carried out two days in advance, such as the capacity allocations (NTC) for the cross-border energy markets. After market has taken its positions, thorough network security calculations are then done one day ahead. Therefore, DLR essentially gets its added value when it can forecast line ratings at a horizon of a few days. Anticipation is the key, as it provides more lead time in the overall decision-making process, which gives access to safer and more optimal solutions, thus preventing incidents, congestions, and ultimately black-outs.
An algorithm using DLR measurement history combined with weather forecast, has been successfully developed for the Netflex Demo within the EU TWENTIES Project (2010-2013), providing an

average capacity improvement of more than 10% over static rating with 98% confidence, on the tested lines (Fig.5). This is a major goal achievement, as those results provide a significant added value to DLR, which can now be used as a market tool, and in day-ahead security calculations.
The implementation for operational use of that medium-term ampacity forecast by the TSO is currently ongoing. ELIA has confirmed its interest in the technology by the forthcoming installation of that DLR system on 6 new lines in its network.

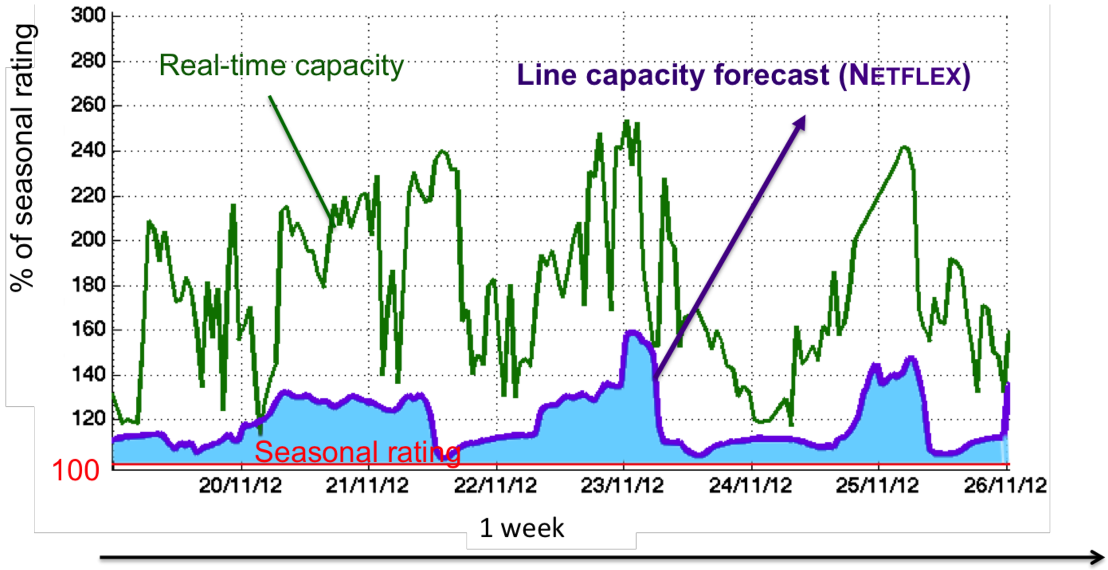

***Fig. 5** : (i) real-time capacity (=ampacity) and (ii) Twenties two-day ahead forecast, developed at the University of Liège, Belgium, guarantees a safe ampacity forecast.*

The goal of NETFLEX was to demonstrate that network flexibility enables getting more transmission capacity where and when it is needed without compromising operational security. It shows how more accurate smart monitoring and enhancement of the grid controls allow TSOs to plan & operate their networks closer to their "true" actual limits. Simulations have been carried out on the Central Western Europe (CWE) region, to assess the combined benefits of using DLR, PST, and PMUs. Added flexibility was demonstrated when using 2-day ahead DLR forecast with smart-PFC schemes (smart coordination of PFCs in CWE).

Confidence interval control in DLR forecast could even find a broader application, when combined with PFCs like PSTs. Indeed, in open transmission systems the vast majority of energy is sold in day-ahead markets, based on a bidding process [5]. With a few exceptions, transmission network owners can only sell firm transmission capacity. Capacity that is "almost" firm has no value in such markets nowadays [6]. However, this situation will probably change in the near future. If smart-PFC algorithm is combined with DLR forecast, higher gain with lower confidence interval on ampacity forecast could be used as well, provided control means are available in real-time, to make up for incorrect forecast when needed.

On the planning side, a strong positive correlation between wind farm generation and an increase of nearby transmission & distribution lines ampacity have been shown in the latest results obtained on the Brugge-Slijkens line equipped with the DLR sensors, in Belgium (Fig. 6). This would allow less curtailment of existing wind farms and/or more wind integration using existing assets.

