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Operation strategy of a multi-terminal HVDC-connected wind farm against a highly fluctuating condition

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Abstract

When a PtP link is expanded into a multi-terminal HVDC (MTDC) system by interconnecting an additional offshore wind farm (OWF) converter, the existing operation strategy changes. The OWF power production should be considered as a determining factor to operate the system. In this paper, a new power capability curve for the existing converters is proposed. This new power capability curve is formulated as a function of OWF power production. Furthermore, different converter control strategies are also described and compared. It has been found that a multi-slope droop control strategy is the most suitable strategy for the 3-terminal HVDC system with an OWF converter.

1 Introduction

The voltage-sourced converter (VSC) is the most promising technology to be used for multi-terminal HVDC (MTDC) transmission systems [1]. The ability to reverse the power direction without the need to switch the DC voltage polarity becomes the main advantage of VSC as compared to line commutated converter (LCC). This will allow a flexible operation of the MTDC system, i.e. each converter can be switched from inverter to rectifier depending on the designated power flow without the need to reconfigure the system.

In terms of the development of an MTDC system, a step-by-step approach might become more feasible, especially in the area where there are several HVDC links in operation or being constructed [1]. As an example is in the south-eastern part of North Sea where there will be at least 12 HVDC links in operation by the year 2020 [2] (11 VSCs and 1 LCC). Furthermore, 7 out of these 11 VSCs have the same DC voltage rating, i.e. ±320 kV, which increases the possibility of interconnecting these links or some of them to form an offshore MTDC system.

In light of this organic development of DC grids, COBRAcable (DK-NL interconnector) is planned to become an MTDC system in the future [3]. Currently, COBRAcable is being built as an ordinary point-to-point (PtP) HVDC link from Endrup in Denmark to Eemshaven in the Netherlands through 325 km submarine DC cables rated at ±320 kV. When an additional converter is connected along its existing cable, e.g. depicted in Figure 1, no significant modifications are expected on the existing system [4]. The studies to prepare this link for future MTDC operation are currently performed in parallel with the installation of the link.

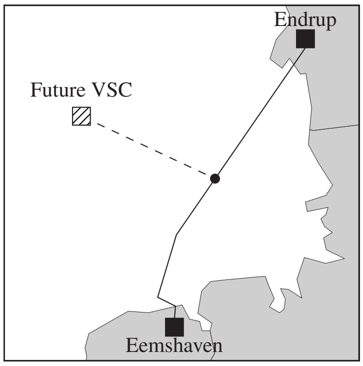

Figure 1: A possible MTDC configuration of COBRAcable. The bold boxes and line represent the existing PtP link, whereas the dashed box and line represent the future expansion of COBRAcable.

Generally, one station in a PtP link like COBRAcable is usually operated in active power control (*PacCtrl*) mode, while the other one controls DC voltage (*UdcCtrl*). The power exchange through the PtP link is reversible and dictated by the *PacCtrl* station which receives the requested power from the operator. However, when this link is expanded by adding a converter to interconnect an offshore wind farm (OWF) as depicted in Figure 1, the operation strategy of the system changes. From the wind farm owner's perspective, both onshore stations provide an alternative path for offshore to onshore power transmission. Hence, the shore-to-shore (StS) power transfer capability (like the original PtP operation) becomes limited by this.

Therefore, this paper focuses on the PtP operation strategy evolution when this link is expanded into an MTDC system by connecting an additional OWF converter. At first, the new operational limits of the existing converters are formulated as a function of OWF power production in Section 2. Since the StS power transfer capability depends on the OWF production, an example of wind power production data is given to show the statistics on how the MTDC system can still be operated for StS power transfer or forced to transmit OWF power to onshore.

Furthermore, as the next step after knowing the capability of the onshore converters within the MTDC system, each of these onshore converters should be orchestrated to reach stability following a disturbance. Different converter control mode strategies, as categorized in [5], are explained in Section 3. The benefits and drawbacks of each converter control strategy are given in order to give a clear view of the suitable control for the expanded PtP link.

2 Power capability of the expanded HVDC link

The main purpose of a PtP link is to transmit active power between the two converters (StS transmission). The converter system components (e.g.: converter transformer, IGBT modules, and DC cables) are rated to allow power transfer up to some amount in both directions, which is usually represented by the *PQ* capability curve. Power transfer beyond the converter's rating (overload condition) might be possible, which is usually limited up to a fraction of the nominal power and for short period of time, e.g. 30% above the rated power for less than 1 hour [6]. However, not all PtP links were designed with this overload capability, e.g. COBRAcable. Therefore, this overload condition is not considered in this paper.

