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An Architecture for a Multi-Vendor VSC-HVDC Station With Partially Open Control and Protection

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ABSTRACT High voltage direct current (HVDC) grids are envisioned for large-scale grid integration of renewable energy sources. Upon realization, components from multiple vendors have to be coordinated and interoperability problems can occur. To address these problems, a multi-vendor HVDC system can benefit from a partially open control and protection system. Unwanted interactions can be investigated and solved more easily in partially open software compared to when applying black-boxed and vendor-specific software. Although a partially open approach offers these advantages, practical aspects, such as the implementation in a real station architecture, have to be addressed carefully. This paper covers this important topic, first by reviewing the required control and protection functions and second by discussing the choice for certain open and closed software parts, their implementation in physical units as well as the required communication and interfaces. The result from this discussion is a first proposal of a station architecture for a multi-vendor HVDC system using partially open control and protection. This architecture will be a helpful starting point to industry and academia working with research and harmonization on this topic as ad-hoc solutions in terms of practical aspects can be avoided.

INDEX TERMS Architecture, converter stations, HVDC transmission, MMC control, open-source software.

I. INTRODUCTION

High voltage direct current (HVDC) systems are increasingly being used for the reinforcement and interconnection of transmission systems [1]. As a result, multi-vendor systems as well as grids are anticipated [2]–[7]. While the core technology — such as the modular multilevel converter (MMC) — is now commonplace [2], [8], challenges remain for vendors and system operators considering the converter's connection in power systems with increasing amounts of converter-interfaced generation and/or in multi-terminal DC networks.

One challenge is that the HVDC converter control and protection (C&P) is rigidly (vendor-)specific and tightly integrated. The C&P software has to coordinate many devices and actions, ranging from the lower converter control loops concerned with the converter's internal behavior — up to,

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e.g., the transformer tap changer setting. These levels of detail and complexity mean that it is not straightforward to achieve multi-vendor interoperability.

Notably, several methods to investigate stability (both AC- and DC-side) and protection in HVDC systems have been proposed, e.g., [9]–[14]. However, they all rely on the exact knowledge of the C&P structures which is typically not available in real projects due to restrictive intellectual property (IP) rights.

Whereas in some business contexts it may be possible to analyze unwanted interactions (e.g., between an HVDC converter and the AC grid [15]), in most projects the HVDC C&P software (and corresponding simulation models) are black-boxed. In some early single-vendor systems [16], [17], harmonic interactions could be solved by a software upgrade provided by the vendor. However, the emergence of multi-vendor systems, e.g., two parallel HVDC links from different vendors [3], requires the respective C&P systems to be coordinated. Preliminary multi-vendor investigations in an early project stage might be possible using generic control systems [3]. However, for detailed interoperability studies, the detailed C&P systems are required [18].

In this context, the study in [19] showed that an HVDC system integrator can specify HVDC C&P systems such that different vendor black-box models can be investigated in a multi-vendor setup. However, the same study also concluded that some interoperability issues were hard to overcome due to confidential vendor IP [20]. Still, some adverse low-frequency oscillations can be dampened with a vendor-independent master controller [21] or an external controller [9]. Another study addressed black-boxed control systems by proposing a method to retrieve the control gains in a specific control structure [22]. However, it is probable that the controller gains may be accessible in an industrial system — whereas the control structure is unlikely to be known.

At this stage, different approaches to achieve interoperability of several control and protection systems in a multi-vendor HVDC environment are conceivable. One important approach is functional specifications. Another complementary approach has been put forward with a proposal for partially open HVDC C&P software [23]–[25]: In a partially open HVDC C&P system, as shown in Fig. 1, a split into two parts is suggested: An open upper level mainly concerned with the converter's external behavior, and a closed lower level mainly concerned with the converter's internal behavior. The upper-level C&P software would be accessible and modifiable. Accessibility would enable solving those unwanted interactions that the upper control levels are responsible for.[1] Note, that Fig. 1 presents a strong simplification of the many different variants of HVDC C&P software which will be discussed in the remainder of this paper.

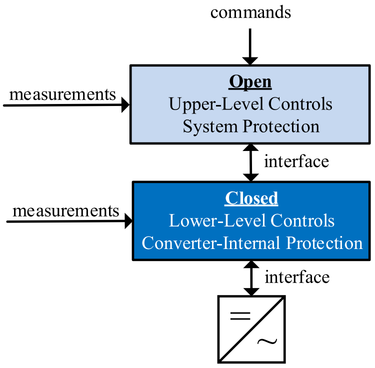

FIGURE 1. High-level proposal for partially open HVDC C&P software.

The first proposal for a partially open HVDC control [24] suggested a specific interface between the open upper control and the closed lower control at the calculation point of the MMC's arm reference voltage. That proposal relies on one specific control implementation described in [26], where the circulating current controller is implemented such that it does not impact the MMC AC side admittance. As a result, the circulating current control is assumed to be positioned in the closed lower-level control. This specific control implementation is the first constraint of the proposal in [24] given that there are also many other ways to control an MMC. The second constraint of the proposal in [24] is that protection aspects are neglected. Protection, however, is essential to consider to ensure a defined system behavior under all circumstances.

Regarding non-technical aspects of a partially open HVDC C&P system, an overview is available in [23] from which two aspects are most relevant for this paper. Firstly, a partially open HVDC C&P can only be implemented if there is sufficient demand from HVDC end-users and collaboration between the involved parties to implement a solution. Secondly, there needs to be an agreement on the responsibility for the behavior of system parts and the overall system behavior. This agreement is a critical non-technical aspect to solve when moving from single-vendor, black-boxed HVDC projects to multi-vendor, partially open HVDC projects.

However, despite these non-technical challenges a partially open approach to HVDC C&P is expected to speed up the integration of HVDC systems into the existing infrastructure. Furthermore, the partially open approach is expected to enhance interoperability in multi-vendor HVDC systems and lastly, is expected to facilitate problem-solving and C&P upgrades — even concerning future grid changes that are unknown today. For example, the control parameter upgrade described in [27], [28] required extensive testing using the HVDC converter C&P replicas in real-time simulations to make sure the black-boxed C&P system does not behave unexpectedly. Such testing procedures may be shortened if more information about the control implementation were accessible.

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[1] Notably, the dynamics of a partially open HVDC system should be identical to a fully black-boxed HVDC system. Furthermore, the methods for stability assessment are identical for partially open and black-boxed systems. Both aspects have been covered in literature to a great extent. Therefore, these two aspects are out of the scope of this paper.

