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Enabling the Existing Point-to-Point VSC-HVDC Control for Multi-Terminal Operation

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***Abstract*—Existing point-to-point (PtP) VSC-HVDC link's control is usually not prepared for a multi-terminal HVDC (MTDC) operation, e.g. the DC voltage droop control might not exist in the PtP link or active power control might not exist in the offshore wind farm (OWF) link. Therefore, an existing PtP link's converter control needs to be adjusted when this link is expanded into an MTDC system by interconnecting new converters into the existing system. If only one vendor is involved in the MTDC system, these MTDC specific controls can be applied directly since the vendor has the knowledge of the installed system. However, if several converter vendors are involved, they need to define a common requirement and adjust their converters to fulfil this requirement. Another option is to implement the MTDC specific control as an extension of the existing converter control. The converter control is operated in DC voltage control, which is commonly found in every PtP link, and the extension gives the appropriate DC voltage reference such that the converter operating point lies along a predefined characteristic. Simulation results show that both implementation approaches can be adopted when a PtP link is expanded into an MTDC system, although each of them has different advantages.**

***Index Terms*—DC voltage control, decentralized control, HVDC transmission, multi-terminal HVDC (MTDC), voltage-sourced converter (VSC)**

I. Introduction

In an area where there are already several VSC-HVDC links in operation, it is more likely to develop the DC grids in steps, i.e. by interconnecting some of these existing links or adding a new converter to the existing link [1], [2]. This is mainly because an organic way of developing the DC grids has a lower investment cost as compared to building the multi-terminal HVDC (MTDC) system from scratch [2]. As an example, in the south-eastern part of the North Sea region, there are 8 VSC links in operation and 3 more are currently being built. Most of these links are located near to each other, some of those have even the same cable route, which increases the possibility of MTDC development in this region.

One of VSC links is COBRAcable, which is currently being built as an ordinary point-to-point (PtP) link and connects Endrup in Denmark and Eemshaven in the Netherlands through 325 km submarine DC cables rated at $\pm$320 kV. At a later stage, COBRAcable is expected to become an MTDC system [3], i.e. by adding one or more converter along its existing cable. Similarly, FAB link is also being considered as an expandable PtP link system as well [4].

Most of the existing PtP links in the North Sea were built less than a decade ago, i.e. still within their lifetime period [2]. This means that when one of these links is expanded into an MTDC system, significant modification or even replacement on the existing system is not expected [5]. In other words, a *plug and play* principle should be applied when a PtP link is expanded.

Furthermore, each converter vendor might have different converter control concept, which is usually protected as intellectual properties (IPs). This is because currently no standard exist regulating interoperability between different converter vendors. However, a way forward to reach the interoperability between various converter vendors has been initiated, e.g. in [6], [7]. In these proposals a set of common converter parameters and converter control functions required for the MTDC operation have been defined.

The main drawback with these proposals is that the existing converter need to be adjusted in order to comply with the requirements. As an example, the existing PtP links are generally not prepared for the MTDC operation. As an example, the DC voltage droop control mode is usually not available in an existing PtP link's converters. Therefore, another DC grid implementation approach has been proposed in [4] to keep the converter control unaltered when this converter is in MTDC operation. This approach uses a primary control interface (IFC) to implement the MTDC specific controls.

However, the comparisons between these approaches are not yet performed. This paper aims to give a clear view on different DC grid control implementation approaches, especially the ones suitable to be used for the expansion of a PtP link. At first, the hierarchy of the DC grid control is described. Then these different DC grid control implementation approaches are explained and compared.

II. DC grid control concept

In a DC grid, the DC voltage can be considered as the power balance indicator [8]. The DC voltage is directly impacted when there is any deviation in the power flow within the DC grid. Therefore, the DC grid control is expected to have the similar hierarchical approach as in the AC frequency control [6], [7], [9], [10]. Figure 2–Figure 4 illustrate the DC grid control hierarchy applied for an MTDC system with n-terminal, i.e. consisted of DC grid secondary (coordinated MTDC control) and primary (converter) control.

The converters involved in the DC grid control are the ones that are not connected to an islanded AC system (e.g. offshore wind farm or offshore oil/gas platform system). The islanded converter is usually operated to control the AC voltage magnitude and frequency, so the coordinated MTDC control could not send the active power or DC voltage set-points [10].