In the StS transmission operation, the received power at the inverter station is equal to the power measured at the rectifier station subtracted with the DC transmission losses. These active power losses (P_{loss}) can be expressed in Equation (1):

$$P_{loss} = P_{loss,converter} + P_{loss,cable} \tag{1}$$

where subscripts *converter* and *cable* represent the power losses at the converter stations and DC cables, respectively. Each converter station losses is estimated at 1% of the nominal power of the converter (assuming modular multi-level technology) [7]. Whereas for the DC cable losses, their value depends on the type of conductor and the length. A typical DC system loss is estimated as 30 kW/km per cable for nominal current transfer of the cable or approximately 0.01%/km of cable's nominal power transfer [7].

When this PtP HVDC link is expanded into an MTDC system, e.g. depicted in Figure 1, the operation of the system changes. Normally, the power flow from the OWF converter is unidirectional, i.e. the OWF converter is operated as rectifier sending out the wind power to either one or both onshore converters [8]. When the OWF power is shared between the two onshore AC grids, both onshore stations are operated as the inverters. The amount of shared power is agreed between the two AC grids, usually as a result of AC/DC optimal power flow analysis.

Another alternative is when the OWF power is sent only to one onshore side. This means that only one onshore station is operated as the inverter. Furthermore, if the OWF power is lower that the existing nominal power, the other onshore side can also deliver power like in the PtP operation. Hence, the MTDC system is operated both for transmitting OWF power and at the same time sending power from one onshore converter to the other. Or in other words, the MTDC system is used for both OWF and StS power transmission.

In this paper, it is assumed that the active power transmission from the OWF has priority over the StS transmission. This means that the OWF owner has the right to sell all his production to the onshore costumer. Therefore, the StS power transfer capacity should be adapted to match the OWF power production, such that the power received in the inverter stations is always below its nominal power. This means that the amount of power injected from the onshore station, which is operated as rectifier, should be limited in order not to overload the inverter station. This limitation is formulated in Equation (2):

$$P_{ONS,cap} = \quad P_{nom} - P_{OWF} + P_{loss}, \quad \text{with } P_{OWF} \leq 2P_{nom} \tag{2}$$

where $P_{ONS,cap}$ is the StS power transfer capability of the onshore converter *ONS* (measured at its point of common coupling). Furthermore, P_{nom} refers to the nominal power of the existing PtP link, and P_{OWF} represents the OWF power production.

In Equation (2), P_{OWF} always has a positive value of active power due to the unidirectional nature of the converter. Furthermore, it is assumed that the existing PtP link system is kept as it is when the OWF converter is connected. Therefore, P_{OWF} value might be up to twice the nominal power of the existing PtP link. Hence, when the OWF power production reaches above the rated power of the existing PtP link, both onshore stations are operated as inverters.

Figure 2 then illustrates the new capability curve for the onshore converter. For simplifying the explanation, the interconnection point is located in the middle of the existing PtP link and the OWF distance from the hub is the same as the distance from one of the onshore station to the hub. Depending on the OWF power production level, the onshore converter can be operated in four operation areas (indicated by letters in Figure 2):

A. A full StS transmission capacity is available when the OWF power production is very low, i.e. close to the StS transmission losses (P_{loss}). However, during this condition, the DC voltage should be adjusted in order to avoid overcurrent through the existing DC cables.

B. As soon as the OWF production surpasses the DC transmission losses for StS power transmission, the OWF power can be transmitted to either one or both onshore converters. In the former option, the MTDC system is still capable of doing StS power transmission, but with a reduced capacity, i.e. equated in Equation (2).

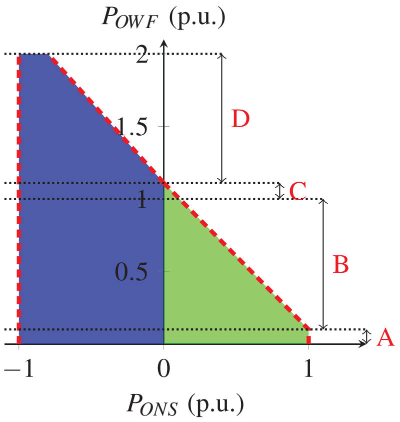

Figure 2: The new capability curve of the onshore converter (*ONS*) in the 3-terminal MTDC system with an OWF converter. Rectifier operation of the converter is indicated by the green area, whereas the blue area indicates the inverter operation of the converter. The dashed red lines represent the power limits. The right-hand limit is formulated in Equation (2)

C. When the OWF power production equals the nominal power of the existing link, all the OWF power can be sent to either one of the converter station or divided between the two onshore stations. In the former one, the power from the other onshore station is used to compensate for the transmission losses, similar to the condition in area A.