Even though all those results speak in favour of large DLR deployment, its implementation is still lagging.
One of the reasons to explain this situation is the current complexity to clearly determine the ROI of the technology, and the proper timing for installation. Indeed, load flows are often changing unexpectedly due to the fast growth of intermittent generation and the very dynamic context of a deregulated market in large interconnected meshed networks, like in CWE, which results in congestion displacement in a matter of years or even months! Another consequence of the

deregulation is the growing difficulty to disconnect a power line for maintenance than it was in the near past (most DLR sensors can be installed live-line to get round this issue).

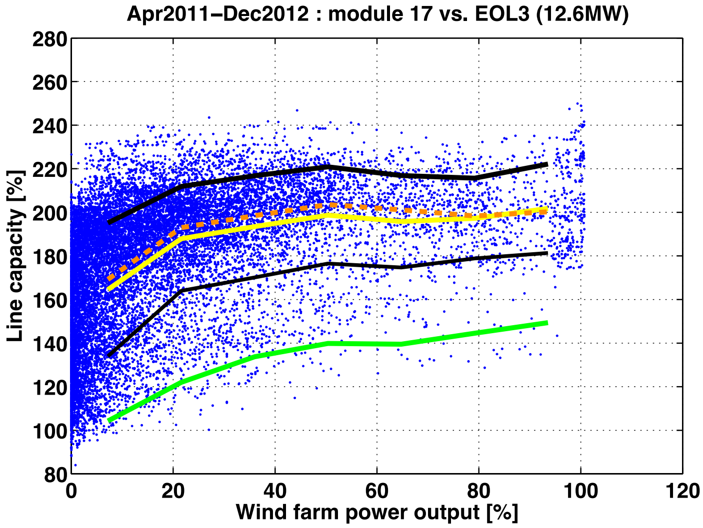

Fig. 6 *: Ampacity for one span of the power line causing the bottleneck versus wind farm generation (relative values to seasonal rating, and nominal power output respectively) for the Brugge-Slijkens line, located about 10km away from the wind farm. Mean (yellow) +/- 1 standard deviation (black), and percentile 50 (dotted orange) are given; percentile 98 (green) of this sample is provided for information purpose.*

Some TSOs we have worked with have expressed their concern about the increasing constraints and moving bottlenecks they have to face. New rules related to trading, generation location and power flow that were not present before the 2000's began to appear [7]. Connection in a short time as possible of new power plants is no longer planned well in advance, and lines connected to it may be below the ideal capacity. Pressure applied to engineers to increase the allowable rating of lines often results in rapid decisions without in-depth analysis [8]. That's where DLR comes in handy to provide more flexibility. Moreover, when congestions move, DLR systems allow to relocate monitoring accordingly, at low cost and rapidly, --- it can be fully operational in a matter of months ---, in contrast with other methods. This aspect may be more critical than it seems, as for other experiments with some less flexible DLR technology, TSOs experimented congestion displacement, leaving that DLR system ineffective. For that matter, DLR seems indeed to be the best option for a network that is subject to power trading, as it allows large dynamic capacity increases for short periods of time [8].

However, no clear methodology has been developed yet to rapidly assess the relevant network configurations to be equipped with DLR. Once the flow-based market coupling (FBMC) is fully implemented (expected at the end of 2014 in CWE region), it will be much easier to assess the potential gain of installing DLR from one line to another. Indeed, in that frame, constraints are real elements in the grid, and in case of congestion, the so-called *shadow price* indicates the marginal gain of welfare for one additional MW of available capacity on a limiting line considered in the FBMC. In fact, ELIA has already been carrying out a reflection to integrate DLR forecast data into flow-based tools and get the most out of that DLR technology as soon as possible.

The diagram depicted in Fig. 7 features the Security of Supply (SoS) domain available for the market.
A power exchange is a market place where the demand and supply bids of a country, or group of countries, on a day ahead basis are collected and matched. This will result in one price and a net import (demand) or export position (supply) per market area for all the coupled countries.
However, the results of the market coupling should be feasible in the grids of the TSOs of the countries involved. Therefore, the TSOs need to assess the capacity that they can provide to the day ahead market coupling algorithm, to facilitate the market in the best feasible way, while safeguarding the Security of Supply. The market coupling algorithm therefore solves a constrained optimization problem, where the market welfare is maximized while respecting the security constraints provided by the TSOs. When one or more of the constraints is hit by the market coupling algorithm, different

market prices are the result in the coupled markets. Congestion income, paid for the scarce capacity, isthen collected by the TSOs. By contrast, when no constraint is hit, the market prices are identical for all countries and no congestion income is collected [11]. By relaxing the constraint on lines equipped with DLR, day-ahead DLR forecast allows to reduce or eliminate the gap between different market prices in a congested situation, it therefore increases global welfare.