A real (single-vendor) HVDC C&P system is, however, much more complicated than the simplified one indicated in Fig. 1. To further add to the complexity, a multi-vendor HVDC C&P system will additionally concern several entities (e.g., operators, converters, other equipment), each requiring a particular function (potentially implemented by a different vendor) to act upon a command. Similarly, certain functions in specific equipment will likely require information from other entities. Moreover, some information about the parameterization of controls, protection and components is likely to be required for a partially open approach (e.g., as shown in [29] for protection). Finally, the interfaces between open and closed elements must be specified (with the inherent implication of an agreed division).

It is unclear how the aspects mentioned above will be reflected in an HVDC system architecture that allows for a partially open and multi-vendor implementation. Previous work on multi-vendor and/or multi-terminal HVDC system architecture addressed layout considerations and communication options [30]. In [4], a multi-vendor setup was suggested using vendor-specific units (intelligent electronic devices (IEDs), DC circuit breakers (DCCBs), and converters including C&P) that are connected in a plug & play fashion. Furthermore, the review in [5] provides an extensive overview of available implementation aspects and possible HVDC station architectures for future multi-vendor systems — however, with a focus mainly on system protection.

Compared to previous works on HVDC architectures, this paper addresses the following:

- An analysis of the key control and protection functions and their association into upper-level and lower-level (Section II),
- A discussion regarding the division of different functions into open/closed software parts (Section III),
- A deduction of function placement in physical devices including the required open/closed parameters for proper functionality and open interfaces (Section III).

As a result, the novel contribution of this work is an HVDC station architecture in a multi-vendor environment using a partially open approach. Based on the developed architecture, future work is discussed in Section IV. Section V draws the conclusions of the paper.

II. REQUIRED CONTROL AND PROTECTION FUNCTIONS

The ensemble equipment in an HVDC station (such as the converter, circuit breakers, filters and much more) must fulfill certain C&P functions — regardless of a single- or multi-vendor implementation. The content in this section summarises the most relevant HVDC C&P functions starting from most upper down to most lower level, following typical hierarchical structures such as [31].

A. DISPATCH CONTROL

The dispatch control is the uppermost control stage where, for example, the power and the voltage set-points are established and operation modes (grid-forming/grid-following) may be selected. Furthermore, the choice of converter control mode, e.g., DC voltage control, AC voltage control, frequency control, power factor control and priority control, etc. can be made at the dispatch control level.

B. CONVERTER CONTROL

The HVDC converter control is commonly divided into two levels, the upper-level and the lower-level control.

1) UPPER-LEVEL CONTROL

The upper-level control receives the converter operation and control modes and set-points from the dispatch control. The upper-level control regulates the grid variables and generates the reference signals for the lower-level control. Depending on the type of AC system that the converter is connected to and the requirements set by the transmission system operator in charge, the control modes may differ. However, there are two main operation modes for normal conditions: grid-following and grid-forming operation.

For the grid-following operation, an *active (d-axis)* and a *reactive (q-axis)* component are commonly defined to realize the independent control of the related power components. Hence, the active power, the DC-bus voltage or the total energy stored within the submodule capacitors can be controlled to determine the reference for the active axis. In contrast, the reactive power or AC-bus voltage is controlled to determine the reactive axis references [8]. These references are sent to the inner current controls which are realized in stationary or synchronous reference frames. A phase-locked loop (PLL) is typically implemented to provide the synchronization reference angle of the AC grid for reference frame transformation.

For the grid-forming operation, the converter controls the AC-side voltage and the grid frequency. Here, the reference angle — as far as required — is no longer provided by the PLL but instead by a separate voltage-controlled oscillator or inertia model. An optional lower-level AC-side current controller is possible. Furthermore, a frequency droop can be used to coordinate the power-sharing between the converter and possible AC generation in an islanded system.

2) LOWER-LEVEL CONTROL

The lower-level control regulates the internal converter variables. Regulating the internal converter variables typically requires circulating current control, capacitor voltage balancing and modulation. The outputs are the switching signals applied to the gate drives of the converter switches. Being the most vendor-specific part of the converter control, the lower-level controls, especially the modulation schemes, impact primarily the converter performance and to a lesser extent the AC and DC grid dynamics.

3) ENERGY-BASED VS. NON-ENERGY-BASED

A different way to view the HVDC converter control is based on the dynamic equations describing the MMC and decomposing the MMC behavior into AC- and DC-side quantities [8], [31]. To control these quantities, two groups of hierarchical, vector-based control schemes are proposed in the literature: non-energy-based control and energy-based control schemes [32].

In non-energy-based control, the energy stored within the MMC's submodule capacitors is not controlled explicitly. This type of control originates from two- or three-level VSCs where energy-balancing is not needed. Hence, additional controllers are required to suppress the circulating currents at twice the line frequency in the MMC [31].

In energy-based control, the energy stored in the MMC submodule capacitors is explicitly controlled. By balancing the converter arm and leg energies, this approach inherently avoids unwanted circulating current components and might improve the dynamic performance in certain events, see, e.g., [33]–[35].

Since energy- and non-energy-based control are different approaches to control an MMC, the views on the placement of specific control loops into the upper or lower control levels may differ. In energy-based control, there is a clear separation between energy control functions (that are often considered upper-level) and current control functions (that are often considered lower-level for AC, DC and circulating current control) [11], [32]–[35]. In non-energy-based control, the same current control functions are also often considered lower-level [32], [36]. However, in non-energy-based control, the current control functions implicitly also control the converter energies. Hence, a consensus on whether the different current control functions (AC-side, DC-side and circulating current) should be considered lower- or upper-level is not easily achieved.

Notably, the only published C&P structure of a real multi-vendor, multi-terminal HVDC station originates from the Chinese Nan'ao HVDC system shown in Fig. 2. This system has a vendor-specific valve and submodule control [37], [38]. The circulating current control is found in the lower control level. However, it is not indicated if the DC- and AC-side current controllers are placed in the lower or upper control level. Therefore, both options are considered in this paper.

C. PROTECTION

The protection system for an HVDC station consists of many protection functions, each fulfilling a specific purpose. These include, for example, DC-side protection, AC-side protection, transformer protection, feeder protection and many more [8], [32]. The aim of the protection functions is (a) to contribute to fulfilling availability requirements on a system level according to the chosen protection philosophy and (b) to protect the expensive HVDC equipment — especially the converters — against permanent damage. Whereas most of the listed protection functions are well-established based on a long experience from AC systems, DC grid-specific and converter-specific protection functions deserve special attention in a multi-vendor HVDC context.