D. In the case when the OWF power production is larger than the nominal power of the existing PtP link, both onshore stations are operated as the inverter to split the OWF power. At this condition, the value of $P_{ONS,cap}$ in Equation (2) becomes negative, which represent the power limit of the converter operated as the inverter.

The height of area *A* in Figure 2 depends on the length of the existing PtP link (formulated in Equation (1)), whereas the location of the OWF converter from the hub correlates with the height of area *C*. This means that the two onshore converters might have different capability curves.

2.1 Example case

A practical example of the power capability of the onshore converters that might change from time to time (due to the highly variable nature of the wind) is shown in this subsection. An example of OWF power production data, the hourly power output of an aggregated OWFs in the Danish DK1 area, has been collected from 01 July 2017 at 00:00 CEST until 01 July 2018 at 23:00 CEST [9]. This data comprises 8784 points, which is plotted in Figure 3. The statistics of this data is given in Table 1.

The DK1 area has a total installed OWF capacity of 849.7 MW, which is mainly located in Anholt (400 MW), Horns Rev I (160 MW), and Horns Rev II (209 MW). As can be seen in Table 1, the annual average OWF power production in DK1 area is around 50% of its rated capacity. Furthermore, 9.36% of the time, the power production reaches above its rating, due to the overload capability of the OWF.

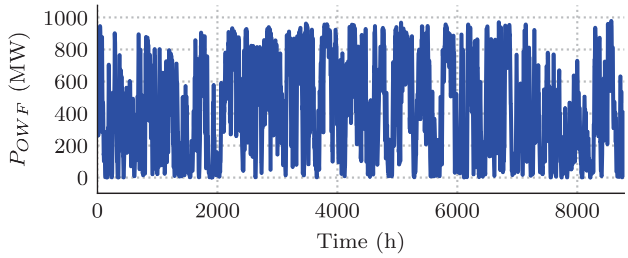

Figure 3: Example of OWF power fluctuations [9]. Time 0 hour refers the condition at 01 July 2017 at 00:00 CEST, while time 8784 hour represents the power measured at 01 July 2018 at 23:00 CEST.

Statistics	Value	
	MW	p.u.
Minimum	0.0082	0.0000
Maximum	977.7441	1.1507
Mean	424.6812	0.4998
Median	405.9593	0.4777
Standard deviation	292.3023	0.3440

Table 1: The statistics of hourly OWF production in DK1 area for 2017–2018 data.

For simplicity, this data is then used as the OWF production for the 3-terminal HVDC system depicted in Figure 4. The DC cable resistance from the offshore converter to HUB1 is 0.0080 Ω/km (2200 mm^2 cable), while for the existing PtP link, the DC cable resistance is 0.0098 Ω/km (1800 mm^2 cable). Both cables data are taken from [10]. The converter power losses are assumed to be 1% of its nominal power.

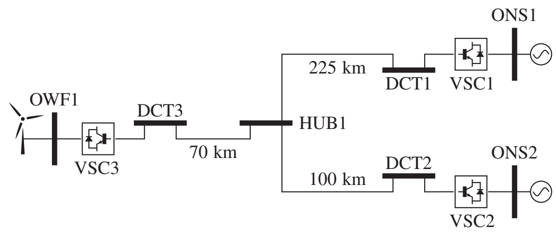

Figure 4: Example of a 3-terminal HVDC system as a result of CIGRÉ's DCS1 test system expansion, i.e. all converters are symmetric monopole type with ±200 kV [7]. Both VSC1 and VSC2 have 800 MW power rating, while VSC3 has 1000 MW.

By using the aforementioned data, the new power capability curve for the onshore stations can be calculated. The height of area A equals to 28.74 MW or 0.036 per unit. Furthermore, since the location of HUB1 is not in the middle (depicted in Figure 4), the height of area C of VSC1's capability curve is around 5 MW lower than the one for VSC2, i.e. 23.47 MW (0.029 per unit) for VSC1 and 28.37 MW (0.035 per unit) for VSC2. The frequency of occurrence for different capability areas for each onshore converter is given in Table 2.