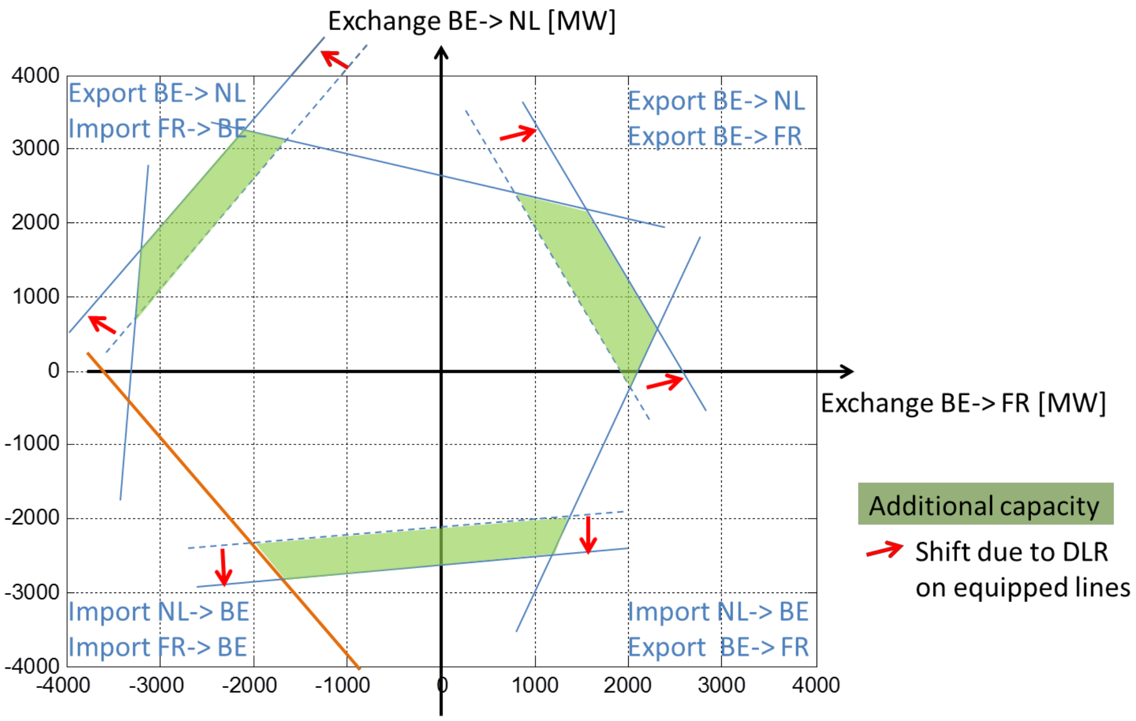

***Fig. 7** : Simplified representation of a two-dimensional SoS domain, delimiting import(-) and export(+) capacities between Belgium and its neighbouring countries in a day-ahead market. The SoS domain can be determined by making assumptions with regard to the foreseen grid situation and by performing contingency analyses. SoS domain is typically delimited by line thermal rating constraints in N-1 situations (blue lines), or network stability constraints (thick orange line) which are not considered in the flow-based DC calculations. DLR forecast allows to expand thermal rating constraints on equipped lines (green area), providing more exchange capacity for the market. Only a few percent increase on critical lines already bring significant gain for the market. The day-ahead DLR forecast algorithm developed inside the EU TWENTIES Project is being implemented for this purpose.*

Without this tool, a case-by-case study is required, to assess the potential ROI of installing DLR on the studied line vs. the potential of other (possibly combined) solutions. Nevertheless, even without in-depth market analysis tools, the availability of 2-day ahead DLR forecast can change a great deal the situation, as substantial gain on congested lines located near wind farms could dramatically reduce curtailment, fostering larger deployment of DLR. TSOs we have worked with are already carrying out a deeper reflection to encompass DLR in operational and planning processes, to follow up on the successful experiments achieved in their network. DLR installation criteria based on line overload level as well as weather statistics are being studied by ELIA. Discussions are also ongoing with RTE, the French TSO, to equip a cross-border line with DLR, to improve global welfare by providing more line capacity to the market with existing assets.

CONCLUSION

The aim of this paper was to explore the criteria that need to be met to allow network operators to effectively use Dynamic Line Ratings in real-life operations, and allow large deployment of this technology, in the framework of the fast growth of intermittent generation and the very dynamic context of a deregulated market.

Four main stages have been identified.