1) DC-SIDE PROTECTION

The DC-side protection in an HVDC station has to cover both the DC busbar and DC lines. These protection functions are concerned with the system surrounding the converter unit and are therefore considered upper-level. Today, several fault detection algorithms are used for point-to-point HVDC links, e.g., DC under- and overvoltage during a pre-defined time, voltage imbalance on the poles, DC overcurrent and busbar differential current [8]. Furthermore, the DC-side protection can be achieved with a $\mathrm{d}v/\mathrm{d}t$ algorithm that detects a fast change of the busbar voltage [8]. For backup, a DC undervoltage and overcurrent criterion can be used [8]. Future multi-terminal HVDC systems will likely use a combination of fast single- and double-ended fault detection algorithms as summarised in [39]. Three concepts for the integration of protection functions into a substation have been suggested in [40], namely, (1) standalone, (2) integrated with the DCCB and (3) integrated with the converter protection and control. Notably, a station architecture using an implementation with several standalone IEDs has been presented in more detail in [4]. However, regardless of the concept, after fault detection [41] the protection has to send a trip signal, e.g., to the correct DCCB(s) for a fully selective protection strategy. For other protection strategies (e.g., non-selective), other equipment needs to act. Together, the fault detection and equipment act upon a trip from the DC-side protection function(s).

2) CONVERTER INTERNAL PROTECTION

HVDC converters use power electronic components which are sensitive to high currents. Hence, MMCs employ internal protection reacting, for example, to arm overcurrents, submodule under- and overvoltages and other criteria [32]. In the case of a DC fault, the DC voltage drop leads to a submodule capacitor discharge, a rise of the arm currents and ultimately an uncontrolled behavior of half-bridge MMCs. Hence, following a DC fault, half-bridge MMCs are typically blocked because of overcurrent [42]–[45]. For additional converter-internal protection, an arm undervoltage criterion can also be used indicating the uncontrolled MMC state. MMCs can also be blocked for voltage imbalance on the poles, busbar differential currents, abrupt changes of the busbar voltage, overvoltage during a pre-defined time and harmonic phenomena [8]. It can be assumed that the MMC may have some margin for tuning these additional protections depending on the surrounding grid. However, the semiconductor overcurrent constraints are fixed.

Currently, operational point-to-point HVDC links would likely open the ACCBs of each MMC upon converter blocking. ACCB opening should be avoided in future multi-terminal systems utilizing DCCBs and/or if the converter is required to ride through a fault to achieve the desired behavior at the system-level [43], [46].

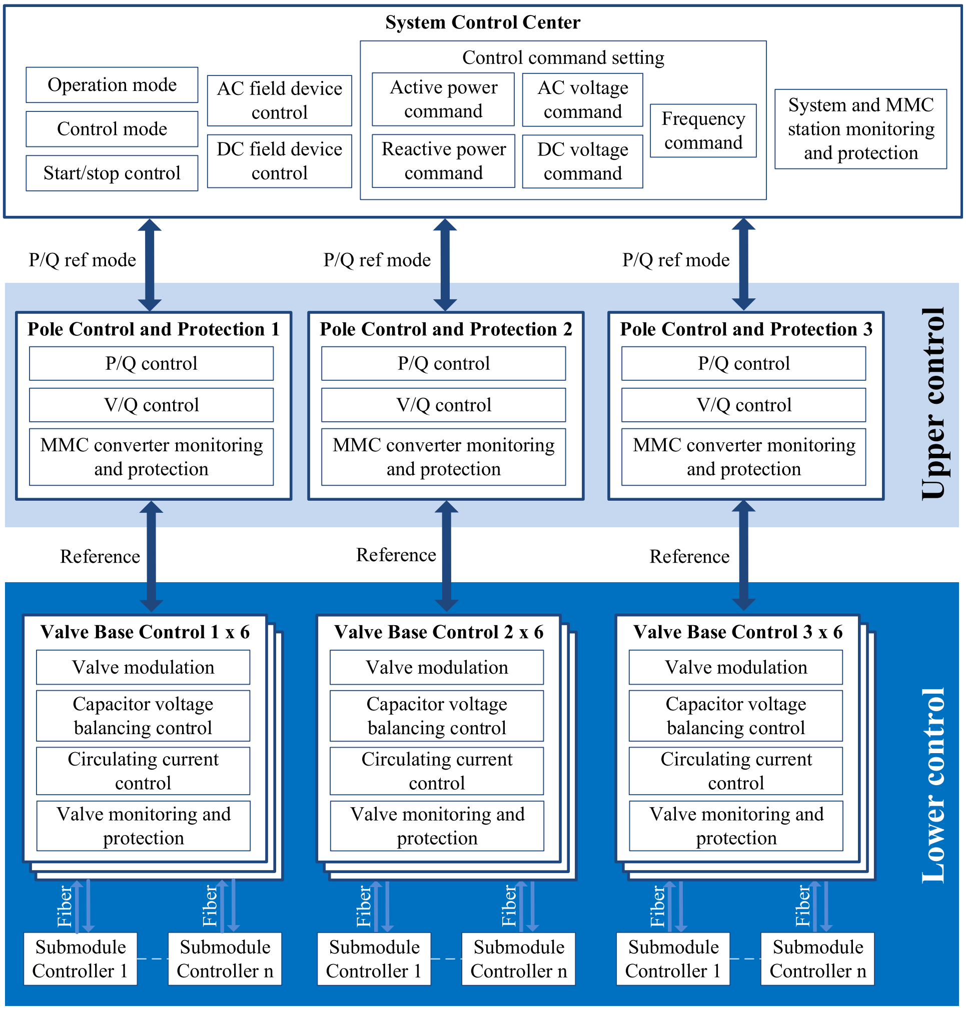

FIGURE 2. Functional control structure of the Nan'ao 3-terminal HVDC system, based on [38].

D. FUNCTION OVERVIEW

A selection of the previously discussed functions to be fulfilled by an HVDC converter station is summarized in Table 1. Here, it is not decided which component or which party could be responsible for fulfilling the functionality. A distinction, however, is made between lower-level and upper-level functions. Functions concerned mainly with the external behavior of the converter station are grouped into the upper level. In contrast, functions mainly concerned with the converter's internal behavior are grouped into the lower level. If the attribution of a function into the upper or lower level is not clear (e.g., because the function may be concerned with both), the function is placed in-between. Note that additional functions are also required which are not shown in Table 1. These include sequences on startup and shutdown, switching between different normal operation modes (grid-following vs. grid-forming), as well as different fault modes, e.g., fault ride-through, pole balancing, and voltage and power ramping modes.

Notably, there is an obvious similarity of the function selection into upper-level and lower-level (Table 1) with their actual implementation in one real multi-vendor setup in China (Fig. 2). Furthermore, for such kinds of multi-vendor setups, it has been stated that "…the external controller and the internal controller are usually provided by different vendors…" [47].

