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Effect of Network Protection Requirements on the Design of a Flexible AC/DC-link

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Keywords: DC-side protection, flexible AC/DC link, voltage source converter, selectivity.

Abstract

This paper explores how protection systems affect the design of a MV flexible AC/DC link (FDCL). To show this impact, two FDCL designs are analysed. The first designed before considering protection and the second created specifically to solve the protection issues realized in the first. One of the main aspects of the FDCL is to be placed into an existing network, reuse existing equipment, and not require any changes outside of the substations of installation. In this way, the converters must be sized in such a way to retain selectivity of the lower network as well as be able to secure a continuous supply of power through the link even in the case of a DC-side fault. How this is performed and the converter overrating requirements are determined for a 10 kV MV link.

1 Introduction

The idea of a flexible AC/DC link (FDCL) is to take an existing electric power transport link and reconfigure it in such a way that it can operate as either AC or DC depending on the network requirements at any given time. The technology would be applied to parts of the network being constrained by load growth and a changing load profile due to new consumer load technologies (such as E-vehicles) and decentralized generation. By operating a link as DC, the link gains transport capacity and the power exchange can be actively controlled. When capacity gain is not necessary, the link can revert to the conventional AC operation with the added benefit of having shunt-connected voltage source converters (VSCs) at either end acting as STATCOMs. More information on the installation and operation concepts can be found in [1].

One goal of this technology is to give greater control to the distribution network operator (DNO), thus it is applied within the medium voltage (MV) network. After multiple discussions with engineers from the Dutch DNOs involved in this project, it became clear that their greatest interest for this technology is within MV-transmission (MV-T) links (10 kV).

The MV-T links generally connect an HV/MV substation (OS) with a regulating or switching station (RS) at distances which often exceed 10 km (as seen in Figure 1). If these links become overloaded, it can be an expensive and timely endeavour to reinforce conventionally (e.g. installing new parallel cables). Therefore, other methods of reinforcement which do not require digging and laying new cables are of interest.

The FDCL concept, as being researched by the TKI Urban Energy project *FLINK* (Flexible and Future Power Links for Smart Grids), would allow a postponement of conventional reinforcement of the network by installing power electronics (PE) within existing substations and repurposing the existing cables. In this way, it is assumed within the research of this project that changes can only be made within the substations of installation and the rest of the network must therefore be able to continue to operate within regulations without any further changes to its infrastructure.

When designing the FDCL, one topic which became a major contributor to the system's design was how it will interact with existing network protection. Unlike inverter-connected DG or point-to-point DC interconnections between networks which may have a limited impact on the networks' short-circuit current ratings [2], [3], operating the MV-T link as DC can significantly reduce the short-circuit current available to the distribution network because its output current is actively limited. Another challenge that became apparent was how to design or repurpose existing protection to be able to protect the link when either AC or DC configuration is enabled.

