Dynamic Rating of HVDC Interconnectors

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Abstract

HVDC interconnectors connect two points of a power system, efficiently transmitting large amounts of power over large distances. These assets contain power electronic-based converters and often buried cables designed to enable the continuous transmission of a fixed nominal amount of power. However, some designs temporarily allow higher capacities.

In this paper, we examine and investigate ways to maximize the economic value of these additional dynamic capacities. We show that significant economic gains can be achieved by offering the dynamic capacity to the market at the right moments. But, we found that these economic gains are hindered by the current market design restricting the optimal utilization of the assets.

1 Introduction

HVDC interconnectors are typically used between distant or asynchronous power systems or when there is a strong technical or economic motivation for additional controllability (e.g. in real power transfer). These HVDC interconnectors help in the cost-optimal utilisation of energy resources and thus increase social welfare.

HVDC interconnectors are high-cost power system assets, and therefore it is important to utilise these systems effectively. The large majority of HVDC projects are promoted by TSOs, with the regulators' approval and set tariffs. Some projects are promoted by private parties referred to as merchant lines. These tend to recuperate their investment from the power flow through the interconnector and the price differences between the connected areas [1]. In this case, the owners of HVDC interconnectors in coordination with relevant TSOs should agree which advanced services could be implemented to allow more efficient use of the network and resources for the benefit of consumers. Hence, a cost-benefit analysis is needed focused on the following principles: investment return, electricity market benefits and security of supply improvement. The ability to provide temporary additional capacity beyond the nominal capacity of a system, i.e. overload capacity, can therefore have economic benefits.

In addition to commercial motivations for overloading, there are also operational benefits, for example, to mitigate challenges in emergency conditions [2].

1.1 Overload capabilities in power system equipment

For economic and operational reasons, it is advantageous to maximise the utilisation of power system assets. The changing power flows in the network demand increased network capacity, and geopolitical tensions have recently impacted energy markets, so there are increasing benefits to fully utilising power transfer capacity.

There are several methods to temporarily increase the transmission capacity of existing power system assets, taking advantage of their transient properties (e.g. thermal) and advanced monitoring to enable higher currents and, therefore, higher power.

For AC transmission lines, Dynamic Line Rating (DLR) provides flexibility using knowledge of environmental factors (e.g. air temperature and weather conditions) to dynamically vary the allowable current rating on an overhead line. DLR applies environmental forecasting and continuous monitoring (e.g. of line sag), and is commonly applied to constrained assets. It has been applied by a significant number of transmission system operators in the last decade, e.g. [3], and is being trialled for cross-border applications [4].

Similarly, the current rating of a transformer is primarily a thermal constraint, and given that transmission system transformers have a high thermal capacity and cooling is dependent on environmental factors, it is possible to perform dynamic rating on transformers with, e.g. 20-50% overloading depending on environmental conditions [5].

Finally, the current through power cables is also limited by thermal time constraints. The thermal constants of cables are expressed in hours [6, 7], and due to increasing usage of monitoring systems [7], there is significant capacity for short-duration overload in both AC and DC cables.

Like in AC transmission systems, there are methods (and benefits) to temporarily increase the transmission capacity of HVDC systems. The constraints of this additional capacity are highly dependent on the technologies applied in the HVDC system.

1.2 HVDC technology

HVDC connections consist of several key electrical elements - an AC/DC converter, an AC transformer, and a cable or overhead line. These are supported by essential systems such as control and protection and cooling.

An HVDC converter consists of large numbers of power electronic devices (e.g. thyristors or IGBTs), and is a highly complex asset which requires advanced control and monitoring to maintain stable operation and reduce the risk of component damage and/or interruption of power transfer. The power electronic devices are highly sensitive to overcurrent and overvoltage, and do not tolerate momentary conditions beyond these (e.g. compared to traditional power system assets such as transformers). Converter stations are therefore operated within strict limits.

HVDC transmission systems use OHLs or cables to transfer energy. Conduction losses result in heating of the conductor, which limits the power transfer capability of the system. In the case of a cable - in itself a high-value asset - temperature rises are particularly high risk and could lead to failure of the cable. Thermal monitoring is, therefore a critical aspect of condition monitoring for an HVDC cable. The thermal time constants of HVDC cables is comparable to those of AC cables.

The power transfer through an HVDC connection is dependent on the continuous operation of numerous systems, e.g. control, protection, and cooling. The nominal (rated) power is a combination of electrical constraints (e.g. voltage limits, current limits, energy storage limitations), thermal constraints (e.g. transformer temperature, cable temperature, converter cooling systems) as well as constraints on the support systems.