III. PROPOSAL FOR AN HVDC CONTROL & PROTECTION ARCHITECTURE WITH A PARTIALLY OPEN APPROACH

The motivation for a partially open HVDC control & protection [23]–[25] was to allow for easier problem-solving in multi-vendor HVDC systems.

Based on the HVDC C&P functions in Table 1, this section develops an architecture, command and information flow in a multi-vendor HVDC station with a partially open approach. Given that parts of such an architecture are inherently connected to the system topology, some specific design choices are first summarized (Section III-A).

After that, recommendations are proposed for individual control and protection elements, considering open/closed software parts, open/closed parameters and open interfaces. Parameters define the behavior of a system part. Parameters include, for example, electrical parameters such as inductances, control parameters (gains) or even Bode plots

TABLE 1. **Selection of functions to be fulfilled by the HVDC converter station (converter control, Section II-B and HVDC protection functions, Section II-C); example classification into upper and lower level.**

Upper-level	
Control	Protection
AC voltage / Reactive power control DC voltage / Active power control Grid-forming	AC-side fault Transformer Feeder AC Busbar DC-side fault DC Busbar Excessive harmonics
Either upper- or lower-level	
Control	Protection
PLL Circulating current control AC and DC-side current control Total energy balancing	
Lower-level	
Control	Protection
Modulation Submodule capacitor voltage balancing Arm energy balancing	Arm overcurrent Submodule under- and overvoltage Submodule open circuit Auxiliary power supply + backup Fire Sensor fault

representing the frequency behavior of a system part. Some parameters have to be open so that they are available and can be used for system design. Interfaces are defined as connections between different systems parts used to transfer information and commands during operation. Likewise, some interfaces have to be open such that the transferred data can be used for different control and protection actions.

This discussion of individual elements considers the converter control (Section III-B), the converter internal protection (Section III-C), and the system control/protection (Section III-D-III-E), In this process, Fig. 3 will serve to illustrate different options for the division of the control software into open and closed parts — whereas no such figure is necessary for the protection elements since the division is straight-forward. An interface 'n' will be indicated by ⓝ in the text. Naturally, all open/closed interfaces need to be defined regarding syntactic and semantic communication aspects. Established interfaces, e.g., for AC-side protection, are not discussed since this paper focuses on multi-vendor HVDC aspects.

At the end of this section, all individually discussed open/closed software parts, open/closed parameters, and open interfaces are summarized in Fig. 4 (the suggested HVDC station architecture), Table 2 (a list of open interfaces) and Table 3 (a minimal list of required open parameters).

A. REFERENCE HVDC SYSTEM

Any electrical system can be designed in different ways. However, the investigated design alternatives must be limited to the most promising candidates. Although there is not yet a universally accepted C&P topology for a multi-vendor HVDC system, the following sections detail design choices, leading to what could be considered a typical vision of a near-future system. This reference design will then be used to propose the architecture of the partially open multi-vendor HVDC systems.

1) HVDC CONVERTER

In this paper, non-fault-blocking MMCs (e.g., using half-bridge submodules) are considered given that they are the dominant VSC topology implemented in the field today [2], [8] and anticipated in near-future HVDC grids. It is envisaged that many of the recommendations given in this paper could also apply to DC/DC converters and fault-blocking AC/DC converters, however, analysis of these future topologies is beyond the scope of this paper.

A typical MMC control structure is applied, including upper-level control, lower-level control and internal protection — as previously detailed in Section II-B and Section II-C2. Interfaces are required between the MMC C&P system and the converter station power hardware. Further interfaces are anticipated for the station controller to coordinate system-level functions, for example, set-point and control and operation mode changes.

2) DC-SIDE PROTECTION – DCCB

The DCCB is now commonly considered for the protection of future multi-terminal HVDC systems and several DCCB topologies have been tested successfully at full scale [48]. Therefore, this reference system will employ protection using DCCBs (and additional series inductances on the DC-side). The discussion and methods considered here are focused on fully-selective but can also apply to partially and non-selective protection strategies [40]. It is expected that interfacing for systems without DCCBs can be a subset of the solution suggested in this paper.

The DCCB is expected to contain a controller to perform operation sequences and monitoring of the device. In this paper, the controller is considered to have an interface with the power circuit of the DCCB (e.g., trip signals to physical components, measurement, and feedback) and will require an interface to the station protection (e.g., for trip command and state feedback).

3) MEASUREMENTS

It is assumed that the station controller and the station protection will receive measurements. This could either be via the converter controller, a direct interface to measurement devices or a separate communication method. It is also assumed that the measurement equipment (which is vendor-specific) will provide measurements in a standardized and compatible format.

4) STATION CONTROL AND STATION PROTECTION

Unlike in existing point-to-point HVDC systems, it is envisaged that in the control and protection of future large-scale multi-terminal systems, controllers performing system-oriented functions would be separated into standalone device(s). In this manner, the station control and protection functions are performed by dedicated devices in each station, i.e., a station controller and a station protection IED.

The station controller receives operator input, dispatch set-points, and collects information from other equipment (DCCBs, the station protection, the converter). Here, it is not decided whether the station controller should act using a decentralized HVDC grid control or a centralized HVDC grid control. In the latter case, one station would also act as the HVDC grid master. In either case, the station master controller can change control set-points for the local converter's upper-level control and make suggestions and/or provide status information for the converter internal protection.

The station protection executes protection algorithms using measurements (e.g., from the line-end) and sends protection-related commands (e.g., trip signals for DCCBs).

Though a split into a station controller and a station protection is applied here, it is also conceivable that these could be implemented in a shared device. Conversely, it is possible to split the protection functions into additional standalone protection IEDs (e.g., as done in existing AC systems and the first meshed multi-terminal HVDC system Zhangbei [4]). In any case, differing configurations for the station control and protection command may still use a subset of the methods and interfaces proposed in this paper.

B. PROPOSAL FOR CONVERTER CONTROL APPROACH

The main aim of a partially open approach to the HVDC converter control is to enable AC and/or DC grid operators to perform control interaction and stability studies more efficiently and, as a result, to resolve interaction problems.

As described in Section II, the control system of each converter in a multi-vendor setup has to fulfill several control functions. From a simplified point of view, these control functions either primarily serve a purpose concerning the AC or DC grid (e.g., controlling the values requested by the dispatch control) or they primarily serve a purpose concerning converter-internal quantities (e.g., submodule energy, circulating currents). Typically, the system-related control functions are grouped into an upper level, whereas the converter-internal related control functions are grouped into a lower level (see Table 1).

