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Online Estimation of Dynamic Capacity of VSC-HVdc Systems – Power System Use Cases

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Abstract

The dynamic capacity describes the capability of high voltage direct current (HVdc) systems to operate temporarily beyond their guaranteed active and reactive power (P/Q) limitations under specific conditions. In this work, the dynamic capacity is intended to be applied in various power system use cases to ensure a more efficient and secure grid operation. In contrast to previous works, the dynamic capacity is considered with a holistic view on the HVdc system's components. Moreover, to overcome existing limitations considering only the HVdc system design, it is introduced to estimate the dynamic capacity based on real-time operational data. In principle, dynamic capacity could help for any power system use case where temporarily additional capacity is required. The article details five use cases, including congestion management, voltage support, frequency response, offshore wind overplanting and grid planning to be of high interest for such a feature. The main HVdc applications, embedded systems, interconnectors and offshore grid connection, and anticipated time frames for dynamic capacity are highlighted from power system perspective. Also, the time-criticality of the remedial actions is outlined.

1 Introduction

In Germany, the concentration of wind power generation in the North and large industrial loads in the South have raised the need to maximize power transfer over large distances and to increase the controllability of the power system. A threefold of Voltage Source Converter (VSC) based HVdc systems, namely embedded systems, interconnectors and offshore wind connections, have been presented in the European network development plan as possible solution towards a more controllable and reliable grid [1]. In addition, multi-terminal HVdc systems are foreseen to become inevitable for the control and operation of the future power transmission system.

In the Kopernikus-project ENSURE, a working group of manufacturers, system operators and academia are developing a holistic approach to calculate and visualize the dynamic capacity of HVdc systems for different use cases.

As presented in [2], VSC-HVdc systems have the capability to operate temporarily outside of their nominal active and reactive power (P/Q) specification under certain conditions. This concept, known as dynamic capacity, has seen applications in line commutated converter (LCC)-HVdc systems [3] and academic works for VSC [4] mostly for the extension of power transmission capacity and post-contingency system stabilization.

However, these works focus mainly on the converter design, whereas the approach of the ENSURE working group investigates the dynamic capacity from a system level perspective and also includes other influencing factors and their interactions, such as the transformer, ac substation, surrounding ac grid and dc cables or dc overhead lines (OHL).

Moreover, in contrast to previous works, this paper addresses the dynamic capacity not only under consideration of the design but relies on operational real-time data from the field. Thus, dataloggers need to be installed in an HVdc system. The data from dataloggers can in general be used for both offline and online monitoring applications and can include among others: voltages, currents, power and temperatures from various data sources (e.g. control and protection system). As an example, offline applications might use the data for event screening in terms of root cause analysis after disturbances. Possible online applications are condition monitoring to derive preventive maintenance actions or improved decision-making in system operations. In the context of the described work, online operational data will be used to determine the dynamic capacity of the HVdc system.

The number of HVdc systems has been rising steadily in recent years and new installations – not only in Europe – are planned. A higher number of HVdc systems will not only contribute to a more flexible operation of the power grid but also increase the relevance of these systems to keep the power grid secure and stable. One important advantage of VSC-HVdc systems is the provision of ancillary services [5] e.g. frequency containment reserves [6], voltage support, fault-ride through (FRT) capability, power oscillation damping, emergency power control, among others [7]. Since typical providers of those services such as large synchronous generators are taken out of service due to conventional power plant decommissioning, VSC-HVdc systems will need to step in to an even broader extent than today.

In this paper, the usage of the HVdc dynamic capacity is intended to provide such services and ensure a more

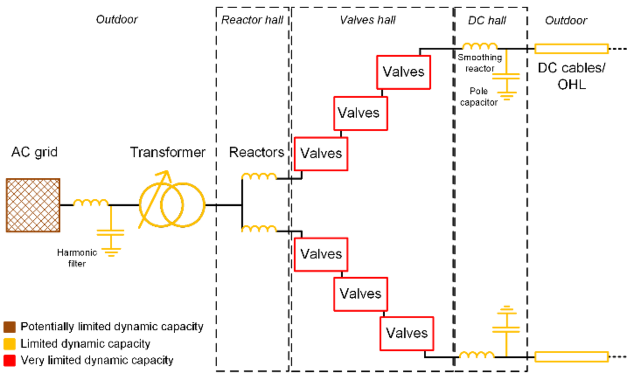

Figure 1: Schematic single line diagram of an HVdc station with indicative dynamic capacity considerations of components.

efficient and secure grid operation. Other use cases for dynamic capacity might be improved availability of the VSC-HVdc system and avoidance of tripping with the help of dynamic safety margins which is not the focus of this paper.

