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A Proposal for Open-Source HVDC Control

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Abstract—Future multiterminal high-voltage direct-current (HVDC) grids are considered an enabling technology to efficiently integrate large amounts of renewable energy into the existing grid. However, already in today's existing point-to-point HVDC links, harmonic interaction issues and instabilities related to the control and protection system of the converters have been reported. The converter control software is usually black-boxed and problems are therefore solved in close cooperation with the HVDC vendor. This paper aims to provide a starting point for a discussion on an open-source HVDC control system. In particular, it covers the control design including technical and non-technical aspects. The open-source approach can be useful to solve current as well as future control-related problems, both in point-to-point links as well as in multiterminal and multivendor HVDC grids.

Index Terms—HVDC transmission, Open source software.

I. INTRODUCTION

Concerns about the climate-altering effects of carbon dioxide emissions have led to a desire to increase the share of renewable energy sources in the energy system. The intermittency of the power supplied from these sources means that the output from many sources across a wide area needs to be combined to provide security of supply. This can be achieved by significantly upgrading the power transmission system. Long distance transmission is the most efficient with high voltage direct current (HVDC) systems, particularly if cables are used. Mostly due to technical complexity, the majority of HVDC connections are of point-to-point type, i.e. they connect two points in an ac grid, or two different ac grids. Typically, both converter stations are then supplied by the same vendor, which simplifies the coordination of the control and protection systems.

Connecting HVDC links together on the dc side into multiterminal HVDC grids could potentially result in costs savings, and reliability improvements compared to point-to-point connections. Some ongoing European projects consider point-to-point HVDC connections with an option for additional terminals at a later stage [1] – [3]. This, however, implies challenges in terms of interoperability of the involved converters. The existing control systems are proprietary to the respective vendor and their exact function is usually unknown, even to the customer operating the converter.

Operating two or more converters from different vendors connected to the same dc network becomes challenging. Control interactions and inadvertent oscillations may occur under unfortunate circumstances causing instability of the dc or ac system. This is a severe impediment to the deployment of multiterminal HVDC connections and HVDC grids.

The following control-related problems have been reported in existing point-to-point HVDC links using voltage source converters (VSC): German transmission system operator (TSO) TenneT experienced problems with high harmonic currents in their offshore HVDC link BorWin1 [4]. A similar problem in a German offshore HVDC link was reported by TenneT in [5]. A switching action in the ac onshore grid resulted in a resonance with high harmonic current on the converter ac side which caused the harmonic protection system of the onshore HVDC converter to trip. To understand and solve this problem, time domain simulations were done by the vendor, who then provided a control software upgrade.

French TSO RTE conducted time domain studies of the future northern French grid with three HVDC links using vendor models [6]. RTE also presented an approach to derive the Norton equivalent of a black box models in time domain [7]. The study also contained comparison of the derived Norton equivalent with a simple analytical HVDC model.

Similarly, Equinor conducted time domain studies of their future offshore VSC-HVDC scheme with two parallel links by two different vendors [8]. Since even a black box vendor model for the first HVDC link was not available for the vendor of the second HVDC link, the interoperability analysis had to be conducted based on a generic model using publicly available information. This generic model might not depict the behavior of the first HVDC converter accurately.

Results from a systematic time-domain interoperability study in multivendor environment were reported in [9]. Three HVDC vendors provided black-boxed converter and control models for use by the academic or TSO project partners. Again, no HVDC vendor had access to another vendor's black box model. The study also addressed practical aspects such as common interfaces between converter models, and a common vendor-independent master controller. Various types of interoperability

issues were observed, but none could be directly fixed by the vendors due to confidentiality of their black-boxed offline models [10]. Yet, some low-frequency oscillations were damped by adding a DC-side Power Oscillation Damping (POD) functionality in a vendor-independent master controller. In a second stage, the existence of adverse control interactions was confirmed using real-time simulation. They were fixed, but at the expense of HVDC control cubicles delivered by converter vendors [11].