The control can be considered to be split into the software control structure/algorithms and the parameterization of these controls. The software is typically designed by a vendor. The parameterization may be performed by the vendor or by the operator/system integrator. It combines the control software and the control parameters that define the control response. Additionally, interfaces between control elements and between the controller and other system parts are required for successful operation. Each of these elements — software, parameters and interfaces — can benefit from some aspect of openness.

1) OPEN/CLOSED SOFTWARE

The upper-level control functions have the primary role of controlling the converter's AC- and DC-side behavior. To resolve control-related interactions, the use of an open upper-level control was previously suggested [23], [24], in particular in multi-vendor scenarios with several control systems. The lower-level functions are mainly concerned with the internal behavior of the equipment which is also closest to the vendor's core competence and respective IP. For that reason, these control levels were considered closed in [23], [24]. However, a decision on open and closed control software parts depends on many aspects.

On the one hand, upper-level control functions are known to have an impact on the behavior of an HVDC converter embedded into a system [15], [49].

On the other hand, details of the lower control levels might also affect the AC and/or DC side behavior [50], [51], making them relevant for a complete stability assessment. Hence, the border between open and closed control parts may not be identical to the border between what is normally considered upper and lower level controls. The agreement on a border has to consider, for example, the responsibility for the involved functionality, (standardized) interfaces, IP rights or the practical implementation of different control parts in various pre-existing control platforms. From an academic and TSO perspective, it would be desirable to define levels so that the control parts most relevant for grid interactions/stability can be accessed from the outside (open level). In contrast, all controls with a negligible impact can stay closed. However, this approach may still require information about specific loops such as the lower current control (often regarded as the core of VSC control, thus vendor-specific and IP-protected) since it can also be involved in grid stability issues [14], [51]. Likewise, considering the plethora of control loops and approaches for MMCs, (compare Section II-B on energy-based, non-energy-based, grid-forming or grid-following control), the impact of different control loops on grid interactions/stability has to be investigated for each control approach.

To account for this uncertainty, two example options for a border between open and closed control parts are presented in Fig. 3. Option A assumes a design with a negligible impact of the black-boxed control parts on the system stability and thus represents an option where only very few parts of the control have to be open. Option B tries to account for all possible controls impacting stability and hence represents a very "open" option. A meaningful agreement on these borders could also lay in between.

2) OPEN/CLOSED PARAMETERS

A border between open and closed control software parts, as indicated in Fig. 3, implies that information about the closed (lower) control parts must be available to design the open (upper) control loops. Otherwise, tuning the open controls without any knowledge about the closed control

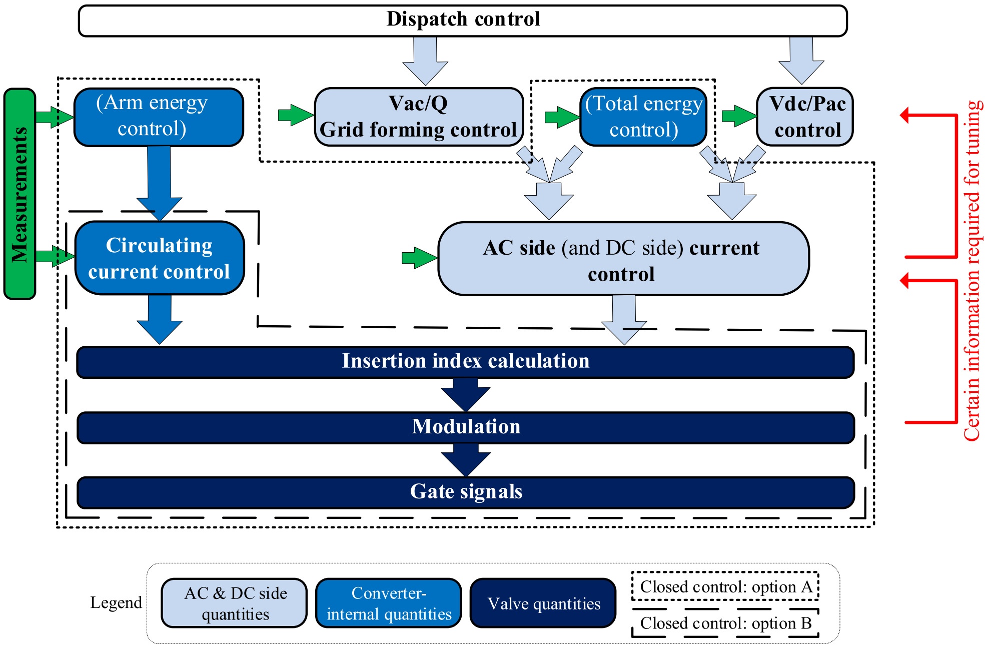

FIGURE 3. Functional control structures for different MMC converter controls. Two options for borders/interfaces between open and closed parts are proposed: option A assumes a design with limited impact of the inner loops on stability; therefore, only access to some upper control layers; option B accounts for different control implementations with different ways of impacting stability; therefore, a higher degree of access to the upper control layers.

structures might result in unstable behavior. Typically, the design and structure of the lower-level controls have their main impact at higher frequencies. In contrast, the design of the upper-level control affects the behavior closer to grid frequency [14]. Hence, among other factors to be determined, information on the frequency behavior of the closed lower-level controls might be a requirement to enable the design of the upper-level open controls and even the station control and protection. Similarly, information about the sampling of the lower-level controls seems to be a requirement for the design of the upper-level controls [51].

3) OPEN INTERFACE DEFINITIONS

The information exchanged through the interface between open and closed converter control parts has to consider the different MMC control options.

For example, option A in Fig. 3 will require an interface ①A that communicates the voltage and power references from the open to the closed control part at the appropriate sampling rate with a maximum allowed delay. Option B in Fig. 3 will require an interface ①B that communicates the arm reference voltages from the open part to the closed part, again at the appropriate sampling rate with a maximum allowed delay.

In turn, the closed control will have to communicate status information back to the open control ①. This information could include, e.g., the availability of the closed controls or controller limits. The latter may be useful to know whether a set-point can be reached and thus avoid controller saturation.

Similarly, the upper-level control needs an interface to the station control ②, possibly for communicating similar information as is done from the lower-level control to the upper-level control, i.e., availability and information about controller limits. In turn, the station controller will provide the upper-level control with set-points, gains, and control and operation mode information (start-up, voltage vs. power control, etc.) ②.