The full StS power transmission capability of the 3-terminal HVDC system can only be done for 6.56% of the time. Whereas 79.23% of the time, the StS power transmission is still possible but with reduced capacity. Furthermore, almost 12% of the time both onshore stations are forced to operate as the inverter to evacuate power from OWF.

Capability area	Range (MW)	(% of time)
A (VSC1 & VSC2)	0.00–28.74	6.56
B (VSC1 & VSC2)	28.74–800.00	79.23
C (VSC1)	800.00–823.47	2.28
C (VSC2)	800.00–828.74	2.77
D (VSC1)	823.47–1000.00	11.93
D (VSC2)	828.74–1000.00	11.44

Table 2: Frequency distribution of the power capability areas for each onshore converter.

3 MTDC control options

After knowing the power transfer capability of the expanded PtP link, the next step is to ensure the stability of the MTDC system after being disturbed. Similar to the frequency behavior in AC grids, when DC power flow within the DC system changes, the DC voltage level starts to change. Depending on the control mode, each onshore converter might have a different reaction to this change, hence, different new steady-state values for different control modes.

Figure 5 shows the onshore converter condition before and after an outage of the other onshore station (due to AC fault at its terminal). It is assumed that VSC2 becomes unavailable and Figure 5 shows the behavior of VSC1 when all the OWF power flows through this station. As can be seen in Figure 5, although the pre-disturbance condition for all the converters in the 3-terminal HVDC system is the same, different converter control strategies might lead to a different post-disturbance operating point.

In general, the onshore converter can stay in the same control mode after a disturbance happens, e.g. depicted in Figure 5(a)–(c), or changes its control mode, e.g. as illustrated in Figure 5 (d) and (e). The former one can be characterized by a single-slope droop line, while the latter one can be represented by a multi-slope droop line. These strategies are discussed further in the following subsections:

3.1 Single-slope droop

Normally, an existing PtP link has the single-slope droop control concept implemented, i.e. one onshore station is operated in *UdcCtrl* mode (characterized by Figure 5(b)), while another one is operated in *PacCtrl* mode (illustrated by Figure 5(a)). These two control modes are usually interchangeable between the two converters, i.e. depending on the power flow direction or operator setting.

However, the most prominent drawback of this DC grid control strategy occurs when the MTDC system loses its *UdcCtrl* station. At this condition, the MTDC system might not be able to maintain its DC voltage. In the existing PtP link, the *PacCtrl* structure might have the DC voltage dependent power order limiter functionality to avoid over or under voltage condition, i.e. abruptly reducing the power reference to zero after the DC voltage reaches a threshold value. However, this function might need to be adapted for MTDC operation. This is because it might be required for the converter in *PacCtrl* mode to reverse its power direction, while maintaining the DC voltage for OWF power transfer, i.e. depicted in Figure 5(a).

Moreover, the maximum DC voltage limit ($U_{dc,max}$) in the existing onshore control might need to be lowered in order to ensure all the converters within the MTDC system are operated within their DC voltage range [8]. This means that the operating characteristics of the *PacCtrl* converter need to be altered from Figure 5(a) to Figure 5(d), which is commonly referred as the voltage margin method (VMM).

Furthermore, the fluctuations of OWF power lead to changes in $P_{ac,max}$, i.e. formulated in Equation (2). Therefore, the onshore rectifier station should be operated in either Figure 5(b)–(e) to avoid overload in the other onshore station, which is operated as the inverter. This means that the existing *PacCtrl* structure should be adjusted to mitigate these limitations.

Since the *UdcCtrl* station keeps a constant DC voltage level (Figure 5(b)), this converter becomes the slack bus for the DC system. This means that the active power transmission through this converter might fluctuates as the OWF production changes.

The power balancing responsibility can then be shared between the two onshore stations by operating these stations in *UdcCtrl* mode. However, the reference for each station should be properly given to achieve a certain power flow condition. Furthermore, the contribution of each onshore stations to balance the DC power flow is then determined by the location of the onshore converter from the interconnection hub. Hence, this control strategy might not be suitable if the system operator wants to control the contribution of each onshore converter.

This limitation is relieved by operating either one or both onshore stations in *DroopCtrl* mode (Figure 5(c)) [1]. In principle, a steeper slope refers to a lower deviation of active power transmission through this station. However, the existing PtP control systems need to be altered in order to implement this control mode, because it is uncommon to have this mode in the existing PtP link installation. Furthermore, as can be seen in Figure 5(c), a single-slope *DroopCtrl* might lead to an over-voltage condition of the system after a disturbance like *PacCtrl* mode. Hence, a multi-slope *DroopCtrl*, like the dead-band control illustrated in Figure 5(e) and explained in the following subsection, should be used in the 3-terminal HVDC system with an OWF converter.