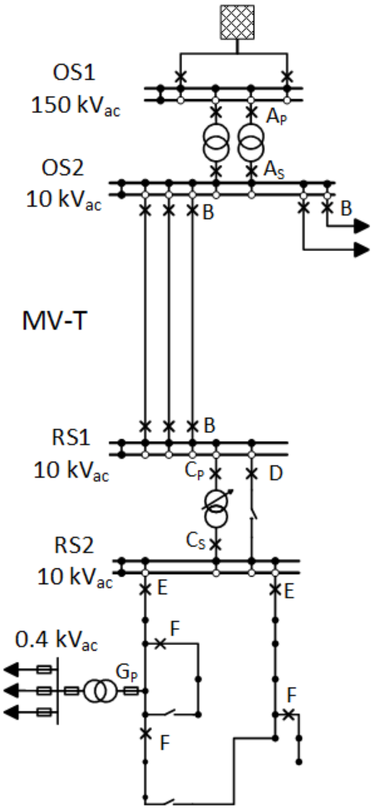
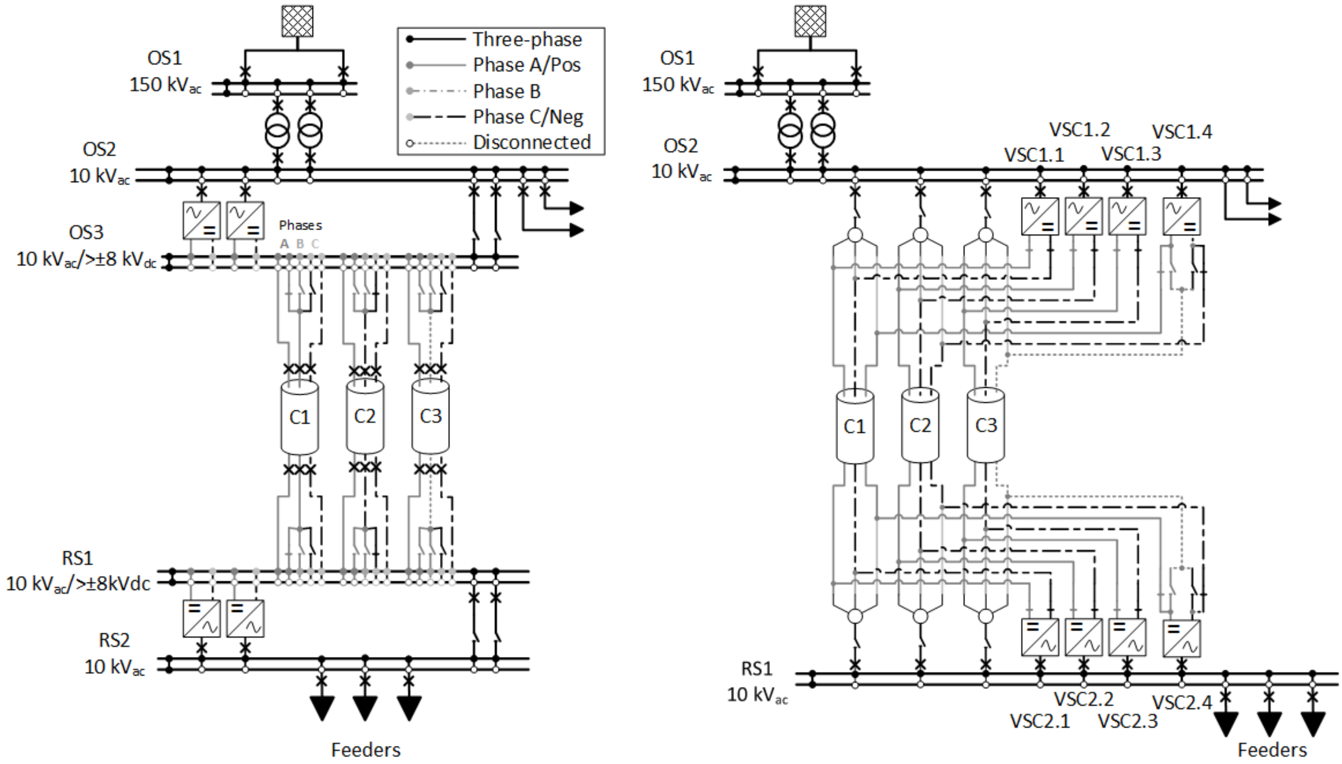


Figure 1 Example of a typical Dutch MV network



(a) (b)

Figure 2 Flexible AC/DC-link (a) Design A (b) Design B

By looking to the existing network protection systems, different designs for the FDCL and its protection have been looked into. This paper will explore two designs for the FDCL that the author has found to be the most simple and realizable to implement within a distribution network. These designs will then be compared with a focus on their effects on component sizing, equipment requirements and network protection.

2 FDCL design background

The MV-T links are often the only path available to fully supply the lower distribution networks they connect, and therefore require protection schemes and system designs which can assure a safe, uninterrupted supply of power.

For the conventional AC system, this supply safety is achieved largely by redundancy. If any one component fails, there is at least one other component which will remain connected to allow the system to continue supplying the load. This also ensures that for any one component failing, all power regulations can still be met. This is known as the *N-1 contingency*.

It is important to note here, that while only two three-phase cables are required to meet N-1 contingency requirements; while in DC operation (and considering the same N-1 contingency), in order for an overall capacity gain to be possible (assuming a rated DC voltage equal to the magnitude of the peak AC phase voltage), a minimum of three cables are required [1].

Downstream from the regulating station, N-1 is no longer a requirement. Instead, if a fault occurs here, in the lower distribution network, the number of customers who experience an outage is limited by proper protection selectivity.

Therefore, in designing the FDCL, two major criteria are to retain N-1 contingency in the MV-T section, while also maintaining protection selectivity for any lower network faults.

2.1 Design A

Based on the N-1 contingency, the first design (Design A) was created, as seen in Figure 2. This design tries to achieve simplicity by repurposing the busbar system that the cables were already connected to (i.e. rails A and C become the positive and negative poles respectively and phase B of the cable switches to one of these rails) and relying on one redundant converter. In this way, the converter is sized such that one converter can supply the full load.

