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Requirements for open specifications in multivendor HVDC protection systems

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Abstract

Integrating multiterminal high-voltage direct-current (HVDC) connections into the existing alternating current (AC) power transmission system is a possible solution for transport of large amounts of renewable energy. Protection is considered a key enabler for multiterminal HVDC (MTDC) grids. Designing such a protection system is a challenge, in particular in a multivendor setup. Fault detection during transients might be required to achieve the stringent speed requirements for HVDC protection. This in turn requires knowledge about the expected system behaviour during faults and involves knowledge from all vendors supplying equipment in MTDC grid. Traditionally, HVDC projects are, however, supplied as turn-key solutions and the control and protection systems are the intellectual property of the vendors and not open for the HVDC end-users. This paper aims to provide a starting point on the discussion which information has to be shared between vendors and HVDC end-users when designing MTDC grid protection. Simulation results show that missing information about certain aspects can lead to a failure of the protection system. A discussion on organization of the available information is added. Open specifications of the used equipment are useful to design safe and reliable MTDC grid protection.

1 Introduction

For many years, the alternating current (AC) grid was built without computer simulations. Today, integration of renewable energy is likely to require high-voltage direct-current (HVDC) technology, especially for long distance and high power transfer of energy. Embedding an HVDC link into an AC grid, or building a multiterminal (MTDC) grid with voltage-source converters, requires extensive simulations to ensure safe and reliable operation. The required information and data to perform these simulations might not always be available [1], [2]. To overcome this problem, open specifications of the HVDC

system are useful. Many aspects could be of interest in this context e.g. the control system [3]. This paper focuses on a set of specifications in MTDC protection that is required to be open i.e. possible to share between vendors and HVDC end-users in order to ensure a safe and reliable protection system. This set of open specifications includes hardware as well as software aspects.

This approach, in particular the software aspect, is different from protection for AC systems. Protection equipment for use in AC power system protection are supplied in a condition ready for immediate use. AC protection intelligent electronic devices (IEDs) for example are ubiquitous in modern transmission systems. Many years of experience, as well as harmonization and standardization of AC system protection and AC IED specifications, allow for routine implementation of AC IEDs into the existing AC system. For this, a protection engineer needs to properly configure the IED which is usually done based on (offline) power system simulation studies. The IED software is black-boxed meaning that the end-user may not fully know all details of the protection algorithm. Nevertheless, experience from the field shows that this approach works in practice and expectations from algorithms are well defined in standardization. One ongoing research and development activity in the field of AC IEDs is the usage of protection algorithms based on fast transients, for example, on travelling wave analysis [4].

Compared to AC systems, protection design for HVDC, especially in a multivendor setup, is less straight forward, mainly due to the small number of projects and less of experience. It can be argued that some of the equipment, e.g. a protection IED, is unlikely to be mass produced, making it difficult for vendors to profit. In this context, new and more dynamic business models might be of interest, such as selling professional services for protection system design. Also, given that most existing HVDC projects are turnkey projects by one supplier, the HVDC protection is embedded into a common control and protection system. Several suggestions for future solutions in multivendor MTDC grids have been made in [6]. Interfaces between a standalone HVDC IEDs and DC circuit breakers were proposed in [7], and requirements for HVDC IED

functional testing in [8]. Notably, a comment from the multivendor protection study in [9] is: “*DC protection requires actual adaptation and collaboration among all involved industrial (both solution provider for the DC protection system and HVDC converters). Based on the experience reported [...], it is quite likely that satisfactory DC protection in a multivendor environment will be most difficult to reach.*”

The presented set of open specifications in MTDC protection system will allow for discussion that is necessary to move towards interoperable and multivendor HVDC systems. This is important during the pre-standardization phase of (multiterminal) HVDC protection.

2 Hypothesis

It is assumed that information about the overall system design such as the system topology, system voltage, current ratings, and converter topology can be shared between the HVDC end-user and vendors. Though the overall system design aspects and protection design aspects should be seen as a whole, the focus in the following will be on protection design aspects.