It should be noted that, depending on the system design criteria, the power rating of different elements in a system may not be identical, e.g. in one known VSC-HVDC system the converter stations have a 20% higher rating than the continuous cable rating [8]. This additional power capacity could be used for short-term overloading in the future.

Although the power transfer/rating is normally set by these physical constraints, many HVDC systems are designed to allow for a controlled increase in the rating over a short period. This overload capacity may come at a penalty of increased losses or other reductions in functional performance and financial cost. The technical limitations are dependent on converter technology and the transmission medium.

1.2.1 Overload capability of LCCs: Line Commutated Converters (LCC) are the traditional converter technology, with significant installed capacity worldwide. An LCC uses thyristor bridges to convert tbetween AC and DC (The conversion incurs conduction losses in the thyristors as well as in the transformer and other components).

LCCs typically have the capability to provide significant short-term overload capability by utilising overheads in their ratings. This dynamic overload capability is dependent on the availability of redundant cooling systems and on the ambient temperature at the converter station. Known LCC systems have wide-ranging overload specifications - between 3 seconds and 8 hours [2], for e.g. 10% to 40% overload capacity [2].

1.2.2 Overload capabilities of VSCs: Voltage source converters (VSC) are a comparatively new technology with the first VSC-HVDC being built in 1997. VSC-based HVDC systems have limited inherent overload capability owing to thermal runaway, over-voltage, and over-current sensitivities of the IGBT switches [9]. In particular, regarding current limits, overload capabilities can be achieved either by over-sizing the converter station (increasing stored energy, increasing arm voltage, or increasing arm current) or controlling the harmonic circulating currents - e.g. with possible short-term overloading of 27.5% [10]. Beyond these constraints, thermal limitations on transformers, cables and cooling systems are considered to be broadly similar to those in LCC systems.

1.2.3 Discussion – technology limitation for overload: Different HVDC system components have different overload capabilities as discussed above, which in turn influence the overall system overload capacity. Cables, conductors and switchgear are known to have higher overloading capabilities for longer duration of time [11]. It is seen that power electronics components (e.g. thyristor or IGBT) have very limited overload capability and can sometimes be used for small short-term overloads. Cooling systems, on the other hand, have larger thermal capacity and can therefore allow longer duration overloads. The thyristor/IGBT valves are weakest in overloading the HVDC systems and, thus, constrain the overall system overload capability. LCC-based HVDC systems are known to have better overload capability than VSC-based HVDC systems. It is, of course, not possible to operate systems outside of limits set by the manufacturer, but it is known that many commercial HVDC systems allow short and medium-term overloading applying the technical methods discussed.

1.3 Known usage of overloading in HVDC systems

Overload capacity is known to be utilised commercially in HVDC systems with both LCC and VSC technologies, for example:

- BritNed: Britned is an LCC-HVDC link between Britain and the Netherlands with 1000 MW (1016 MW at the midpoint) capacity. Since 2019, a long-term trial is being carried out to determine the volume of overload capacity (maximum 50 MW), time duration and the operating conditions under which this capacity can be offered [12].
- Nemolink: Nemolink is a 1000 MW (1012 MW at the midpoint) VSC-HVDC link connecting Britain with Belgium. In December 2019, an additional 20 MW transient overload facility was announced for this link for power flow in the direction of Belgium to Britain. This additional capacity is limited to 5 hours every day between 1700-2200 CET [13].
- Estlink: Estlink-1 (VSC-HVDC) & 2 (LCC-HVDC) are 350 MW and 650 MW links between Estonia and Finland. In winter, 15 MW temperature-dependent overload capability can be used for Estlink-1. For Estlink-2, an additional 16 MW overload capacity is available [14].
- Kontek: Kontek is a 600 MW LCC-HVDC link between Germany and Eastern Denmark. An overload capacity of 50 MW can be used for disturbance reserves on this HVDC link [14].

2 Numerical Study

This section introduces a numerical framework to examine the added value dynamic rating of HVDC interconnections can bring.

2.1 *The capacity of an interconnector*

HVDC interconnectors have a long-term *continuous* capacity and a short-term dynamic rating. Any dynamic capacity on top of the continuous capacity can only be made available for trades in the short-term - including day-ahead - timeframe.

The EU regulation on HVDC links [15] defines "maximum HVDC active power transmission capacity (P_{max})" as "the maximum *continuous* active power which an HVDC system can exchange with the network" limited by either the connection agreement or the asset. This definition is often used synonymously with nominal capacity, but importantly, it includes losses and only the continuously available capacity.