C. PROPOSAL FOR CONVERTER INTERNAL PROTECTION APPROACH

The aim of a partially open approach to the converter internal protection is to facilitate integration with upper control and protection functions (and their design), in particular in a multi-vendor HVDC environment. The HVDC converter-internal protection is considered a lower-level function as discussed in Section II).

1) OPEN/CLOSED SOFTWARE

Being a lower-level function and thus closely connected to the converter hardware, it is assumed that the converter internal protection software is vendor-specific and closed.

2) OPEN/CLOSED PARAMETERS

To integrate the converter internal protection with the different HVDC control levels and the HVDC system protection, some parameter or high-level aggregated characteristic of the converter internal protection will be required. Such a high-level characteristic should — as a minimum

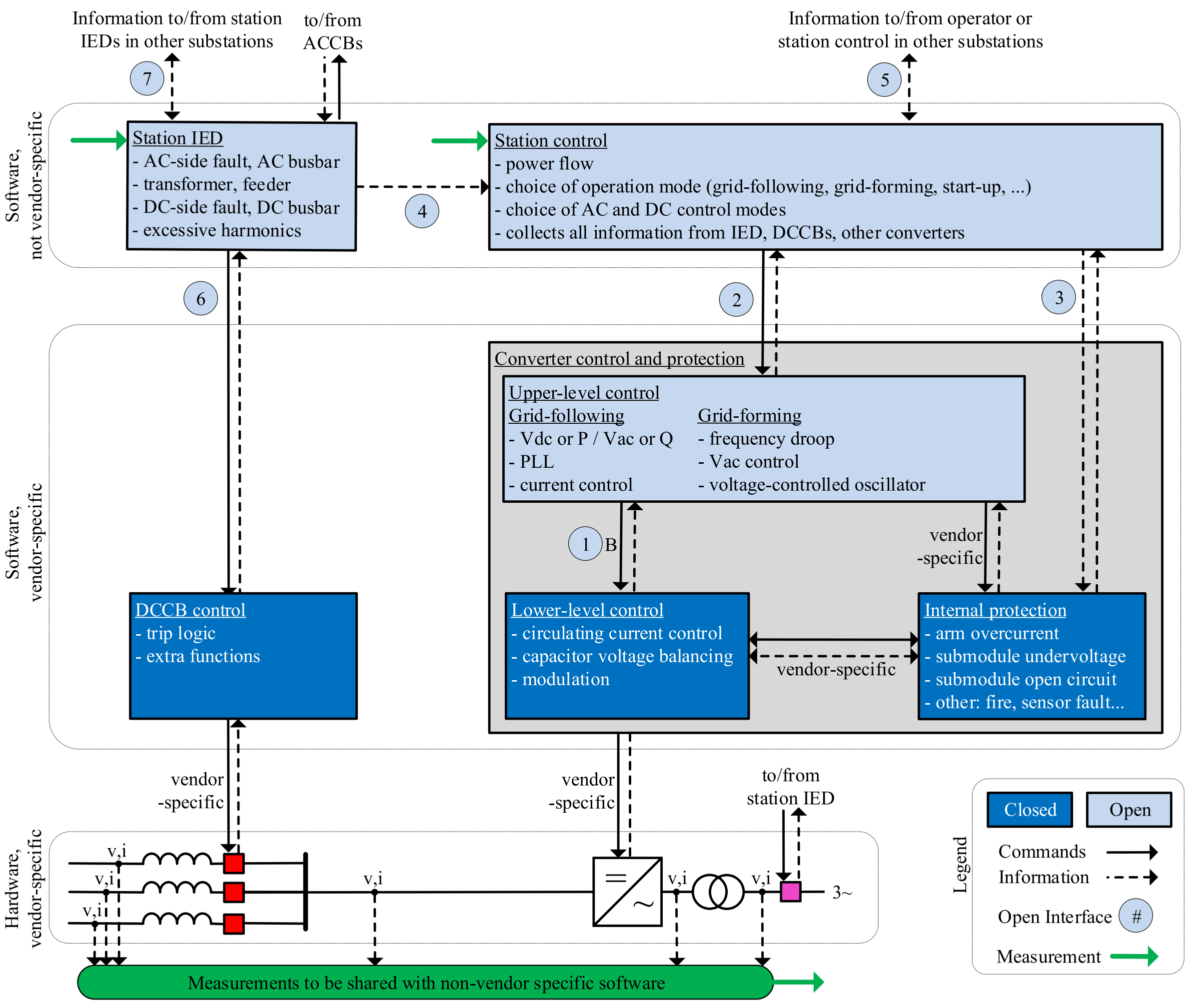

FIGURE 4. Example proposal for an HVDC station architecture with partially open control and protection software (Option B in Fig. 3).

requirement — provide the maximum arm currents over time at which the converter will not enter a blocked state (in kA per μs). From a vendor perspective, such a characteristic would allow designing a blocking behavior including margins without revealing details.

3) OPEN INTERFACE DEFINITIONS

Additionally, status information about the converter internal protection has to be available to the station controller ③, e.g., a blocking and availability indicator. The station (and ultimately the HVDC grid controller) require this information to know what behavior can be expected from the converter. For choosing the most robust control after temporary blocking, optional information about a triggered blocking criterion (submodule under-/overvoltage, arm overcurrent, ...) may be communicated from the converter internal protection to the station control.

In the opposite direction, the converter internal protection may receive other optional input ③ from the station controller, e.g., the status of DCCB fault current limiting or DCCB auto-reclosing. These signals may be useful to allow the converter internal protection to not immediately block/trip and instead ride through a fault — if possible from a hardware point of view.

Within the MMC C&P system, interface(s) will be present between the converter control and the converter internal protection. Both elements are anticipated to originate from the same vendor and are close to the specific, IP-critical converter hardware. Therefore no open interface is required.

D. PROPOSAL FOR STATION CONTROL APPROACH

The aim of an open approach to HVDC station control is to facilitate control interaction and stability studies involving the system-related control functions and — as a result — solve them. Being at a higher level than the open converter control, a closed station control functionality does not make sense. The station control is assumed to have open functionality, combining open software and open parameters.

TABLE 2. Open interfaces requiring commands and information, optional aspects in brackets.