The DC grid secondary control has a typical time response between 1 second and 1 minute and receives measurements from all converter within the MTDC system. Combining these parameters with the dispatched power transfer at the AC point of common coupling (PCC), the set points for each converter control can be determined. An optimal power flow (OPF) can be used within this control layer to calculate the optimal condition for the MTDC system, e.g. transmission losses minimization [10].

The DC grid primary control has a typical time response of a few millisecond until 0.5 s. There is no direct communication between each converter control. So, the coordination between each non-islanded converter to achieve a certain power flow condition is done by sending the appropriate references from the DC grid secondary and then the converter will work locally (autonomously) to achieve these referred values.

In theory, operation characteristic of the non-islanded converter can be illustrated using the active power (P_{ac}) and DC voltage (U_{dc}) relationship, i.e. similar to the frequency characteristic of AC grid [1], [10]. Figure 1 shows the typical characteristic of this converter. It should be noted that the DC voltage droop control mode is specific only for the MTDC system. A more advanced converter control can also be considered by activating different modes depending on the active power and DC voltage condition [8]. In this paper, only these basic converter modes are considered.

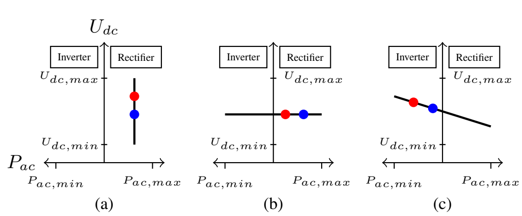

Fig. 1. The basic converter control modes represented by a single slope U_{dc}–P_{ac} relationship: (a) active power control *PacCtrl*, (b) DC voltage control *UdcCtrl*, and (c) DC voltage droop control *DroopCtrl* mode [8]. The pre-disturbance operating point of the converter is indicated by the red dot, while blue dot represents the post-disturbance operating point.

III. DC GRID CONTROL IMPLEMENTATION APPROACHES

When a PtP link is expanded into an MTDC system, the coordinated MTDC control needs to be established. The communication channel between the coordinated MTDC control with each converter within the MTDC system is required, e.g. to exchange the measurements signals and set-points.

An example of the parameters exchanged between the DC grid secondary and primary controls are given in Table I. It should be noted that the parameters in Table I are only related with the *PacCtrl* and *UdcCtrl* modes. This is due to the fact that the non-islanded converter has the capability to independently control the active and reactive power. Furthermore, the reactive power (and AC voltage) are a local parameter, which could not be sent through the DC network. A complete list of the parameters including the ones related with the reactive power and AC voltage controls can be found in [6], [7].

TABLE I
PARAMETERS FOR THE d-AXIS OUTER/RMS CONTROLS BEING SENT/RECEIVED BY THE CONVERTER [6].

Parameter	Type	Unit
Control mode (*PacCtrl*, *UdcCtrl*, or *DroopCtrl*)	input	-
Active power reference	input	MW
Active power reference ramp rate limitation	input	MW/s
DC voltage reference	input	kV
DC voltage droop slope (k_{droop})	input	kV/MW
DC voltage reference ramp rate limitation	input	kV/s
DC voltage upper and lower limits	input	kV
Active power measurement at AC PCC	output	MW
Pole-pole DC voltage measurement at DC PCC	output	kV

As listed in Table I, the non-islanded converters within an MTDC system should be able to be operated in different modes depending on the DC control strategy enforced by the DC grid secondaty control.

However, the *DroopCtrl* structure is usually not available in an existing PtP link. Furthermore, if the expansion involves a link which is connected to an islanded or very weak AC system in one side (e.g. OWF link), *PacCtrl* structure might not be available on the onshore converter. Therefore, the existing converters of the PtP link might need to be adjusted in order to implement these control modes. These new control modes for the PtP link's converters are referred as the MTDC specific controls.

There are different ways to realize the DC grid control:

A. Single-vendor approach

In Figure 2, the same vendor supplies each converter control and the coordinated MTDC control. This implementation is the one adopted in the Nan'ao and Zhoushan MTDC projects [11]. These projects were built from scratch, i.e. not an expansion of a PtP link.

This approach might simplify the expansion of a PtP link, because the converter vendor already has the knowledge on how to adjust the existing converter control in order to implement the MTDC specific controls. Furthermore, if the links were installed at different time, the rapid advancement of HVDC technology might result in different converter control versions, which make the older one obsolete. The replacement of the obsolete part, while leaving the rest unaltered, can only be performed by the same vendor, since they have the details of the converter control that has been implemented.