All HVDC systems have losses, the exporting node consumes more power than what is injected at the other end, this asymmetry based on the flow direction can cause some confusion. To simplify the accounting for losses, in the rest of this paper, we define the nominal capacity as the continuous active power transmission capacity at a fictitious mid-point of the interconnection. For an interconnector capable of delivering 1000 MW with a 2.4% loss factor, this capacity would be 1012 MW. This number fittingly corresponds to the concepts of the current long-term transmission rights procedures on the channel interconnectors using "Mid-Interconnector" nominations [16].

We use the term Dynamic Capacity to refer to the portion of capacity offered on top of the nominal capacity. For example, a 1032 MW capacity offer from the example interconnector would correspond to 20 MW of Dynamic Capacity.

2.2 *The value of capacity*

Transmission capacity between two bidding zones of a market has vastly different economic values depending on the market's needs. In the spot market, capacity enables a fixed amount of trade between the two price zones, which can be valued by the price spread. In long-term markets, traders may pay above the expected price spread for the capacity to use it as a hedging instrument. European trends lean towards pricing capacity implicitly in the day-ahead market and using "Financial Transmission Rights" in the longer-term markets. The remaining available capacity is usually free for intraday and balancing trades. But alternative designs exist, some borders in the EU still offer Power Transmission Rights in the long-term markets, giving their owners the right to "Use-it-or-sell-it" in the day-ahead timeframe. A small portion of borders, notably all interconnectors between Great Britain and the continent since Brexit*, rely on explicit capacity trades also in the day-ahead markets. In addition, some interconnectors may also use their technical capabilities to offer services in the auxiliary services markets. These markets introduce new ways to earn revenues for interconnection operators; at least some of them could provide great value for dynamic capacities.

Not considering this complexity in this paper, we rely on a simple assessment framework centered around congestion revenues in the day-ahead market. We assume that the price spread is earned if it coincides with the direction of the dynamic capacity. Increasing capacity - in theory - leads to better price convergence and diminishing returns for added capacity. We neglect this effect by considering that the prices are not affected by the offer of the dynamic capacity. In this framework, value scales linearly with capacity.

2.3 *Interconnectors studied*

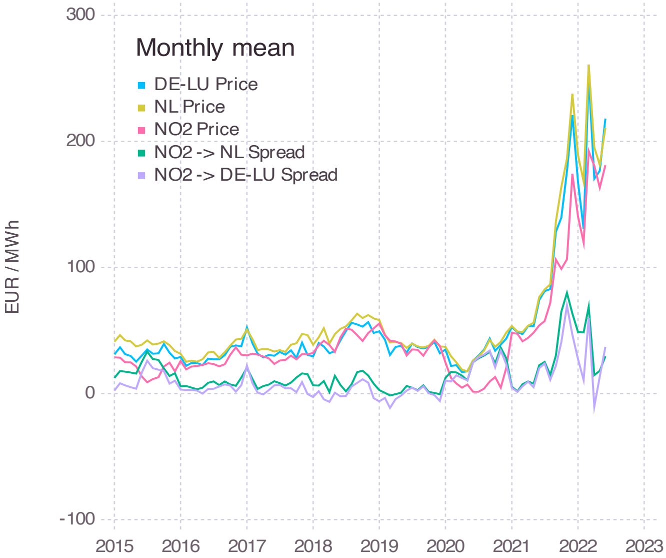

Fig. 1 Monthly mean of hourly prices and spreads not adjusted by volume (base).

We study the case of two oriented bidding zone borders, from Norway (NO2) towards the Netherlands (NL) and the German-Luxembourgish (DE-LU) bidding zones. These are borders already served by interconnections NordLink (1400 MW equipped with VSCs) and NorNed (700 MW LCC type). In the proposed framework, the only input data we need to rely on is the day-ahead prices in the concerned bidding zones. These have been collected from the ENTSO-E Transparency platform. Where necessary, artificial hourly prices were generated as the mean of the half-hourly prices. Historical prices for the Germany-Austria-Luxembourg bidding zones

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**Awaiting the implementation of a more complex trade protocol called Multi-Area Loose Volume Coupling outlined in the Brexit agreement but only ever used operationally for 10 days on the Kontek cable in 2008 [17]* are used for periods before the Austro-German split. Figure 1 shows the evolution of the prices and spreads over the study period, in recent months both have significantly increased.