There are several use cases for which HVdc systems can be utilized and consequently, for which the dynamic capacity can be relevant. The possible use cases depend on the HVdc application. In this paper the following applications are addressed:

- Embedded HVdc: At least two converter stations of the HVdc system are physically connected within a single synchronous area along the ac power system.
- HVdc interconnectors: At least two converter stations are connected to separate asynchronous ac systems.
- HVdc offshore grid connection: The HVdc system connects an offshore wind park to the power grid.

The paper is structured as follows: Section 2 introduces the concept of VSC-HVdc dynamic capacity and its online estimation based on operational real-time data. In section 3, various power system use cases of the HVdc dynamic capacity will be presented and the requirements needed to operate the HVdc system will be thoroughly discussed. Finally, section 4 is dedicated to the conclusions and gives an outlook to future work.

2 Dynamic capacity of VSC-HVdc systems

As introduced earlier, dynamic capacity describes the capability of an HVdc system to operate temporarily beyond its guaranteed P/Q limitations under certain conditions. The calculation of the dynamic capacity focuses on the converter station. As an HVdc system consists of at least two HVdc stations and of dc cables or dc OHL (except for back-to-back systems) the whole system has to be considered. For multi-terminal systems, multiple dc links and even more components are relevant (e.g. dc breakers). An HVdc station itself is a system of components and subcomponents, namely, the valves, reactors, filters, power transformers and the ac terminal infrastructure (switchgear, circuit breakers). All these components have individual thermal limitations dependent on their individual physical parameters, design criteria, pre-loading conditions and the current operational status. The HVdc dynamic capacity will be always limited by the most critical component.

Figure 1 depicts the components of an HVdc station alongside with an indication of their individual limitations on dynamic capacity. Most prominent, the valves have a very limited dynamic capacity given the small thermal constant of power electronics. However, in a real station these are not necessarily the most critical components depending on the original design approach or the specification. Other main circuit components, such as ac harmonic filter, transformer, arm reactors, smoothing reactors and pole capacitors on the dc side might have a limited dynamic capacity which needs to be considered. Each component is either an outdoor or indoor installation. Indoor installations are separated between different halls namely the reactor, valve and dc hall as highlighted in the figure. The local temperatures in these halls might differ from the ambient temperature dependent on the cooling system applied and is therefore considered to be a relevant input for the dynamic capacity calculations. The ac grid can also be a limiting factor for the usable dynamic capacity. If N-1 security is violated next to the ac connection point, because of the higher contribution of the HVdc system, the full dynamic capacity potential might not be applicable.

The value of the dynamic capacity can be separated into active and reactive power values, however, the actual limitation by voltage and current are the root boundaries besides the thermal capabilities. Similar as for normal operation, dynamic capacity for reactive power primarily needs to be considered for the respective HVdc station, whereas for active power the whole HVdc system is to be taken into account.

Application of dynamic capacity would imply significant control and protection (C&P) system changes, but particularly legal, additional testing, and reliability, availability, maintainability, and safety (RAMS) aspects. It must be stated that the dynamic capacity in the scope of this working group is targeting the inherent capability, meaning no or minor hardware changes would be required for its final application in the field. Besides that, software tools need to be developed to support the use of dynamic capacity in system operations. Two streams are to be followed: 1) an offline model with a reduced set of inputs outputting a feasibility range for different time scales and 2) a model which calculates the dynamic capacity dependent on actual operational data. The offline model could be used in use cases such as long-term grid planning or operational planning (e.g. day-ahead). The online model might be located close or fully integrated into C&P but needs at least continuous data inputs from the actual operation of the HVdc system. Dataloggers usually used for condition monitoring are a suitable tool to enable access to the operational data for the dynamic capacity feature.

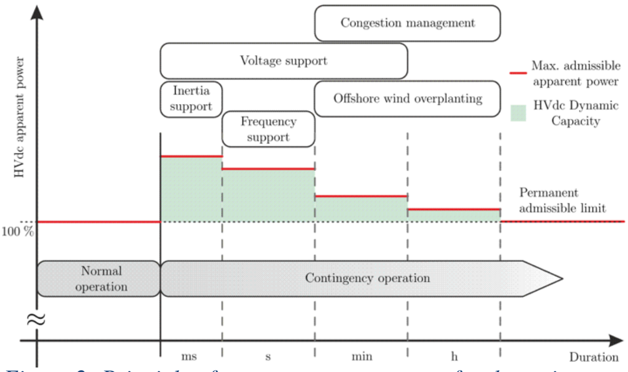

Figure 2: Principle of power system use cases for dynamic capacity of VSC-HVdc systems.