To understand and overcome control-related problems in VSC-HVDC, time or frequency domain analysis, or mathematical techniques taking into account the control parameters can be used [12], [13]. It was shown that the converter control has an impedance-shaping effect, hence it impacts stability [14], [15]. However, the controls which dictate the converter behaviour are developed and protected by the respective vendors, and might be provided as black-boxed model to the HVDC end-user (TSO or commercial). Thus the control scheme and its parameters are unknown and the HVDC end-user's means to understand and modify the HVDC control depend largely on the HVDC vendor. However, the HVDC end-user, is responsible for successful operation of the HVDC link in the corresponding ac grid. To facilitate successful operation, this work proposes a new open-source approach for HVDC control in Section II. Implementation and non-technical aspects are presented in Section III and Section IV. Licensing and patents are addressed in Section V. The proposal is discussed in section VI and conclusions are drawn in section VII.

II. PROPOSAL FOR OPEN-SOURCE CONTROL DESIGN

It is proposed that the HVDC converter control software is split into two distinct parts as shown in Fig. 1. One part is open-source, and one part is proprietary to the vendor, and not openly accessible. The first, open part, will contain software elements that have the greatest impact on the external behavior of the converter. The latter, closed part, will contain the internal control elements. The control is intended for modular multilevel converter (MMC) topology as it is assumed that this topology will be dominant in future point-to-point VSC-HVDC links and multiterminal HVDC grids due to low losses and good harmonic performance. Splitting a control system into different parts is a common approach as described in IEEE standard 1676-2010 [17] and CIGRE guide 604 [18]. Notably, Chinese multiterminal HVDC system Nan'ao has a modular control system with several higher-level layers and vendor-specific valve and submodule control [19], [20].

A. Open External Control Part

The open external control part will contain software elements that have the greatest impact on the overall behavior of the converter. This includes e.g. current control, ac voltage and power control (active and reactive), dc voltage control, and also frequency control in case of islanded mode operation.

B. Closed Internal Control Part

The closed internal control part will contain elements such as circulating current controllers, cell capacitor voltage balancing

Fig. 1. Proposal for open-source MMC control based on [16].

and pulse width modulation. Typically, these elements have a limited impact on the external behavior of the converter. Therefore, it is assumed that the closed control part is not responsible for the stability issues described in Section I. It was shown in [14] that, for a specific control scheme, neither the circulating current nor the circulating current controller impact the MMC ac-side admittance and are therefore not responsible for the resulting instabilities. In fact, for the described control scheme, the MMC ac-side admittance coincides with the ac-side admittance of a two-level VSC. It is furthermore assumed that harmonics resulting from semiconductor switching (modulation) are filtered out to a non-critical level.

III. IMPLEMENTATION ASPECTS

Today's HVDC controllers have joint implementation (code) and functionality (algorithms). However, from a technical perspective it is possible to split implementation and functionality. This has been proposed e.g. for ac grid protection [21]. The vendors' proprietary protection algorithms ("functionality") could then be implemented as black-boxed code on the same physical unit. For this to be feasible, the software interfaces need to be well-defined. For an open-source HVDC control, two solutions are possible:

- The open and closed control parts are implemented in different physical units. The interface introduces a small communication delay, however with modern fast communication protocols this delay might very well be acceptable. Well-defined communication interfaces (data link, application layer, data models, etc.) are needed.
- The open and closed parts are implemented in the same physical unit. This avoids a communication delay, but requires a well-defined software interface between open and closed parts.

IV. NON-TECHNICAL PERSPECTIVE

Introducing an open-source approach into HVDC control has several non-technical aspects to consider. There are the following technical parties in the scope of HVDC: The vendor

TABLE I
OSI DEFINED LICENSES, TABLE ADAPTED FROM [23]

License	Type	Free Distribution	Derivative Works	Patenting
Massachusetts Institute of Technology (MIT), Berkeley Software Distribution (BSD)	All permissive	Yes	no restrictions	Not stated anyhow
Apache 2.0			Apache name cannot be used for marketing	Free licensing required
Mozilla public license (MPL v2)	GPL or MPL			
Lesser general public license (LGPL)	GPL or LGPL			
General public license (GPL)	GPL			
Commercial licenses	All restrictive	No	Not allowed	Restricted

and HVDC end-user (TSO or commercial), which both operate the actual equipment, as well as consultants and academia from a more theoretical perspective. The responsibility for a functional open-source upper control layer can be assigned in different ways:

- 1) The vendor is responsible: Corresponds to the current situation (“black boxes”) and is therefore no improvement.
- 2) Academia or consultants are responsible: Does not apply because of lack of experience with actual equipment.
- 3) Both vendor, customer, consultants, and academia are responsible: Is problematic in terms of liability.
- 4) The customer (TSO or commercial) is responsible and interacts with vendors, consultants and academia: Combines the strengths with clear responsibility.

Naturally, there are different goals and problems for the technical parties in HVDC. An open-source approach for the external control layer will discharge the specific stakeholder from its specific problem.

An open-source external control layer would facilitate interoperability because the corresponding studies could be done with the actual external-layer controller(s) (compare Equinor’s parallel VSC-HVDC links from two different vendors [8]). Having clearly defined interfaces between the open and closed control part, an HVDC vendor would benefit from facilitated implementation of external input, such as research results e.g. from universities and independent research laboratories. Also, as ensuring system stability is the HVDC end-user’s responsibility, a shift towards an open-source external control layer could – with certain conditions – release HVDC vendors from having to solve system-related problems. Particularly having to work with other vendor’s HVDC equipment would be facilitated. Another benefit for industry is the expected development of standards related to the separation between black-boxed internal and open external controls. Given the current absence of control standards, this would certainly accelerate the development of multivendor, and consequently, more complex HVDC systems in the future. From a vendor business perspective, an open-source approach would entail a shift from license-based to service-based pricing.

V. LICENSING AND PATENTS

Choosing an open-source license can be difficult because the vendor’s business models and patents need to be considered. In

the context of HVDC control, it is important to choose an open-source license that allows for closed extensions building upon existing open-source code for use in a commercial product. A summary of the most common OSI-certified licenses (OSI = Open Source Initiative [22]), adapted from [23] is given in table I. Derivative work refers to a work that has sufficient changes compared to the original work so that the derivative work becomes independent. In the context of this paper, the derivative work would refer to a new external control method.

Open-source licenses can be distinguished into “permissive” and “restrictive” licenses. With permissive licenses, distribution of code for derivative work is permitted, but not obligatory [23]. Restrictive open-source license require that alterations of the original code are published back into the community.

On the one hand, it could be argued that permissive licensing results in a risk that improvements or extensions are not given back to the community. Also, code could then be used in closed IPs for a competitive product (“forking”) [23].

On the other hand, experience from other industries shows that a dynamic open-source community has a strong incentive to contribute back – even in case of permissive licenses – because it is more efficient for maintenance in the long term. Furthermore, even with restrictive viral licenses, it is not possible to guarantee that improvements are contributed back to the community. A party unwilling to work with the community could decide to distribute its code separately within its own channels. The general public license (GPL), for example, requires that derivative or combined work (e.g. a product) is made public under the same license (“GPL contamination”) [23]. On top of the above described problems, this means that it would be problematic to re-use the open-source control in a broader commercial offline simulation and study platforms. GPL-like licenses discourage vendors from joining the open-source community and should be avoided.

Less restrictive licenses are Apache 2.0, Mozilla public license (MPL v2) or the lesser general public license (LGPL). Several industrial open-source projects have adopted an Apache 2.0 license [24]. While Apache 2.0 does not require that alterations of the original code need to be made public, MPL v2 and LGPL require publication using the same license or GPL. Apache 2.0 being a permissive license has no relevant restrictions on derivative work (here: new external control) which could be published or kept closed. MPL v2 requires

derivative work to be published under MPL or GPL. LGPL requires derivative work to be published under LGPL or GPL. In MPL v2 and LGPL, a combination with new code that is not a derivative work (here: internal control) can be licensed under another, even proprietary, license [23], [25], as long as the original code (here: external control) is still accessible and configurable by the end-user. Apache 2.0, MPL v2 or LGPL can be an option both in case the external and internal HVDC controller are implemented in different or the same physical unit. In that latter case, the open external control would still be accessible by the end-user while the vendor implements black-boxed internal control. The concept can be compared with dynamic link libraries (“.dll”). The external controller would be a library which the internal controller links to.