	Interface		Commands ⟶	Information ⇢			
①	Upper-level control ⇳ Lower-level control	↓	option A: voltage and power references, option B: arm voltage references	availability, (controller limits)	⇡		
②	Station control ⇳ Upper-level control	↓	power references, gains, operation mode, control mode	availability, (controller limits)	⇡		
③	Station control ⇳ Converter internal protection			availability, blocking signal, (triggered blocking criterion)	⇡	⇣	(status DCCB proactive mode, autoreclosing, fault current limiting, see ⑥
④	Station IED ⇓ Station control					⇣	Trip occurrences: yes/no, Information about trip events: e.g., GPS time, transient fault recordings, (status DCCB proactive mode, autoreclosing, fault current limiting, see ⑥)
⑤	Operator or other station controls ⇳ Station control	↓	operator input, dispatch set-points, (status other stations)	status	⇡		
⑥	Station IED ⇳ [52] DCCB control	↓	trip DCCB, (proactive mode), (autoreclosing), (fault current limiting)	DCCB status: open/closed, DCCB readiness: yes/no, (status DCCB proactive mode: yes/no), (status DCCB autoreclosing: yes/no/attempt), (status DCCB fault current limiting: yes/no)	⇡		
⑦	Station IED ⇳ other station IEDs			(data for double-ended fault detection)	⇡	⇣	see left

1) OPEN/CLOSED SOFTWARE

The use of a station controller with open software is assumed. The station control's main responsibility is concerned with the system behavior (e.g., power flow, choice of AC and DC control modes, choice of operation mode). Without knowledge about the control software, the desired system behavior, in particular in connection with other stations, cannot be ensured.

2) OPEN/CLOSED PARAMETERS

As with the station control software, its respective parameterization is also assumed to be open. Together, the station control software and its parameterization put requirements on other system elements. For example, if the station control demands a very fast power-ramp, the station protection (assuming it is designed without knowing the parameterization of these fast power ramps) may interpret that fast current rise as a fault, resulting in a trip and an overall C&P malfunction. In the same example, it has to be made sure that converter hardware (and its internal protection) will function such that the demanded power ramp is achieved. Similarly, the station's power controller response time and bandwidth are relevant for the proper design of the underlying lower-level control loops. In an extreme and hypothetical example, the bandwidth of the power controls may be faster than the bandwidth of the underlying upper-level controls, resulting in an unstable overall system. In summary, open station parameters are important for proper hardware and software design, as well as parameterization of the station protection and the lower control and protection levels.

3) OPEN INTERFACE DEFINITIONS

The station control requires interfaces with the converter control ② and with the station protection ④. An interface to an operator and/or station control in other stations will also be required ⑤. Given that the station control is required to be open in software and parameters, the interfaces should also be openly defined. The interfaces to the converter control ② are needed to provide power references and control mode commands for the AC-side and DC-side of the converter. Feedback from the converter internal protection to the station control is needed such that station control can adapt to, e.g., converter blocking. The interfaces from the station control to the station protection ④ may be required to coordinate protection actions (e.g., DCCB operation) or switching for maintenance and operational reasons. The interface to the operator and/or remote station controls ⑤ is required for system-level coordination and/or manual control and monitoring.

E. PROPOSAL FOR STATION PROTECTION APPROACH

The aim of an open approach to the HVDC station protection is to enable effective operation of the station-level protection (with the implicit goal of protecting the overall HVDC system), facilitate protection coordination between equipment from different vendors, e.g., DCCBs and the station control, as well as coordination with the converter control.

It is chosen to implement the system-related upper-level protection functions in one station protection unit. The choice of just one station protection unit is made based on the assumption that protection coordination will be simplified if only one device is used. An alternative setup could use several standalone line protection IEDs [4]. It is argued that using one station protection unit fulfilling the same line protection functions will be easier. Similarly, there will be less need for communication interfaces which may be desirable in the first step. Note that for redundancy purposes, an identical station protection unit is required.

1) OPEN/CLOSED SOFTWARE

Similarly to the upper-level converter control and the station control, the station protection is mainly related to the system behavior. The design of the station protection software (e.g., protection algorithms, filtering, protection sequences) impacts the performance of the system following a fault and therefore also impacts the converters. For example, the implemented algorithms and their sampling step have a considerable impact on the protection margins [29]. Lack of knowledge about these aspects could jeopardize dependable and secure protection. Additionally, individual vendors will be interested in knowing how the station protection would impact their equipment. The system-level control and protection may also contain less sensitive vendor IP, so openness may be acceptable. Thus, the station protection software is assumed to be open.

a: OPEN/CLOSED DCCB SOFTWARE

Similarly to the converter internal protection, it is assumed that the DCCB control and associated internal protection is vendor-specific and closed but can provide status feedback.

2) OPEN/CLOSED PARAMETERS

In a multi-vendor setup, the threshold settings have to be available to the system integrator designing the protection [29]. The fault detection algorithm and IED sampling step are ideally openly available to ensure the design of a robust multi-vendor protection [29]. Furthermore, relevant hardware aspects (line inductor, characteristics of the cable and DCCB surge arrestors) also need to be openly available [29]. Similar to that of the converter internal protection, a high-level characteristic of the DCCB internal control and protection may be required for system design.

3) OPEN INTERFACE DEFINITION

The following interfaces are required for the integration of the station protection into a system with DCCB(s).

To allow for system protection, the station protection will have to communicate trip signals to DCCBs, as well as optional commands to go into a proactive mode, to auto-reclose and to use fault current limiting ⑥. In the opposite direction, any DCCB will have to communicate its status (open/closed) and its readiness (yes/no) to the station protection ⑥. Details on a possible interface including these optional functions can be found in [52]. In case a double-ended fault detection is used to protect the DC-side, relying on information from the remote line end, an additional interface ⑦ to/from the station protection in other substations is required. The interfaces to/from the ACCBs are considered established and are not discussed further in the scope of this paper focusing on multi-vendor HVDC aspects.

TABLE 3. Minimal parameters needed for design of a partially open HVDC control and protection.

Element	Required parameters	Reason
Closed lower-level converter control	frequency behavior, control system sampling	to be able to design upper control loops for sampling: [51]
Closed converter internal protection	characteristic describing the blocking behavior, e.g., a maximum arm current over time for which the converter does not block	to be able to design upper control and protection without converter blocking
Open station control	control parameters and control structure	to be able to properly parameterize the station protection and lower control levels, has to fit with hardware design
Open station IED	sequences, thresholds, algorithm, IED sampling step, [29] line inductor size, cable characteristic, surge arrestor characteristic [29], DCCB characteristic	to be able to design a dependable and secure multi-vendor protection [29], protection coordination

To coordinate the system protection with the station control ④, optional signals from a DCCB to the station controller include a status on fault current limiting operation (yes/no) and auto-reclosing (yes/no, which attempt). Similarly, the station protection will have to communicate trip occurrences (yes/no) to the station control. This information may be useful information for the station control to adapt to fault situations. For post-fault analysis, the station protection may communicate information about trip events (primary, backup), the trip instant GPS time, the algorithm and protection margin, as well as transient fault recordings to the station controller.