3 Power system use cases for dynamic capacity of VSC-HVdc systems

The expected advantages of VSC-HVdc dynamic capacity for advanced power system operation are manifold: higher loading of the grid through curative congestion management, better suited to handle the volatility of renewable energy-based power grids, more flexible safety margins of the HVdc system itself, unlocking additional functionalities due to innovations during lifetime, and an effective measure to delay and reduce grid expansion. However, it must be considered that the inherent dynamic capacity should not infringe the stable operation of the HVdc system itself. The usage of VSC-HVdc dynamic capacity in services to the power system as presented in Figure 2 might pose additional requirements on the HVdc system. In this section, a classification of these service use cases depending on, among others, the HVdc application (offshore wind connection, interconnectors and embedded systems), active or reactive power contribution, and requested power capacity and duration of service is given.

3.1 Congestion Management

Congestion in power grids are typically tackled in a preventive way. High flexibilities of equipment (e.g. power electronic-based equipment) and consequently low reaction times offer an easy and secure possibility to act curatively after congestions occur. This curative approach enables higher loading in normal operation, which reduces costs as preventive measures like redispatch might not be required [8].

Embedded HVdc systems are a very suitable option for managing congestions curatively as the HVdc system often affects a lot of relevant ac circuits. In normal operation (pre-fault, without contingencies), the permanent admissible rating of the HVdc system determines the maximum loading of the HVdc system. After the occurrence of a relevant contingency (post-fault), the rating is determined by the value according to the dynamic capacity assessment. Usually, this dynamic action needs to be applied temporally only for a duration of 15 minutes up to two hours as conventional remedial actions can be activated within this time range (see Figure 3(a)).

The dynamic capacity needs to be considered in the different system operation processes. In operational planning (OP) the dynamic capacity of the HVdc is determined based on forecasts. The contingency analysis (CA) in OP applies the HVdc system with its temporary higher rating, which can reduce the number of costly preventive remedial actions, as higher power transmission capacities are available in relevant N-1 cases. The dynamic capacity represents the maximum available power of the HVdc system, which can be used curatively in the optimization problem. As a result, the CA provides the operating points to the HVdc systems which are applied curatively for specific contingencies. In addition, it has to be assessed by the operator if other remedial actions, which can be activated in the short term, can relieve the potential congestion, as the dynamic capacity of the HVdc can only be applied for a limited time window.

In real-time operation the dynamic capacity is calculated based on the information from the datalogger. The threshold is considered in the CA of the SCADA system. The operator assesses if the curative action is still sufficient and adapts the reaction if necessary and if capacity reserves are still available according to the dynamic capacity calculation. In case of a real occurrence of a contingency in real-time operation the operating point is automatically adapted under consideration of the dynamic boundaries of the HVdc system. After that the operator activates manually conventional remedial actions (e.g. redispatch, grid topology adaption) and returns the loading of the HVdc system into a permanent admissible operating range.

3.2 Voltage Support

Voltage support through controlled reactive power exchange of the HVdc stations with the connected ac grid is one of the key features of VSC-HVdc systems. Dynamic capacity could enable the reactive power exchange to go temporally beyond the guaranteed limits. Three time frames are of interest for voltage support: steady-state voltage support during normal operation, dynamic voltage support after FRT and FRT itself (see Figure 3(b)). Steady-state voltage support might act during time ranges up to 30 minutes, until other remedial actions can be activated. Provision of reactive currents during fault ride through would be needed in time ranges of 150 ms to trigger protection schemes and support the voltage of the ac grid. Dynamic voltage support after the FRT continues the support up to ~1s. Due to the short activation time for FRT and dynamic voltage support after FRT, only the design based dynamic capacity might be used for these use cases.

Voltage support is valid for all three considered HVdc applications: a) Embedded HVdc b) HVdc interconnectors, and c) HVdc offshore wind connections. For c), only the onshore station's dynamic capacity for voltage support is of interest given that this station is integrated into the larger synchronous grid whereas the offshore station interfaces the collection grid. If in the future offshore collection grids are interconnected on ac side offshore, additional requirements for dynamic capacity for voltage support might also rise for the offshore station.