To enable secure and dependable DC side protection in an HVDC grid with several vendors, information about the following aspects in other vendors’ protection equipment is a minimum requirement:

- Thresholds,
- Line inductor size,
- Sampling frequency for data acquisition,
- Surge arrester voltage-current characteristic for DC breaker and cable,
- Fault detection algorithm,
- Filter for fault detection.

In the scope of this paper the following approach is chosen: if an example showing that missing information results in failure of the protection, this information is required to design a working protection. This assumes absence of standards in HVDC protection design for multivendor setups which is currently the case.

In the following Section 3, a multivendor case study network will be examined with discussion around methods and design choices that vendors may have implemented, in order to examine the possible impact of not providing open information.

3 Simulation Study

The system under study is similar to the Scottish Caithness-Moray HVDC link and its possible future extension to Shetland in a 3-terminal connection. The simulations are based on an open-source version of the models in [10]. The final system

is shown in Fig.1. For the study done in this paper, a fully selective protection in the connecting star DC switching station using DC breakers is assumed. The corresponding protection on the converter line ends using AC circuit breakers is out of the scope of this paper. The assumption of the design stages is as follows: The Caithness-Moray link (in the following link 1 and link 2 due to the split in the switching station) is built by vendor A. Given the future anticipated extension with link 3 to Shetland, vendor A equips the DC switching station with a fully selective protection system using DC breakers. Later, vendor B designs the protection for link 3 taking into account the existing equipment.

This multivendor scenario is used here because it is closest to the current approach of turn-key solutions in HVDC point-to-point links and assumes that the respective vendors design and implement the HVDC protection for their equipment as per order of the HVDC end-user. A different multivendor scenario where the HVDC end-user or another party make design choices for the HVDC protection would result in similar questions and discussion. Note also, that depending on the specific HVDC end-user and project, there could be different preferences about who takes the lead in HVDC protection system design and the following simulation study is meant as a thought experiment to show which information is required to ensure a safe and reliable protection system.

Vendor A thus designs the protection system taking into account the future extension with an unknown technology from an unknown vendor B. Ideally, the cable length and some parameters and specifications of link 3 are known so vendor A’s simulations are as close to reality as possible. For fully selective protection, vendor A chooses a fast fault detection algorithm using dv/dt criterion. Vendor A runs simulations to determine the expected dv/dt signal for close faults, remote faults and backward faults, taking into account the measurement sampling and filtering. Vendor A decides for a threshold that is twice the value caused by a backward fault wave for which the fault detection is not supposed to trip the DC breaker. This can be seen as a dependability margin of 100%. Note, that vendor A has no information about the future line inductor (if any) on link 3. However, given that there will be DC breakers installed, vendor A assumes at least a small line inductor (15 mH) which is considered the worst case assumption given the breaker speed and breaking current capability. A larger line inductor (for slower DC breakers) would give even more dampened dv/dt signal from a backward fault. Note also, that

Fig. 1: Three-terminal test system.

in the scope of this paper, a full protection design is not possible. In summary it is assumed that vendor A uses the following specifications:

- Fast DC breakers,
- Line inductors 15 mH,
- Sampling for both voltage and current at 50 kHz (for simplicity same for voltage and current),
- Measurements filtered with first-order butterworth filter, 2 kHz cutoff frequency,
- Fault detection using dv/dt criterion based on the instantaneous and last sample,
- Threshold link 1 and 2: twice the maximum expected wave for which the protection is not supposed to trip (expected in section 3.1).

Now, vendor B designs the protection for link 3 and has to take into account the behavior of link 1 and 2 during fault. Ideally vendor B would have information about the used DC circuit breaker, its operating time, the protection threshold settings, the line inductor size, the measurement sampling frequency, the surge arrester curves, the algorithm used for fault detection, as well as the used filter in the measurements.