Another important aspect when choosing an open-source license are patents. Large parts of HVDC technology are patented by the respective vendors. Making a part of the HVDC control system open-source will infringe on patents.

The BSD and MIT license allow patents using the licensed code parts or derivatives [23] which means that there is a risk to use open-source code that is patented by a vendor. This is an issue. For the restrictive open-source licenses, the open external control cannot be part in a patent [23], however closed internal control can, in case of LGPL. GPL stipulates patent grant alongside the license given that the source code needs to be published.

One approach could be to grant patent licenses for royalty-free use under the condition that the license conditions are kept in case the original material is changed. Grant of patent licenses such as stipulated in the Apache, MPL or LGPL licenses seems a requirement to enable an open-source HVDC project. The interrelations between open-source licenses, patents, and business models are complex. The legal details require a thorough investigation. Note, that it is possible to develop a tailored HVDC open-source license to address the specific needs.

VI. DISCUSSION

Ensuring a functional HVDC control system from a technical perspective is of utmost importance. However, non-technical aspects such as the ability to work with the HVDC equipment, are also important. Taking into account licenses and technical parties, four open-source control proposals are shown in Fig. 2.

In proposal 1 shown in Fig. 2a, the external and internal controller are implemented on two physical units. The external controller with GPL would most likely not originate from a vendor given that the code needs to be fully open and there is no business model for the vendor. Also, the software knowledge of the vendors is not taken into account. Another issue would be the reuse of GPL algorithms into broader commercial simulation and study platforms. As a result the external controller hardware would need to be in-house made by the HVDC end-user also open-source. This scenario seems possible, but for a limited number of HVDC end-users only.

Proposal 2, 3, and 4 shown in Fig. 2b to 2d, are more reasonable solutions for an open-source approach using less

Fig. 2. Possible implementations of open-source HVDC controller.

restrictive licenses (Apache 2.0, MPL v2 or LGPL) that allow for closed extensions. Still, it would be required for the external open-source controller that HVDC end-users, consultants and academia could access and configure the code. Naturally, only the owner (HVDC end-user) would be allowed to change the actual product. Practical reasons, such as already existing control platforms, or cyber-physical considerations, might result in a preference for proposal 2 (one control cubicle) or proposals 3 and 4 (two control cubicles). Compared to proposal 3 (only vendor A), proposal 4 contains two vendors A and B. On the one hand, it can be expected that vendor A has objections to an external controller from another vendor. On the other hand, the open-source approach would allow for vendor A to know the behavior of an external controller from vendor B. To some extent, proposal 4 is the most realistic, because it has already been implemented [19], [20]

A change towards an open-source HVDC control would require willingness and active participation from HVDC end-users, commercial HVDC customers, and vendors. Information

about control and protection structures, systems and models in HVDC is traditionally very closed because of patents. Also, compared to other “organically-grown” open-source communities, HVDC already has a strong knowledge base. In summary, the technical, legal and commercial situation in HVDC is very complex and introduction of an open-source approach therefore requires careful planning.

VII. CONCLUSION

The development of interoperable and multivendor HVDC systems is hampered by proprietary control IPs. Also, the adaptation of controllers for different conditions (e.g. offshore) could most likely be facilitated by an open-source approach. With closed IPs, the technical understanding and ability for the HVDC end-user to solve problems is tightly coupled to the HVDC vendor. At the same time, HVDC vendors are confronted with having to solve control problems without access to relevant knowledge of other vendor’s converters and control in the grid. This work motivated and discussed the real-world benefit for both HVDC vendor and customer. Possible implementation of an open-source HVDC control approach, as well as technical and non-technical aspects were addressed. Using open-source in HVDC is expected to facilitate smooth operation of point-to-point HVDC links, enhance interoperability in multivendor HVDC system, and facilitate planning as well as problem-solving.

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