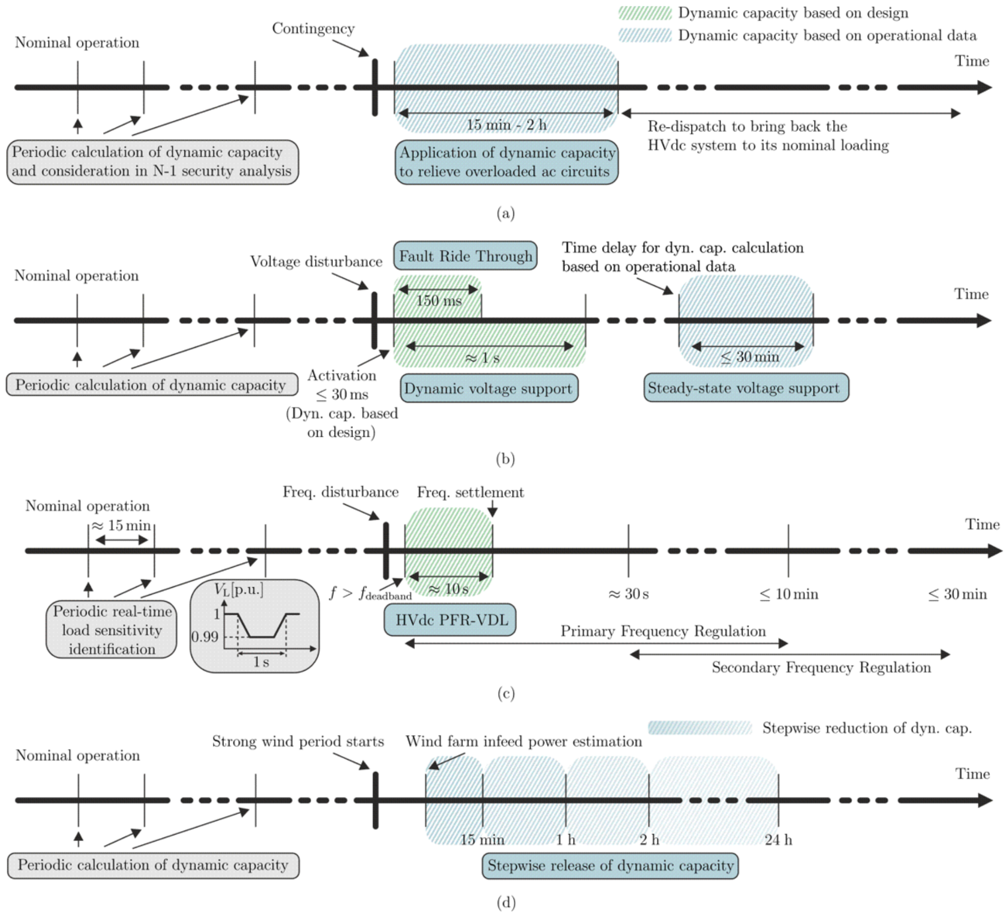

Figure 3: Timeline of dynamic capacity use cases in power system: (a) Congestion Management, (b) Voltage Support, (c) Frequency Support and (d) Offshore Wind Power Overplanting.

3.3 Primary Frequency Regulation Controlling Voltage Dependent Loads

HVdc interconnectors can be used for primary frequency regulation (PFR). Conventionally, the HVdc controllers are equipped with overlaying droop controller, which linearly changes either the dc voltage or active power set-point following a variation in the frequency. However, in the supporting grid area, additional power is temporarily drawn which causes unwanted frequency variations in that area. In embedded systems, due to the synchronous coupling of the two areas, a simple power transfer would not limit the frequency drop effectively.

Instead, in [9], after a contingency, both HVdc interconnectors and embedded HVdc systems are used to control the power consumption of nearby voltage-dependent loads (VDL) to perform the PFR. This approach is known as primary frequency regulation controlling voltage dependent loads (PFR-VDL). Considering a real-time estimation of the load sensitivity, the grid voltage at the HVdc point of connection is varied to extract the same amount of power from the loads as requested by the HVdc droop controller. Hence, effective frequency regulation can be provided with minimum impact in supporting areas. A similar control method has been proposed in [10] to provide additional emulated inertia to the grid.

The dynamic capacity could be used to supply the reactive power, which is needed to regulate the grid voltage in a short time interval of approximately ten seconds after the contingency and which otherwise would eventually exceed the HVdc continuous power limit (see Figure 3(c)). Due to the short activation time, only the design based dynamic capacity might be used.