In the following it is assumed that one aspect is not known for vendor B.

3.1 Missing information: thresholds

Vendor B wrongly assumes that thresholds used by vendor A are twice the maximum expected fault wave that can result on link 1 and 2 from a fault on link 3. However, vendor A has chosen thresholds that are only a factor 1.3 higher than the value caused by a backward fault wave for which the fault detection is not supposed to detect a fault. This can be seen as a dependability margin of 30% as is typically done in AC systems. Vendor B, who has a very fast breaker technology, therefore sees the possibility to use a 40% smaller line inductor than assumed in vendor A's design. Vendor A assumes that link 1 and 2 will not trip for faults on link 3. The simulation results in Fig. 3 show that this choice results in an unwanted trip on link 1 for a fault on link 3.

3.2 Missing information: inductor size

Vendor B wrongly assumes a much larger line inductor in link 1 and 2 (50 mH instead of 15 mH). Vendor B's simulations for backward faults result in a certain expected wave on link 3. Vendor B chooses a threshold for line 3 that is twice that value. This is convenient for vendor B, because link 3 is long and the local fault detection is supposed to detect remote faults, too. However given that the real inductors used in link 1 and 2 are much smaller than expected, a backward fault, e.g. for a fault on line 2 cause a high enough wave that trips line 3 as shown in the simulation results in Fig. 4.

3.3 Missing information: sampling frequency

Vendor B wrongly assumes that the sampling frequency used by vendor A's measurement and algorithm is 10 kHz (and not 50 kHz). Vendor B's simulations do not result in any unwanted trips. However, if the threshold is set as twice the maximum wave expected from a remote fault (as done in all previous cases except Section 3.1), then the difference in sampling consumes up to half of the margin (grey area) as shown in Fig. 5. Though it is not the case in this example, the unnecessary consumption of margin might require vendor B to increase the inductor size or change the thresholds. Note that at the same time vendor B assumes a smaller fault peak on link 3 as would be the case if the sampling frequency was known. Note also, that the test case shown here does not take into account different fault inception times.

3.4 Missing information: surge arrester

Vendor B wrongly assumes a different curve (black in Fig. 2) than vendor A (red in Fig. 2) for the DC breaker and cable surge arresters. The cable surge arrester was scaled to 1.8 p.u. of the system voltage. A different surge arrester results in different voltage and current behaviour after a DC breaker trip. An example for a fault on link 3 is shown in Fig. 6. The wrongly assumed surge arrester curve results in an error in vendor B's simulation of the dv/dt fault detection signal. This error consumes up to ca. 30% of the margin as shown in Fig. 7. Note that a trip is issued when the signal surpasses 1 p.u. The threshold is twice the maximum signal for which the detection is not supposed to trip (0.5 p.u.). An error of 0.15 p.u. consumes thus 30% of the margin. In this example, the error is in the direction that lets vendor B assume a higher margin than would be the case (grey area is not crossed by dashed lines) which could result in thoughts about reducing the line inductor on link 3. Note that missing information about the surge arrester results in errors in other fault detection criteria than dv/dt . A local travelling wave extraction criteria ($TW = dv/dt - R \cdot di/dt$) results in a timewise slightly higher or lower error because not only the voltage, but also the current change is taken into account. Note also, that the test case shown here does not take into account surge arrester curve variations.

Fig. 2: Different surge arrester curves.

Fig. 3: Missing information about thresholds: Fault detection criteria and currents.
The grey area is the margin assumed in vendor B's design. A trip is issued at 1 p.u.

Fig. 5: Missing information about sampling frequency: Fault detection criteria and error.
The grey area is the margin assumed in vendor B's design. A trip is issued at 1 p.u.

Fig. 4: Missing information about inductors: Fault detection criteria and currents.
The grey area is the margin assumed in vendor B's design. A trip is issued at 1 p.u.