In conventional point-to-point DC-links, the link is protected with AC circuit breakers on either side of the link [4]–[6]. This is done because of the difficulty of breaking a DC fault current, whereas the AC side can utilize the zero-crossing to break the current flow.

For this design, however, AC-side protection alone is not sufficient, as it would lead to the disconnection of the entire link in the case of any DC-side fault (e.g. single-line-to-ground). Therefore, this design requires DC circuit breakers to disconnect only the faulted cable.

It is assumed here that a DC circuit breaker would be able to operate for either the AC or DC case. However, the relays would have to be reprogrammed for flexible operation. Looking at the Dutch DNO, Alliander's, network. It is common practice to protect the MV-T links with differential protection. Therefore, this infrastructure and relays would be able to be repurposed for flexible use. The operating principle is the same for AC or DC: if a fault occurs within the link, the current magnitudes at either end will differ and the faulted cable is disconnected. While the functionality is the same, new measuring devices will be required in order to measure for both AC and DC currents.

Undervoltage relays may also be used to quickly detect a DC-side fault, as is a common practice for point-to-point DC-link protection [7].

2.2 Design B

Design A's goal was to be the most simple design, however, due to the DC-fault protection requirement, it quickly became significantly difficult, relying DC circuit breakers and many assumptions of the capabilities of the existing protection infrastructure. Furthermore, DC circuit breaker technology is still in early stages of development at these voltage and power levels and are much more expensive than AC circuit breakers. Therefore, a new design was developed which could avoid the need of DC circuit breakers by relying on conventional point-to-point DC-link protection which utilizes AC circuit breakers to disconnect the full link at the sign of a DC-side fault, such as described by [4].

In design B, every two conductors becomes its own point-to-point DC-link. In this way, if there is a line-to-ground or line-to-line fault, the faulted link(s) can be disconnected at either end through the AC breakers. It is assumed in this project that any one fault will lead to the disconnection of one three-phase cable.

For this design, the total number of converters is equivalent to the number of circuits available in nominal operation ($n_{conv} = m$). With an even number of cables there is no extra conductor to switch in, leading to the loss of two circuits (disconnection of two links). However, any odd number of cables will have one unused conductor which can be switched in as either polarity. This is done with VSCs on a dedicated reconfigurable circuit which connects the VSCs on just one phase per cable. In this way, for any cable failure, one of these converters may lose at most one pole which can then be reconfigured to the excess conductor.

With three cables, four VSCs are required at either end of the FDCL. For the case of a fault in cables 1 or 2 (as seen in Figure 2), the fourth VSCs' connections are reconfigured to continue power transfer through three links. An example of how this scales up from three cables can be seen in Figure 3.

With this design, DC circuit breakers can be avoided and conventional DC-link protection techniques can be used.

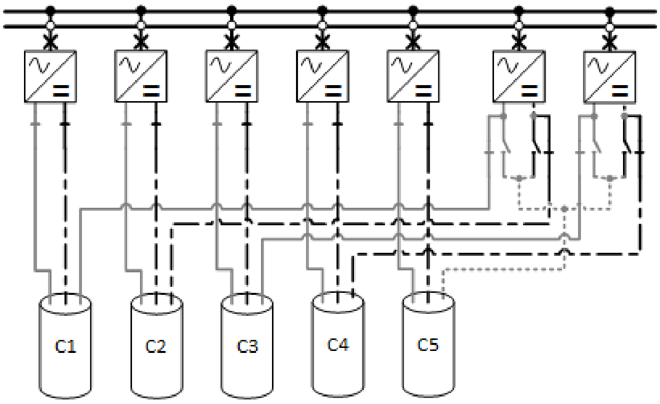


Figure 3 Reconfiguration circuit scaling for Design B (AC bypass is not included in the diagram for readability)

3 Converter sizing and protection selectivity

To size the converters, the link capacity and network selectivity is considered. First the converters are sized to the capacity required of the DC-link. This value is then checked against the required rating for downstream faults to determine if the converters need to be oversized.

3.1 Nominal converter rating

The nominal rating comes from looking into the DC-link power rating and distributing it over the number of installed converters.

3.1.1 DC-link rated power

For simplicity, we will assume that all parallel cables are of equal (or significantly similar) impedance.

The link must be able to supply the full load with the loss of any one cable. Therefore, the nominal rating of the link's transfer capacity is equal to its N-1 capacity.