3.2 Multi-slope droop

In this type of converter control strategy, the converter shifts its control mode, e.g. from *PacCtrl* to *UdcCtrl* (depicted in Figure 5(d), when the measured DC voltage or active power reaches a threshold. Different slope numbers within the operational range of the converter can be stacked to characterize the operation of the onshore converter. In Figure 5(d) and (e) two slopes have been considered, i.e. the normal slope where the converter is operated in *PacCtrl* mode (Figure 5(d)) or *DroopCtrl* mode (Figure 5(e)), while the converter is disturbed the converter changes to *UdcCtrl* mode.

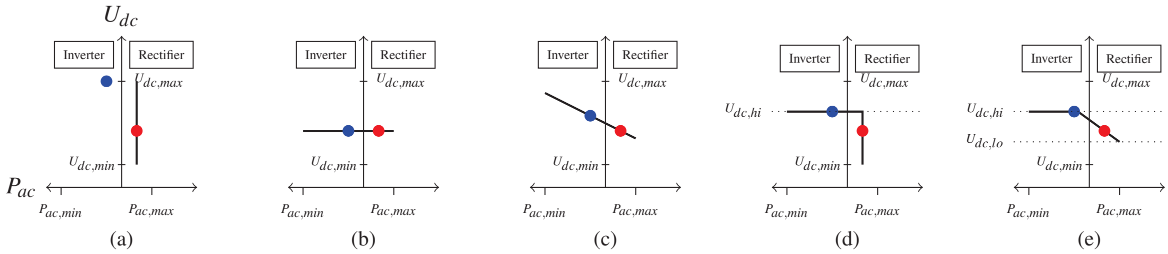

Figure 5: The onshore converter characteristics represented by the relationship of DC voltage (U_{dc}) and AC active power (P_{ac}) for different control strategies: (a) *PacCtrl*, (b) *UdcCtrl*, (c) *DroopCtrl*, (d) voltage margin method (VMM), and (e) dead-band control [5, 11]. The pre-disturbance operating point of the converter is indicated by the red dot, while the blue dot represents the post-disturbance operating point.

By using the multi-slope droop control strategy, the onshore converter can have a different reaction following OWF power fluctuations or forecast mismatch. Thus, by using the multi-slope droop, there is no need to send new setpoints for each onshore station every time the OWF production changes. Furthermore, these changes can be divided into some ranges, which are then used to determine several dead-band ranges for activation of different converter characteristics.

As an example, the wind farm in Figure 4 is currently producing 724 MW, which is transmitted equally through VSC1 and VSC2 (each of the onshore converters transmits 350 MW to the AC grids). For the next 72 hours, the deviation of the OWF power production is expected to be 100 MW or less, which is decided (as an example) to be taken care by ONS2 (VSC1 is injecting a constant power of 350 MW to ONS1). However, if the OWF power deviation magnitude is larger than 100 MW, both onshore stations should share the deviation and equally adjust their power transmission level. Hence, the multi-slope droop characteristics for both onshore stations illustrated in Figure 6.

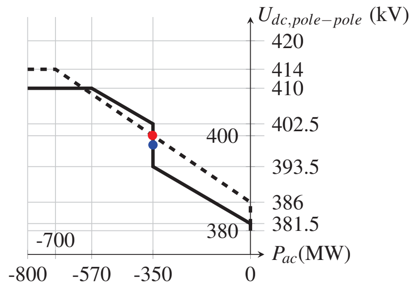

Figure 6: The operation characteristics of VSC1 (bold line) and VSC2 (dashed line). The steady-state condition of VSC1 is represented by the red dot, while the blue dot represents the condition for VSC2.

Although the converter can be operated ±5% from its nominal voltage (±20 kV), the maximum DC voltage is reduced to ensure a safe operation of the system. VSC2 has a higher DC voltage margin since the interconnection point is 125 km closer to this station than to VSC1. Furthermore, it is also assumed that both VSC1 and VSC2 are used to evacuate power from OWF, therefore when the OWF power reaches 0, the MTDC power flow is also zero. Hence, in this condition both onshore stations operate as *PacCtrl* at 0 MW represented by a straight vertical line at 0 MW in Figure 6. Moreover, when both onshore stations are operated in *DroopCtrl* mode to share the same amount of deviation, VSC1 and VSC2 do not have the same slope. This is because the hub is not located in the middle of the line, i.e. different droop constants to count for the power loss between the HUB1 and each onshore terminals.