F. OVERALL RECOMMENDATION

Based on the previous sections, the resulting station architecture with closed and open software parts — and interfaces between elements — is suggested in Fig. 4. Note that this figure is valid for option B for a border between open and closed converter control. A list of interfaces containing information and commands is provided in Table 2. Some of these signals are optional, depending on the chosen equipment. The required open parameters are summarized in Table 3.

TABLE 4. Comparison of the proposed station architecture with previous, publicly available work.

	Type	Scope	Use of several physical units	C&P functions + placement in levels	Interfaces	Communication protocols	Partially open software	Open parameters
Siemens [53]	Industrial	single-vendor, point-to-point	not mentioned	not mentioned	not stated in detail	not stated in detail	no	no
ABB [54]		single-vendor, point-to-point	not mentioned	functions mentioned, but not their placement		IEC and IEEE, CAN for binary I/Os, proprietary lower-level communication, EtherCAT between I/Os and main computers	no	no
GE [55]		single-vendor, point-to-point	yes	functions + placement in levels mentioned (but no association to physical units)		IEC 61850 and variants, no details on lower-level communication	no	no
Nan'ao [37], [38]		multi-vendor with strong system integrator, multi-terminal	yes, vendor-specific valve C&P, other vendor for higher controls	see Fig. 2		not mentioned	unclear	unclear
[5] on HVDC protection	Academic	multi-vendor, multi-terminal	yes	functions + placement mentioned (only protection)		IEC 61850 DC digital substation, no details on lower-level communication	no	no
[30]		multi-vendor, multi-terminal	yes	system-related functions + placement mentioned (no converter C&P)	not stated		no	no
Proposed architecture		multi-vendor, multi-terminal	yes Fig. 4	yes Section III	yes Table 2	no details see Section IV	yes	yes Table 3

G. COMPARISON WITH EXISTING ARCHITECTURES

The proposed station architecture addresses several aspects that are not addressed in previous published work. An overview is shown in Table 4. However, it has to be kept in mind that a candid comparison should consider the type and scope of the available reference work.

IV. FUTURE WORK

To enable a partially open approach to HVDC C&P, responsibilities between the different stakeholders need to be clearly defined. This is a non-technical aspect and is out of the scope of this paper. However, with the proposed architecture for partially open HVDC C&P as starting point, future work should focus on the following technical aspects.

A. DESIGN PROCEDURES

Design procedures for control will rely heavily on the split between open and closed control parts and their control structures. Here, comparing different control structures (energy-based/non-energy-based) with a different loop placement in the open or closed control part may reveal if a specific structure may be preferable in terms of tuning and grid stability. With an agreement on a split between closed and open control parts, functional requirements for different control levels should be specified (gains, bandwidths, etc.) such that the overall system behavior can be known. In case that, for IP reasons, it is not possible to get detailed insight into models, it might be a first step to know the control structures and the parameters implemented which in terms of stability analysis will greatly simplify studies. Currently, black box models can be used, but the structure is not fully known which is a challenge for stability assessment. Furthermore, from a global perspective, it also has to be acknowledged that the criteria used for stability assessment may differ depending on the grid code of a specific region (if in place). This adds additional complexity to the work on partially open HVDC control and protection software.

Design procedures for protection will have to allow coordination between different protection functions. For example, specific knowledge from the closed converter-internal protection (“MMC blocking characteristic,” see Section III.B) may be needed to design the higher protection levels. Additionally, information from higher protection levels may be required to coordinate the MMC internal protection (e.g., fast de-blocking sequences or concepts that coordinate the timing of an MMC trip with a DCCB disconnecting a fault [56]–[58]). Also, backup protection and system-level coordination in partially or non-selective strategies are required.

B. COMMUNICATION AND INTERFACES

The functional requirements of interfaces between different components in the future HVDC station need to be clearly defined and agreed upon between all stakeholders.

An alternative approach to hard-wired communication may be the use of a communication bus (e.g., such as done in IEC 61850). Using such a communication structure would allow, for example, to pre-process, filter and bundle measurements locally in a merging unit before sharing them with other equipment. However, much faster communication is required for HVDC systems, e.g., fast DC-side protection [59].

On the one hand, hard-wired communication is less flexible and extensible than bus communication. On the other hand, the communication required for a multi-vendor HVDC station will be slim, i.e., only the necessary information to not touch upon vendor IPs. For that reason, the effort to establish a bus communication could be perceived as too high. Similarly, hard-wired communication could be perceived as less prone to cyber-physical problems. Notably, a setup using a communication bus still allows using fast measurements for the most low-level converter-specific controls, while less time-critical measurements are shared on the communication bus.

Regarding specific protocols for intra-station communication, it can be argued that today's challenges are less about technical aspects. Several industrial implementations show that the required communication speed, reliability and redundancy can be achieved (for example the switch-over between primary and backup C&P units). These technical challenges have been solved by different HVDC vendors using a variety of communication protocols (see Table 4). As a result, the new challenge is about agreement and ultimately standardization. For protocols on inter-station communication, optical fiber communication is the most suitable technology because of the long distances between stations. This technology has been employed in many HVDC projects. However, one new technical challenge on the latency for the SCADA system appears since several HVDC stations will have to be considered in a multi-terminal arrangement. These latencies are acceptable and have been analyzed in detail in [60].

Lastly, open interfaces in a partially open HVDC C&P approach likely allow for more data storage possibilities and subsequent prognostics compared to today. On the other hand, open interfaces may raise security concerns. The openness of interfaces can and should be limited to the HVDC system parts requiring the information (mainly in the same HVDC substation or to/from neighboring substations). In that case, the security concerns are identical to today's security concerns for single-vendor black-boxed HVDC C&P — with one additional new aspect on hypothetical intra-vendor/end-user security concerns. However, all vendors supplying equipment to the HVDC substation and the end-user have an interest in the secure operation. Therefore, a partially open approach to HVDC C&P results is not expected to result in additional security concerns.

V. CONCLUSION

In this paper, the first proposal of a substation architecture for a multi-vendor HVDC system with partially open control and protection was derived. Depending on the underlying initial MMC control structure, several options for a border between open and closed software parts were presented. The need for a master controller and master protection was explained. Furthermore, one list of information and command signals and another list of minimal parameters required for the design of a partially open HVDC control and protection were derived. These results lead to the conclusion that the implementation of a multi-vendor HVDC station using a partially open approach to C&P appears feasible even from practical aspects.

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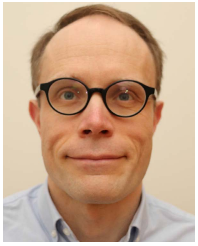

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