For either design, if there is an even number of cables, all conductors are used nominally and any single cable failure will lead to the loss of two circuits. (In design A, the transfer capacity is rated based on the maximum current for the lowest number of conductors per pole, therefore if one cable is lost it is equivalent to losing two circuits.)

For an odd number of cables, the extra conductor can be switched in to make up for any one of the lost conductors (it is left open to avoid a polarity reversal). In this way, only one circuit is lost for any single cable failure in either design.

Therefore, the number of circuits is calculated as:

$$m' = \begin{cases} m-2 & N \text{ is even} \\ m-1 & N \text{ is odd} \end{cases} = \begin{cases} \dfrac{3n_{cab}-4}{2} & N \text{ is even} \\ \dfrac{3n_{cab}-3}{2} & N \text{ is odd} \end{cases} \tag{1}$$

Where:

m = Total number of DC circuits available

m' = Number of DC circuits available after the loss of one three-phase cable

n_{cab} = Total number of three-phase cables

The rated link capacity, $P_{link,dc}$, is thus calculated as:

$$P_{link,dc} = m' \cdot 2 \cdot U_{dc,0} \cdot I_{0,cab} \tag{2}$$

Where:

$U_{dc,0}$ = Rated DC pole-to-ground voltage magnitude [kV_p]

$I_{0,cab}$ = Rated cable phase current [kA]

This power is used as the base power for per unit calculations.

3.1.2 Design A converter rating

For design A, the rating of the converter, $P_{0,conv}$, is sized according to worst N-1 contingency (in this case the loss of any one converter), described by:

$$P_{0,conv} = \frac{P_{link,dc}}{n_{conv} - 1} \tag{3}$$

Where n_{conv} is the total number of converters on one end of the link.

For the case of one redundant converter, each converter must be sized to handle the full load. In this case each converter is overrated by 100%, which will be seen in section 3.1.4.

3.1.3 Design B converter rating

Since every circuit has a dedicated VSC at either end, the worst case N-1 contingency of the system is the loss of the most converters, which is equivalent to the loss of link. Each converter is therefore rated as:

$$P_{0,conv} = \frac{P_{link,dc}}{m'} \tag{4}$$

3.1.4 Comparison of designs considering link rating

The percent each converter is overrated (which can be shown to be equal to the total installed capacity overrating) can be calculated as:

$$\%overrated = \frac{P_{installed} - P_{link,dc}}{P_{link,dc}} = \frac{P_{0,conv} - P_{conv,\min}}{P_{conv,\min}} \tag{5}$$

Where $P_{conv,min}$ is the minimum converter rating (disregards any N-1 contingency) and $P_{installed} = n_{conv}P_{0,conv}$. From equations (3) and (4), this can be calculated for each case as:

$$\%overrated = \begin{cases} \dfrac{1}{n_{conv} - 1} \times 100 & \text{Design A} \\ \left(\dfrac{m}{m'} - 1\right) \times 100 & \text{Design B} \end{cases} \tag{6}$$

A comparison of the different designs' overrating for a varying number of parallel cables can be seen in Figure 4. The overall system for design B is much less overrated than the case of design A. This is due to the use of many (smaller) converters running links independently in parallel instead of relying on two converters (one redundant) running in parallel to supply one link (with parallel transport paths).

3.2 Converter rating for selectivity

Since the location of the FDCL separates the load from the large, synchronous generation, when operating the link as DC, the short-circuit current must be actively controlled to come from the HV transmission, through the PE and into the lower network for a downstream fault. However, for a fault on the AC side of a PE, the output current is regulated to not go over its rated value to protect the sensitive electronic components [8]. Within the FLINK project, only components within the substations can be adjusted. Therefore, if the only protection exists within the RS, then they can be reconfigured for the DC-link settings based on the maximum converter output current. This may be possible as most feeders are only protected at the top (seen as circuit breakers [CBs] E in Figure 1). However, if there is further protection down the feeder, for example long feeder protection and second-branch protection, then, if the RS CBs' pick-up values are adjusted, the selectivity of the rest of the network would likely be at risk. Furthermore, even if the only protection available is in the RS, it is preferable for project FLINK to impose as few changes to the network as possible, and if the current protection could be used without severe oversizing of the converters, it is preferred over adjusting the relay settings for each operating state. Therefore, the PE will be sized to operate with the existing protection structure and compared with its nominal sizing from the previous section.

3.2.1 Protection system under investigation

Referring back to Figure 1 and Figure 2, it can be seen that the PE replaces the regulating transformer in the RS. (The bypass switch will be connected when operating the link AC while the voltage is regulated via the shunt-connected VSCs.)