Fig. 6: Missing information about surge arrestors: Fault detection criteria and currents.
The grey area is the margin assumed in vendor B's design. A trip is issued at 1 p.u.

Fig. 7: Zoom: Missing information about surge arrestors: Resulting error in fault detection criteria (dv/dt and TW). A trip is issued at 1 p.u.

Fig. 8: Missing information about software filter: Fault detection criteria and zoom. The grey area is the margin assumed in vendor B's design. A trip is issued at 1 p.u.

3.5 Missing information: filter for fault detection

Vendor B wrongly assumes a first-order butterworth filter with 10kHz cutoff frequency in link 1 and 2 instead of 2kHz. In vendor B's simulations that results in a different and much higher first filtered wavefront as had been assumed by vendor A during design. Results for a fault on link 3 are shown in Fig. 8. Assuming a higher cutoff frequency as done in this case could be acceptable because the first wavefront that has to result in a trip is more pronounced in vendor B's design. Vendor A's initial assumption could be seen as on the safe side. At the same time the slower changing waves on link 1 and 2 (that should not result in a trip) lose a small portion of the dependability margin due to lack of information about the filter.

4 Discussion

Designing a protection system for multiterminal HVDC grids with several vendors is a challenge from technical and non-technical perspective. The shown simulation results as well as practical aspects will be discussed in the following.

4.1 On simulation results

The above simulations results showed that missing information about thresholds and inductor size can result in unwanted trips. Similarly, the fault detection margin is consumed by missing knowledge of the sampling frequency (here ca. 50% of margin consumed), and the surge arrester (here ca. 30-35% of the margin consumed depending on fault detection algorithm). Though it was not the case in the presented simulation results, it cannot be excluded that an unfavourable combination of these cases results in unwanted trips and/or overdesign of the line inductors. Missing information about the filter used for fault detection algorithms might be acceptable as long as small line inductors are present. In general, the shown test results are a good argument for higher margins.

At the same time, though the case study is in some ways simplified, it can be argued that it is close enough to reality to be used as an example of effects that could be observed on a real network. Also, influencing factors such as cable parameter uncertainties and variations, and ageing effects have not yet been taken into account. The same applies to the DC bus capacitor size, converter aspects (blocking, arm inductor size, overcurrent capability, fault current limiting or blocking capability), backup protection (backup algorithm, threshold, timing), recovery (converter ramp rates, coordination), and communication aspects and IED trip times. These aspects have not been investigated but may need to be shared as well.

4.2 On practical aspects

Another challenge when sharing information about HVDC equipment is that this information (even if available) is to be used in different simulations. These simulations can be either offline (e.g. PSCAD, EMTP-RV) for design studies or real-time (e.g. RTDS, Opal-RT) for commissioning and interaction

studies. Inconsistencies between the types of simulation and the different tools can be expected.

A method to assess these inconsistencies in offline simulations for HVDC was presented in [11]. It was suggested to decrease the inconsistencies by using equation-based modeling language for model exchange [12], but this approach has limitations when it comes to protection studies that need to take into account sampling or delays that can be associated with implementation of a certain functionality in hardware.

The HVDC end-user in [13] summarizes different tools and methods for managing the information in offline and real-time simulations. For example, the use of common information model, conversion tools, testbenches for automated execution and assessment of simulations, as well as software version control are mentioned. According to [13], the closest match between the HVDC equipment in the field and a simulation is achieved using a real-time simulation connected to replica of the control and protection system of the HVDC link. Note that access to such replica and real-time models of the HVDC link does not mean that the HVDC end-user has access to the detailed internal behaviour (which might be black-boxed) or would be allowed to share it. Still, it needs to be possible to share the the minimum information mentioned in Section 4.1 in order to design a functional multivendor protection system.

The HVDC end-user in [14], for example, has a requirement for open-source offline models for static and stability studies, but that does not include protection. A need for common information models in HVDC has also been acknowledged by system operators in [15].