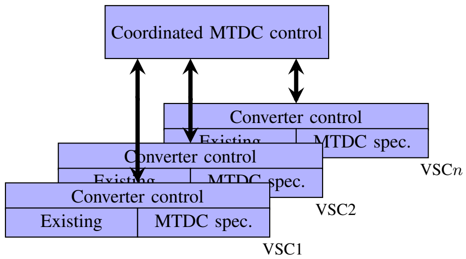

Fig. 2. The DC grid control implementation implemented by only one vendor (*blue*).

B. Multi-vendor approach

In order to illustrate a multi-vendor condition, there are three vendors considered in Figure 3: *purple*, which supplies the DC grid secondary control; *red*, which supplies the existing link (two converters); and *green*, which supplies an additional converter to be interconnected with this existing link (VSC1 and VSC2).

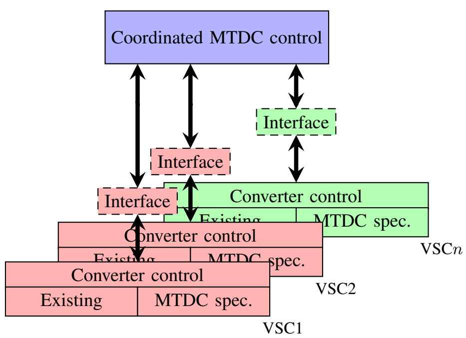

Fig. 3. A multi-vendor DC grid control implementation. An interface block is optional.

These vendors need to agree on the parameters exchanged between the coordinated MTDC control and each converter controls, e.g. given in Table I. By adopting the implementation approach depicted in Figure 3, the converter control structures are vendor specific solution, but some of their parameters should be made accessible by different vendors. Therefore, this approach is essentially similar to the single-vendor one, because each vendor should follow a strict requirement before their converter can be connected with different vendor.

An interface might be considered in order to adapt the signals from the DC grid secondary controls, such that the converter control can comply with the requirement without the need to change its philosophy [12]. As an example, the control mode in Table I might use 0, 1, and 2 to define the converter control mode. However, another vendor might use different numbering format.

C. Multi-vendor with primary control interface (IFC)

A primary control interface (IFC) has been introduced in [4], such that the existing control can be used for MTDC operation without the need to change it. Figure 4 illustrates this implementation approach. In this approach, the MTDC specific controls are implemented inside the IFC instead of altering the existing converter control.

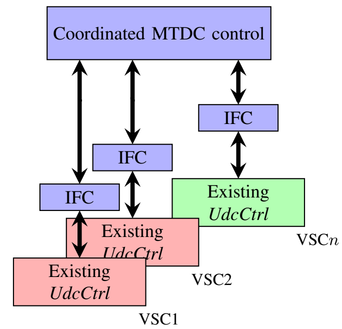

Fig. 4. A multi-vendor DC grid control with primary control interface (IFC).

As mentioned before, the *UdcCtrl* is usually available in every non-islanded converter. Furthermore, there is resemblance between the DC voltage in DC system and AC frequency in AC system, i.e. controlling the DC system can be achieved by controlling the DC voltage [8]. Therefore, with this approach, each non-islanded converter is operated in *UdcCtrl* and the IFC generates a specific DC voltage reference for the converter, such that the measured active power and DC voltage of the converter lies along a predefined droop curve [4], [13].

IV. Simulation Results

A 4-terminal HVDC system depicted in Figure 5 has been considered as the test system. This MTDC system is assumed to be formed by interconnecting two PtP links, VSC1–VSC2 with VSC3–VSC4. The ratings of each converter in Figure 5 are 800 MW and $\pm$200 kV. Further electrical parameters of the converters are given in [14].

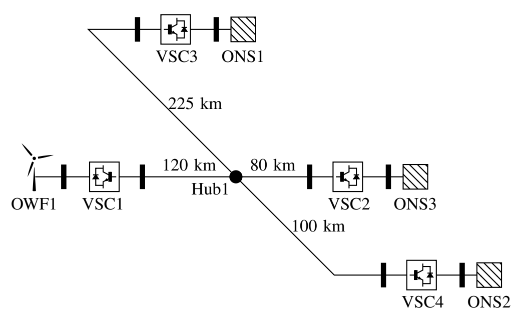

Fig. 5. The 4-terminal HVDC test system.