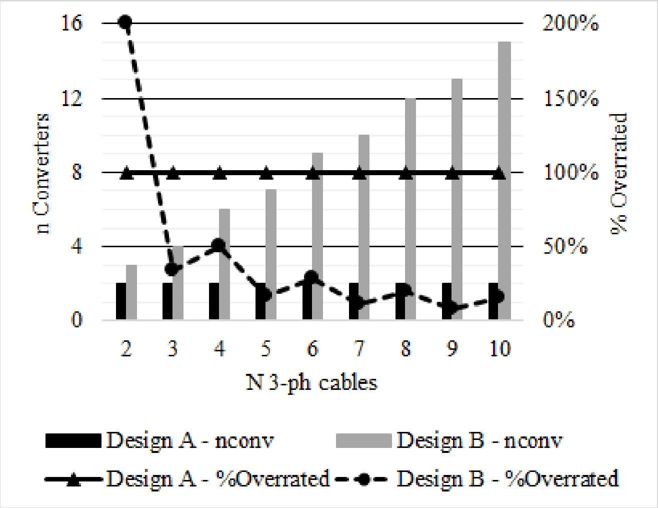


Figure 4 Number of converters and %overrating versus the number of parallel three-phase cables

The protection of the RS link is unaffected as it is only in operation when the link is operated in conventional AC mode. Therefore CBs *C* and *D* are not considered in this study.

Any fault upstream of the OS VSCs will be largely unaffected, unless there is a significant amount of DG in the downstream distribution network that feeds into upstream faults. In this study it is assumed to not be the case and thus any upstream protection should function as normal.

For the MV-T link protection, in the case of design A, a completely new protection system is required which can break a fault for the both the AC-link (conventional protection), and for the DC-fault. For design B, the link protection for AC is unchanged, and AC-side converter protection is used for the DC operation. Because the protection of the link is either unchanged or must be redesigned in either case, it is not taken into consideration for the sizing of the converters.

To size the converters, therefore, the only existing protection that needs to be regarded is the downstream protection. The PE must be able to supply enough fault current into the lower distribution network to trip the protection as set.

3.2.2 Converter sizing for selectivity

To size the converters for fault protection selectivity, its total rated AC output current, $I_{tot,ac}$, must be high enough to supply the highest pick-up current for the longest duration. This technique was used in a real-world test connecting large battery storage in an islanded LV microgrid [9].

If the converters are sized according to the link capacity, as performed in the previous section, it can be shown that the maximum total AC output current from the converters (assuming ideal converter [$P_{dc} = P_{ac}$]), in the worst case scenario (i.e. 1 converter and 2 converters out of service for designs A and B respectively) can be calculated as:

$$I_{tot,ac} = \frac{P_{link,dc}}{\sqrt{3}U_{ac,0}} \qquad (7)$$

Where $U_{ac,0}$ is the rated AC line-to-line voltage.

If $I_{tot,ac}$ is less than the required pick-up magnitude, then the converters must be oversized further to accommodate the required output current (in this case $I'_{tot,ac} \geq 2000$ A). The overrating from the nominal ratings found with equations (3) and (4) can be determined as (for both designs):

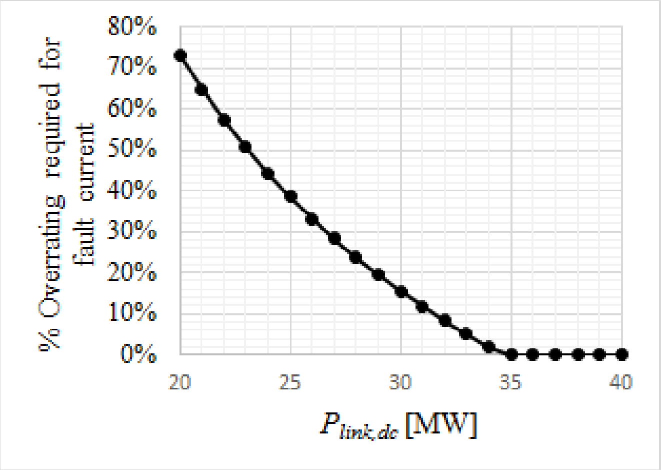


Figure 5 %Overrating required for fault current versus DC link power transfer ratings [from Equation (8)]

$$\begin{aligned}\%overrated &= \left(\frac{I'_{tot,ac}}{I_{tot,ac}} - 1\right)\times 100 \\ &= \left(\frac{\sqrt{3}U_0 I'_{tot,ac}}{P_{link,dc}} - 1\right)\times 100\end{aligned} \qquad (8)$$

From equation (7) and (8), it can be seen that the percent overrating from the nominal converter rating can be ascertained with just the link information, regardless of FDCL design. Using the voltage ratings found in Table 1, the percent overrating from (8) can be calculated in a range of expected MV-T link transfer capacities. These results are found in Figure 5.