5 Conclusion

A certain degree of standardization is required in a multivendor environment for HVDC protection. At the same time, a lot of unknowns are present and a rapid development is ongoing. Given the unknowns it can be argued that larger protection margins than the ones used here are required. It can also be argued that too formalized specifications (e.g. the IED trip time) do not necessarily contribute to better protection systems. Instead, it is suggested that an approach with a certain degree of openness is adapted where several vendors and the HVDC end-user can share relevant information. The minimum information necessary are the used thresholds and inductor size. Missing information about the sampling frequency and surge arrester curves in combination with the fault detection algorithm have not resulted in unwanted behavior in the presented simulation, but consume a large portion of the protection margin. Therefore it is recommended to include them in the list of required open specifications for multivendor HVDC protection.

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References

- [1] K. Sharifabadi et al., "Parallel operation of multivendor VSC-HVDC schemes feeding a large islanded offshore Oil and Gas grid," in *Proc. CIGRE Session*, Paris, 26–31 Aug. 2018, 13 pages.
- [2] O. Despouys et al., "Assessment of interoperability in multi-vendor VSC-HVDC systems: interim results of the BEST PATHS DEMO #2," in *Proc. CIGRE Session*, Paris, 26–31 Aug. 2018, 10 pages..
- [3] I. Jahn et al., "A Proposal for Open-Source HVDC Control," in *Proc. IEEE ISGT*, Bucharest, 29 Sept.–2 Oct. 2019, 5 pages.
- [4] E. O. Schweitzer, III, et al., "Locating Faults by the Traveling Waves They Launch," in *Proc. 67th Annu. Conf. for Protective Relay Engineers*, College Station, TX, 31 Mar.–3 Apr. 2014, 16 pages.
- [5] L. Zhu et al., "Standard Function Blocks for Flexible IED in IEC 61850-Based Substation Automation," *IEEE Trans. Power Deliv.*, vol. 26, no. 2, pp. 1101–1110, Apr. 2011.
- [6] CIGRE WG B4/B5.59, "TB 739: Protection and Local Control of HVDC-Grids," CIGRE, Paris, Aug. 2018.
- [7] M. Wang et al., "Pre-standardisation of Interfaces between DC Circuit Breaker and Intelligent Electronic Device," in *Proc. CIGRE Symp.*, Aalborg, 4–7 Jun. 2019, 18 pages.
- [8] G. Chaffey et al., "Requirements for functional testing of HVDC protection IEDs," in *Proc. CIGRE Colloq.*, Johannesburg, 1–5 Oct. 2019, 12 pages.
- [9] Best Paths WP9, "Best Paths DEMO#2 Final Recommendations for Interoperability Of Multivendor HVDC Systems," Tech. Rep. D9.3, Dec. 2018.
- [10] D. Guo et al., "Interoperability of Different Voltage Source Converter Topologies in HVDC Grids," in *Proc. IET ACDC*, Coventry, 5–7 Feb. 2019, 6 pages.
- [11] R. Rogersten et al., "A quantitative method for the assessment of VSC-HVdc controller simulations in EMT tools," in *Proc. ISGT Europe*, Istanbul, 12–15 Oct. 2014, 5 pages.
- [12] R. Rogersten et al., "Towards consistent model exchange and simulation of VSC-HVdc controls for EMT studies," in *Proc. PES General Meeting*, Denver, CO, 26–30 July 2015, 5 pages.
- [13] S. Denetiere et al., "Supporting Energy Transition in Transmission Systems," *IEEE Power & Energy Mag.*, Apr. 2019.
- [14] J. Glasdam et al., "Requirements and Quality Assurance of HVDC Digital Models for Power System Analysis," in *Proc. CIGRE Symp.*, Aalborg, 4–7 Jun. 2019, 14 pages.
- [15] ENTSO-E, "CGMES Roadmap," Rep., May 2018.