3 Results and Discussion

Dynamic capacity offered on top of the nominal capacity has, at most, the same benefits as an increase of equal size in the nominal (continuous) capacity. This upper limit, of course, can not be achieved as the capacity is only available part of the time, however, by choosing the right moments to use dynamic capacity, a significant portion of the full benefits can be captured. The influence of this timing choice and the conditions under which this choice could be made optimally will be discussed in this section.

To our knowledge, all of the current market clearing frameworks treat individual network branch capacity as known and fixed[*] - independent of the decisions taken in the market clearing stage. This framework forces HVDC interconnector operators to decide when to offer the dynamic capacity without knowing the market bids or exact price spreads.

An alternative framework would be to provide the market-clearing algorithm with constraints describing the exact technical capabilities of the interconnector and let the algorithm choose when to use the dynamic capacity. In this case, the timing choice could be made with knowledge of the bids and benefits maximized for all market participants. Computationally this would introduce some - difficult to solve - non-convexities, but existing literature on min/max on and off-time constraint formulations could provide solutions [18, 19].

A day's market time units (MTU)[†] can be ranked by decreasing price spread, the obvious choice is to offer the dynamic capacity for the MTU ranking top on the list. In figure 2 the historical period spanning 2015 to July 2022 is analyzed for the Norway - Netherlands border based on the frequency of each hour to rank at a given position. This figure clearly shows that the MTUs with the most value differ between days, and while some patterns can be observed, sticking to a fixed schedule inhibits earning potential.

We modeled multiple offer strategies to understand the impact of when dynamic capacity is offered on the expected returns (see Fig. 3). The optimal strategy would always choose the hours with the highest price spread, while the worst-case strategy would always choose the hours with the least. Any other offer strategy would deliver returns in between these. Some interconnectors are required to offer their dynamic capacity at consecutive hours, the expected returns, in this case, are somewhat sub-optimal. A distinct case we also modeled refers to offering the dynamic capacity always at a fixed period of the day. We plotted the expected returns for a simple strategy that always starts at 15:00 daily, trying to capture the price spread in the afternoon hours.

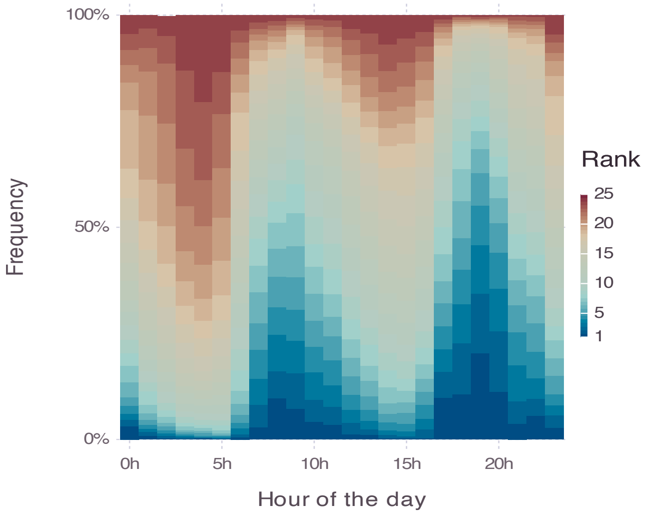

Fig. 2 Distribution of rank based on the hourly price spread within the day on the bidding zone border NO2 to NL. Lower rank signifies hours with the highest price spread during the day. The plot was created based on historical prices.

On Fig. 3, we can see that a large portion of the total value can be captured by making dynamic capacity available for only a few hours a day.

For this numerical study, we assume that a fixed magnitude of dynamic capacity is available for a given number of hours. Given some of the technical constraints related to heat management, it is plausible that a larger amount of dynamic capacity could be offered for shorter periods. Knowing the relationship between duration and available dynamic capacity, one could extend this analysis to more complex offer strategies and enable operators to increase their revenues further.

4 Conclusions

Maximizing the utilization of the already built assets is a priority for any HVDC operator looking to increase their profits or lower the recovery time of their investments. One way to achieve this is by offering the full technical capabilities of the physical assets to the market. According to the current literature, overloading HVDC systems is possible but only limitedly explored in practice (mainloy not used in market scheduling).

In this paper, we showed that making additional capacity available to the market for a few hours can significantly increase returns. However, the magnitude of these returns is highly dependent on when this capacity is made available.