It is interesting to see that when the DC-link reaches 35 MW or above, no additional capacity is required from the FDCL to supply enough current for a downstream fault for the protection to function as normal.

*3.2.3 Comparison of selectivity sizing to nominal sizing*s

For a practical example of the selectivity of a network, an Alliander MV network model was analysed. This network model consists of four distribution networks similar to the example given in Figure 1 (i.e. a ring/meshed network operated radially connected to an HV/MV substation via a relatively long MV-T link). However, one of these links only has two cables in the MV-T leading to capacity loss instead of gain when switching to DC, therefore this network is not considered. The details of the studied networks (labelled A-C) can

Table 1 Converter ratings for Alliander MV networks using formulas derived in section 3
In each case: $U_{ac,0} = 10\ \text{kV}_{LL}$; $U_{dc,0} = 8.16\ \text{kV}_p$

	MV-T link			**FDCL**		**Converter ratings**					
						Design A			**Design B**		
Network	n_{cab}	$I_{0,cab}$ **[kA]**	$S_{ac,rated}$ **[MVA]**	$P_{link,dc}$ **[MW]**	$I_{tot,ac}$ **[kA]**	$P_{0,conv}$ **[MW]**	$P'_{0,conv}$ **[MW]**	***%overrated***	$P_{0,conv}$ **[MW]**	$P'_{0,conv}$ **[MW]**	***%overrated***
A	6	0.280	24.2	32.0	1.85	32.0	34.6	116.5%	4.6	4.9	39.2%
B	3	0.575	19.9	28.2	1.63	28.2	34.6	146.0%	9.4	11.5	64.0%
C	4	0.575	29.9	37.6	2.17	37.6	37.6	100.0%	9.4	9.4	50.0%

be found in Table 1, where $S_{ac,rated}$ is the total link capacity ratings (rated for N-1 operation) for the AC case, $P'_{0,conv}$ is the final (minimum) rating of the converter considering the downstream protection and the %overrated shown is the total overrating of the converters (the overrating of the initial converter rating can be found in Figure 4).

Looking to the protection downstream of the RS, the worst case that the PE would have to provide is a total output current of over 2000 A for at least 0.4 seconds. (The magnitude was the case for each of the four lower distribution networks, with the time varying between 0.3 and 0.4 s.)

Out of the three cases, one case could provide the full fault current requirement without further reinforcement, whereas networks A and B required a further overrating of 8.2 % and 23.0 % respectively.

4 Conclusions

The initial planning for a FDCL was based on the conventional design of a substation but replacing transformers with PE. In this design, the cables are connected to one busbar and two converters are installed running in parallel for redundancy. The idea for this design was simplicity. However, this design encountered challenges when it came to protecting the link from DC-side faults without resulting in black-out for the entire lower distribution network. A second design was then laid out, in which every two conductors acted as its own DC-link with dedicated VSCs. In this way, conventional DC-link protection, using more technically and economically feasible AC circuit breakers, could be used to remove the faulted link and continue supplying power to the load on the remaining healthy links.

By giving each two conductors its own DC-link, the number of converters that is required to be installed naturally increases. However, the size of each converter is also much smaller than the case of one converter which can supply the entire load, as the case of design A. In design B, not only is each converter smaller, but because of their numbers and connection, they are also overrated to a much lower degree than the case of design A (100 %). This leads design B to have an overall lower system overrating.

To determine if the converters would be able to supply enough current to trigger the existing protection in the lower distribution network, it turned out that the design was irrelevant, as both system designs were rated for the capacity of the link itself. In this way, it was determined that for any link at or above 35 MW, no further oversizing of the converters would be required for a 10 kV_{LL} (±8.16 $kV_{dc,p}$) link with maximum 2000 A output required.

Further research needs to be performed on the dynamic performance of the system, as well as rating of the converters for different fault types and locations (e.g. a fault at a further distance increases the impedance to the fault and may therefore require greater power output). Also in this paper, it was assumed that the DG in the lower distribution network was low enough to not affect the protection for an upstream fault, however, the case of a significant amount of DG presence should also be considered in a future study.

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