The difference between the DC grid control implementation approaches explained before lies on the implementation of the MTDC specific controls. In both single-vendor and multi-vendor approaches (conventional), the MTDC specific controls are implemented within the converter control. While, in the multi-vendor with IFC, the converter control is always operated in *UdcCtrl* and the MTDC specific controls are implemented within the IFC. The same coordinated MTDC control approach can be used in both conventional approaches and the one with IFC. Therefore, the simulation has been performed to show the difference between realizing the MTDC specific controls within the IFC or by making these controls available in the existing converter control. The details in the control structures and parameters used in the test system are provided in [14].

The coodinated MTDC control is not implemented. However, it is assumed that the onshore converters' characteristics depicted in Figure 6 are the output of the coordinated MTDC control, such that VSC3 and VSC4 are operated in *DroopCtrl* mode, while VSC2 is in *PacCtrl* mode, and VSC1 is in voltage and frequency control mode.

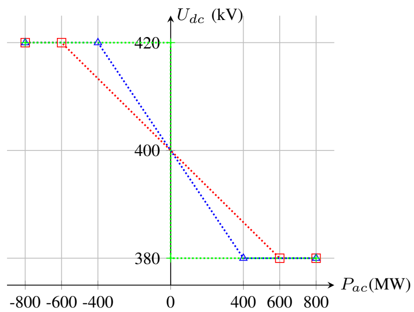

Fig. 6. The droop references for the onshore converters in Figure 5. The blue line represents the reference for VSC3 ($k_{droop} = 0.05$ kV/MW), the red one represents the reference for VSC4 ($k_{droop} = 0.033$ kV/MW), and the green one represents *PacCtrl* mode of VSC2 with reference of 0 MW.

The steady-state condition of the test system is without any power transmission trough the MTDC system, since at the beginning the OWF1 power is zero. At 2.1 s, the OWF1 power production is ramped-up from 0 to 500 MW in 4 s. Following this ramp, the active power reference in VSC2 is changed to 350 MW at 4 s with a ramp rate limiter of 200 MW/s. At 7 s, a three-phase fault occurs in the AC-side PCC of VSC4, which lead to the deactivation of VSC4.

Electro-magnetic transient (EMT) simulations have been performed using PSCAD/EMTDC software with a time step of 50 μs. The simulation results are depicted in Figure 7, for the active power (P_{ac}) measured at the AC PCC of each converters, and Figure 8 for pole-pole DC voltage (U_{dc}) measured at the DC terminal of VSC2 and VSC3.

With the IFC, each onshore converters (VSC2, VSC3, and VSC4) are operated in *UdcCtrl* mode. This means that the IFC for VSC2 provides DC voltage reference to mimic *PacCtrl* mode. From 2 to 4 s, this converter should be operated with 0 MW power reference even when there is a disturbance (a ramp up of OWF1 production). Only VSC3 and VSC4, which reacts on this disturbance and found another steady-state point along the specified droop curve depicted in Figure 6.

From Figure 7 and Figure 8, both DC grid implementation methods can achieve the same steady-state condition after a disturbance (between 6.1 and 7 s or after 7.5 s). This shows that the IFC can provide the same functionality as the "real" *DroopCtrl* (for VSC3 and VSC4) or the "real" *PacCtrl* (for VSC2) used in the conventional implementation method.

However, there are some discrepancies between the approaches during the dynamic. These discrepancies become more prominent for a faster dynamic phenomena, i.e. AC fault case (see P_{ac} waveform for VSC2). Since the IFC relies on the existing *UdcCtrl* mode, the time response of the converter becomes slower than the case with the MTDC control implemented directly inside the converter control (conventional approach).

This is because with the IFC, the new DC voltage reference will be given by the IFC depending on how far the converter operating point (P_{ac}–U_{dc} relationship) deviates from the designated droop curve. Furthermore, the dynamic in the DC side is not directly reflected in the AC side due to the energy storage provided by the converter capacitance. However, this becomes an advantage since the MTDC system has a smoother transient response.