The 3-terminal HVDC system depicted in Figure 4 has been implemented in DiGSILENT PowerFactory to perform an RMS simulation with OWF power fluctuations. The averaged value model (type 6) has been considered to represent all the converters in this MTDC system [7, 12]. The electrical and control parameters of the system are the same as in [7, 12]. Furthermore, the OWF converter is used to control the offshore AC-side frequency and to simplify the implementation, the DC grid control concept proposed in [11] is considered in both onshore converters.

The measured OWF power is then assumed to be the one given in Figure 3 from 01 March 2018 at 05:00 CEST (5839 h) until 03 March 2018 at 04:00 CEST (5910 h). It should be noted that for the simulation, the time has been scaled down such that 1 point of data means 3.6 s of simulation. The simulation results are plotted in Figure 7 (time plot) and Figure 8 (*xy* plot).

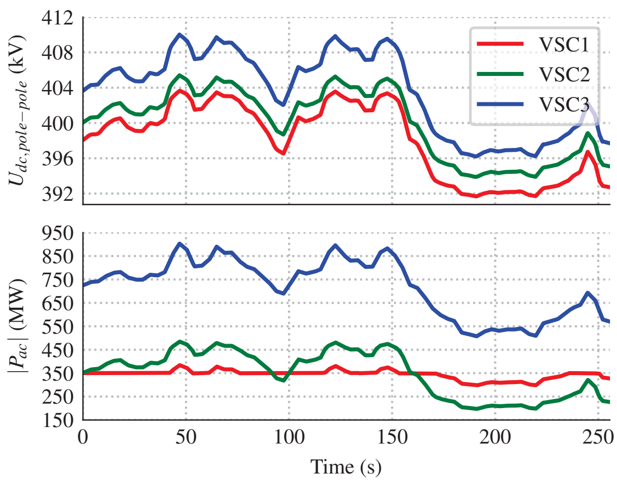

Figure 7: The pole-to-pole DC voltage (above) and the absolute value of active power (bottom). The absolute value is chosen to give clarity on the plot and there is no power reversal event in the system. Both onshore stations have a negative sign (inverter operation).

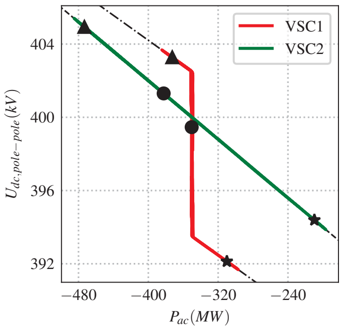

Figure 8: Figure 7 plotted in P_{ac}–U_{dc} plane. The ●, ▲, and ★ represent the condition at 10, 45, and 200 s, respectively.

As can be seen in Figure 7, both onshore stations operate as expected. When the OWF deviation is less than 100 MW, only VSC2 that mitigates the fluctuations. VSC1 starts to contribute to balance the DC power only when the VSC2 power level magnitude reaches more than 450 MW or less than 250 MW. This means that at this condition, the deviation of power in VSC2 is reduced by half.

4 Conclusion

In this paper, the operational consequences of expanding a PtP link into MTDC system by interconnecting an additional OWF converter has been described. As the main purpose of the PtP link is to transmit power between the stations, this StS transmission capability reduces when this link is expanded. This is because the OWF power output could not be controlled like in the conventional generators. By considering the hourly measured OWF data for the whole year as an example, it was found that the MTDC system has the capability to fully support StS transmission only 6.56% of the time.

After defining the new power capability curve for the onshore converters within the 3-terminal HVDC system, the next step is to coordinate these converters. In general, the converter control strategy can be represented by a single- or multi-slope droop characteristics. In the former strategy, the onshore converter station stays in the same mode following a disturbance, while the onshore converter shifts its control mode in the latter one.

It has been discussed that the multi-slope droop concept becomes superior to be used in the expanded system. By using this control strategy, the onshore converter can endure different disturbances by switching its control mode to match the condition of the system.

The discussion in this paper is limited only for the expansion of a PtP link by interconnecting an additional OWF converter. Further analyses are required for a more complex MTDC system. Furthermore, a DC over voltage might occur when there is a surplus of OWF power production, due to unavailability of one or both onshore converters, Mitigation alternatives, e.g. DC chopper or OWF power reduction, need to be investigated.

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