3.4 Offshore Wind Power Overplanting

This use case relates to HVdc offshore grid connections only but might also be relevant for future interconnectors which are combined with offshore wind [11, 12]. HVdc offshore grid connections for offshore wind integration are usually designed according to the maximum wind power infeed at the offshore connection point. The maximum power infeed consists of the sum of nameplate rating of all installed wind turbine(s) minus the power losses in the offshore collection grid(s), any loads and potential safety margins (e.g. control margins and reactive power provision). Taking the variability of the wind and the availability of the wind turbines in account, it might be techno-economically feasible to overplant the offshore wind farm. Overplanting consists in installing more nameplate capacity than the grid connection capacity [13]. At wind speeds below rated wind speed and turbine unavailability a higher power output can be reached whereas at wind speeds above

Table 1: Power system use cases of dynamic capacity for VSC-HVdc systems. Use cases, measure, application, active/reactive power and time frames for dynamic capacity.[1]

Use Case	Measure	HVdc Application	Active/Reactive Power	Focused Time Frame
1 Congestion Management	Active power set-point during congestions as curative measure	Embedded Interconnector	Active power	15 min to 2 hr
2 Voltage Support	Temporary use of additional reactive power during normal operation and during and after fault ride through	Interconnector Embedded Offshore wind connection	Reactive power (normal operation, dynamic voltage support) or reactive current (FRT)	30 min / 1 s / 150 ms (normal operation/dynamic voltage support/FRT)
3 Primary Frequency Regulation Controlling Voltage Dependent Loads	Reactive current injection to influence system voltage magnitude, primary frequency support	Interconnector Embedded	Reactive power	30 s
4 Offshore Wind Power Overplanting	Reduction of curtailed energy for overplanted offshore wind farms	Offshore wind connection	Active power	15 min to >2 hr, larger intervals could be of interest e.g. 2-3 day-long strong winds
5 Grid Planning	Consideration of dynamic capacity in grid planning processes	Interconnector Embedded Offshore wind connection	Active power	15 min to 2 hr

rated wind speed or turbine availability excess energy must be curtailed. An increased temporary admissible transmission limit of the grid connection might reduce the amount of curtailed energy. This dependency is independent of the used grid connection technology – ac or dc.

According to the dynamic capacity assessment, temporally more power than the permanently admissible transmission limit could be transferred to shore which leads to an even higher utilization of the transmission asset and would be a plus for overplanting. The magnitude of overplanting reported in literature varies between 8 and 20%, highly dependent on wind climate and capital expenditure share between generation and transmission assets, among others [13,14]. The time frames are expected to be in the range of 15 min to 2 hours but if possible, also longer durations might be of interest, e.g. during a 2-3 day-long strong wind period (see Figure 3(d)). As already described in section 2, the dc submarine cable can be also a limiting factor for the dynamic capacity to be used. Especially for sea cables it has to be considered, that the increase of temperature around the cable must not exceed a threshold of 2 K. A temperature monitoring for cables can help to determine that cables are not overloaded from a thermal perspective and that regulatory requirements are fulfilled.

3.5 Grid Planning

Required grid expansion measures are identified by the four German TSOs and are described in the grid development plan. The measures are derived based on the so-called NOVA principle, which states that grid optimization has a higher priority than grid reinforcement and expansion. In the last version of the grid development plan a transmission capacity of 5 GW was considered to be compensated in the future by innovative solutions (e. g. grid boosters). The dynamic capacity approach described in this paper could be an option to be considered in the grid development plan as an innovative optimization concept for the planned embedded HVdc systems to contribute to the 5 GW goal.

The approach would be similar to those described in section 3.1. The HVdc system in the contingency analyses of grid planning would have a higher transmission capacity according to the results of the dynamic capacity calculation for relevant N-1 cases. As the calculation approach for the dynamic capacity cannot be based on real-time data a simplified approach has to be developed which would use forecasts or estimations for the corresponding input data.

4 Conclusions and Future Work

VSC-HVdc systems can temporarily operate outside their nominal power limits. This dynamic capacity can be estimated online based on real-time operational data and applied in system operations. The online estimated dynamic capacity can be used to increase power system security both in the short time after a contingency and to avoid costly remedial actions. This paper presents and classifies possible use cases of the VSC-HVdc dynamic capacity considering multiple influencing factors in the HVdc system. Five use cases were considered reaching from planning to operational time horizons for different HVdc applications. It can be concluded that HVdc dynamic capacity is of great interest for all applications and for a broad range of ancillary services mainly in the context of optimized utilization of existing assets.

[1] Measure: Remedial action which makes use of the dynamic capacity, HVdc Application: Embedded HVdc, HVdc interconnectors and/or HVdc offshore wind connections, Active/Reactive power: Active or reactive power (currents) provision, Focused time frame: Time duration of remedial action. The actual time duration might be lower than the stated time frame.

In future work, the authors intent to investigate the tangible calculations of the VSC-HVdc dynamic capacity under consideration of real operational data from the field, which includes an assessment of the parameters and signals from various sub-systems as well as potential external inputs. The results will be disseminated in subsequent publications.

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