Based on historical data and day-ahead price forecasts, one could aim to choose hours with the highest price spread earning the operator the maximum returns. In the current market framework, this choice needs to be done ex-ante (without knowledge of the exact bids or prices). This sub-optimality could be eliminated by enabling the operators to provide more detailed information about their assets to the market clearing

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[*] *The flow-based approach still uses static branch capacities that get translated into bid acceptance-dependent zonal trade capacities.*

[†] *Hours in our case.*

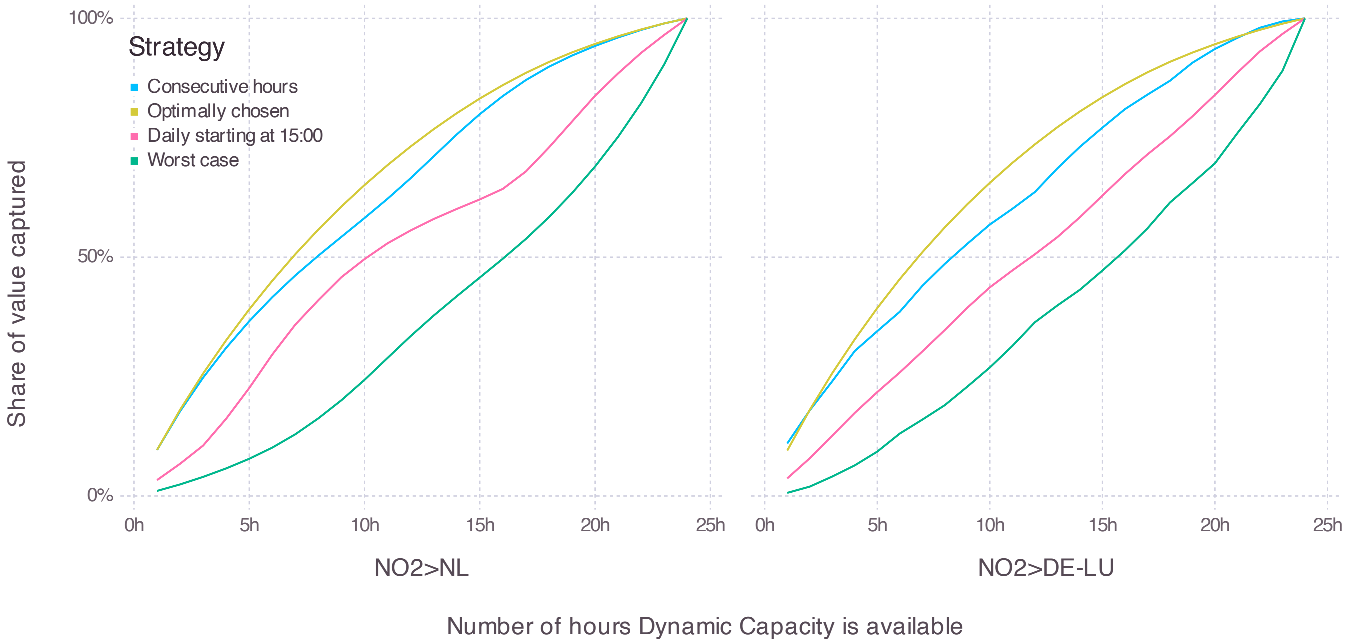

Fig. 3 The expected value captured by different offer strategies for dynamic capacity expressed as a share of value an increase of similar magnitude in the nominal capacity would produce. Shown for the studied bidding zone borders, based on historical prices.

algorithm and letting the algorithm choose when to activate dynamic capacities.

In practice, we have observed operators offer a few percentages extra capacity for a couple of hours. For example, NemoLink, the Belgian-Britain interconnector, provides an approximate extra 2% capacity to the market for the afternoon hours daily. Literature suggests that the true overload capabilities of some of the HVDC links are far higher, raising the critical question of why operators do not make better use of them. We argue that this is partially a market design issue, whereas capturing the total value dynamic capacity could bring is hindered.

Throughout this paper, we assumed that prices would not be affected by the additional trade enabled by the dynamic capacity, this assumption, however, leads to some level of overestimation of the potential benefits. We only explored offer strategies for assets where the dynamic capacity magnitude and duration are known and fixed. In theory, some assets could provide a larger increase in capacity for a shorter duration, enabling even higher returns.

We anticipate our papers to be a starting point for a more detailed analysis of the value dynamic rating of interconnectors can create, market design changes that would incentivize operators to better valorize their assets, and ultimately for HVDC system developers to make overload capacity a more standard offering. This would enable better trade potential and increased welfare for society and has potential implications for the security of supply.

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