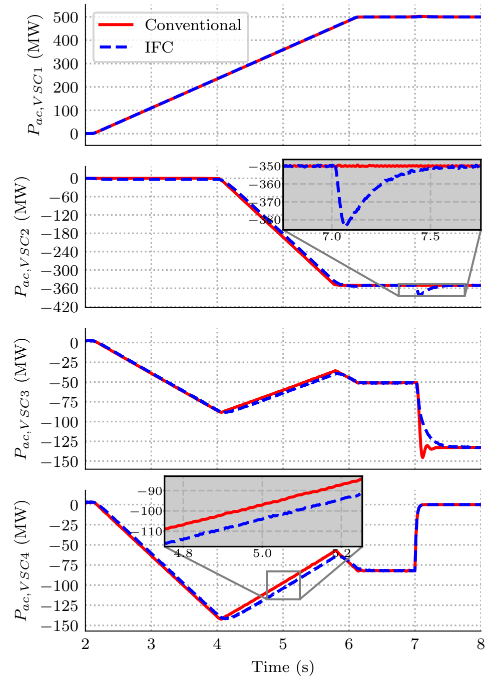

Fig. 7. The active power (P_{ac}) measured at the PCC of (from top to bottom): VSC1, VSC2, VSC3, and VSC4.

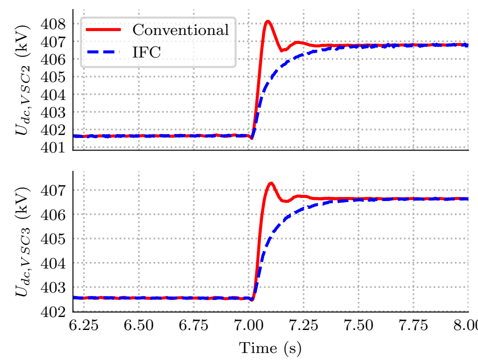

Fig. 8. The pole-pole DC voltage (U_{dc}) measured at the DC terminal of VSC2 (top) and VSC3 (bottom).

V. Discussions

As shown in section IV, either the MTDC specific controls are implemented within the converter control or within the IFC, both approaches can be adopted. It should be noted that these results are retrieved by considering the same controls has been implemented in all the models of the onshore converters, i.e. a single-vendor implementation approach. The studies can be performed without any interoperability issue since apart from the same control structure, all the parameters can be communicated perfectly.

With the multi-vendor DC grid control implementation approach, all the vendors involved in the MTDC system should have an agreement of the list of parameters to be exchanged (e.g. listed in Table I). Different vendors might then provide a black-box model to be used for the studies. Although the requirements have been fulfilled by the model, interoperability issue might still occur. In [6], there are some adverse interactions between the converter models supplied by different vendors for some converter control modes combinations, i.e. shown in 15% of the dynamic simulation cases.

By using the IFC, only one converter control mode should be provided by the black-box model, i.e. the *UdcCtrl* mode. Whereas the IFC is implemented as a separate model. Furthermore, the measurement signals (e.g. given in Table I), needed by both DC grid secondary control and IFC, can be generated from separate measurement units in the simulation case instead of relying on the output of the black-box model. Hence, the DC voltage reference becomes the only signal to be exchanged from the IFC to the vendor specific model.

In reality, with the multi-vendor DC grid control implementation approach, each of the vendors within the MTDC system has the freedom to adapt their system to comply with the requirements. Hence, as compared with the single-vendor approach, some of the existing converter control cubicle might be left untouched.

By using the IFC, the existing system only needs to ensure their converter has *UdcCtrl* mode available with adjustable reference, which makes the required signals are less than the ones listed in Table I. Furthermore, the IFC is realized as an additional control cubicle separated from the existing converter control. Therefore, the existing control cubicles remain untouched, except for enabling the communication of DC voltage reference from the IFC. This means that with the IFC, a faster realization can be achieved than the previous approaches.

As shown in the simulation results, the IFC approach is able to mimic the behavior of the *PacCtrl* mode. The IFC only gives benefit for the OWF link, because the onshore converter might not have the *PacCtrl* mode installed. If the converter already have the *PacCtrl* structure, the IFC approach might degrade the performance of the "real" *PacCtrl* since this control mode depends on the existing *UdcCtrl*. However, the same auxiliary functions, e.g. frequency and power oscillation damping (POD) controls, found in the existing link can be used together with the IFC, i.e. explained in [4].

It is expected that all the converters within the MTDC system can be operated independently to each other. This means that one converter can be blocked while the rest of the converters are operating. Therefore, the interlock between converters in a PtP link should be relieved before the DC grid control can be implemented.

VI. Conclusions

Conventionally, the converter control needs to be adjusted to implement the MTDC specific controls. The IFC is introduced in order to avoid the changes in the existing converter control. Simulation results show that these two approaches are applicable. However, the implementation using IFC is more favorable since it keeps the existing converter control unaltered.

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