Stage 1 & 2: Confidence in the technology as well as full IT integration are required. Those stages have been successfully achieved through our experiments and close cooperation with the DLR manufacturer and integrator, and with involved TSOs these last years.

Stage 3 & 4: Development of adapted processes related to DLR (for operation and installation) and the availability of a methodology to assess the relevant network configurations to be equipped.
Those stages are underway, we believe they will be stimulated by the practical return of investment (ROI) and the added flexibility generated by the medium-term ampacity forecast, which has been validated in the field and which is now being implemented for operation. Flow-based coupling tools, still in development, and expected by 2015 in CWE will greatly enhance ROI estimation, and further DLR deployment.

Bringing line capacity forecast into operation will certainly add significant value for DLR on the market, in particular regarding wind power integration. Effectively using that uncovered line capacity will generate substantial welfare by lowering overall generation costs. Following the EU Twenties project – Netflex Demo results, additional flexibility can be found by combining various control and monitoring tools : DLR, PST, PMUs, FACTS, HVDC, ANM, DSM,…

ELIA, the Belgian TSO, is looking forward to using the leverage that DLR technology offers by confirming the installation of 6 new lines in its network, and is already setting the stage with neighbouring TSOs for DLR forecast implementation into day-ahead operational security calculations and market tools on cross-border power lines.

In-the-field results show that Dynamic Line Rating can provide immediate benefits in today's networks, but how about looking ahead into the future? Enhancing network flexibility means increasing grid utilization. It is a better way to use existing asset, though it does not create additional permanent capacity as such. Today, as most decision-making issues are dealt with using a deterministic approach, DLR allows to close the gap between congestions appearances and the effective commissioning of new pieces of network that takes between 5 and 10 years. But with the development of flow-based market coupling, and probabilistic planning, DLR combined with other smartgrids tools could find a much broader use by being included in the overall planning, market, and operation processes.

ACKNOWLEDGMENT

These developments have been made possible owing to EU support inside the TWENTIES project, which is part of the seventh framework program (www.twenties-project.eu).
The partners of NETFLEX demo inside Twenties have to be thanked owing to their major contribution:
ELIA, coordinator (Belgian TSO), CORESO (European supervisor of the network), Siemens Belgium (hardware integration), ULg, KUL and ULB (three Belgian universities), Ampacimon SA (sensor manufacturer as well as global integrator of DLR part inside Coreso). In particular the collaboration between ULg power system department (authors) and ULg topo-climatology department (Pr. M. Erpicum and S. Doutreloup) was particularly useful.

BIBLIOGRAPHY

[1] ENTSO-E, 2012, *Statistical Yearbook 2011,* Secretariat of ENTSO-E, Berlin, Germany, 10.

[2] ENTSO-E, 2012, *10-Year Network Development Plan 2012,* ENTSO-E AISBL, Brussels, Belgium, 62.

[3] P.Schell, J.-L. Lilien, H.-M. Nguyen and al., "Large penetration of distributed productions: dynamic line rating and flexible generation, a must regarding investment strategy and network reliability", *CIRED Workshop*. *Lisbon*, IET, paper 280, 2012.

[4] H.-M. Nguyen, B. Godard, P. Schell, J-L Lilien, "Reinforcement learning using weather forecast and power line sensor as a key to optimize your power line assets in a changing world for DSOs and TSOs", CIGRE Symposium, Auckland, NZ, paper 345, 2013.

[5] K. De Vos and J. Driesen. "Balancing management mechanisms for intermittent power sources A case study for wind power in Belgium.", 6th International Conference on the European Energy Market, pages 1–6, May 2009.

[6] Working Group SC B2-36 CIGRE. TB498 : "Guide for Application of Direct Real-Time Monitoring Systems.", June 2012.

[7] Paul J Werbos. "Computational Intelligence for the Smart Grid History, Challenges and Opportunities." IEEE Computational intelligence magazine, (August):14–21, 2011.

[8] R. Stephen. B2-201: "Description and evaluation of options relating to uprating of overhead transmission lines.", Cigré Paris, 2004.

[9] R Puffer, M Schmale, B Rusek, and *al*. B2-106 "Area-wide dynamic line ratings based on weather measurements.", Cigré Paris, 2012.

[10] H.-M. Nguyen, "Dynamic Line Rating and Medium-term Ampacity Forecast of Overhead Lines using vibration sensor", PhD thesis, University of Liège, Belgium, 2014.

[11] M. Aguado, R. Bourgeois, J.Y. Bourmaud, and *al*. C5-204 "Flow-based market coupling in the Central Western European region - on the eve of implementation –", Cigré Paris 2012