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► **To cite this version:**

Joan Sau Bassols, Serge Poullain, Florent Morel. Solutions for the step-wise development of HVDC-based high power corridors. Jicable HVDC'21, Nov 2021, Liege, Belgium. hal-03517136

**HAL Id: hal-03517136**

**<https://hal.science/hal-03517136>**

Submitted on 7 Jan 2022

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# Solutions for the step-wise development of HVDC-based high power corridors

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## ABSTRACT

*High power corridors (HPC) are expected to be required to integrate and transmit the increasingly installed offshore power from renewable sources. High voltage direct current (HVDC) is seen as the technology to implement those HPCs stretching long distances. First, this paper discusses the need and characteristics of these HPCs. Then, different technical solutions are suggested to further develop the HPCs: converting existing AC overhead lines (OHL) into DC links, moving into a multi-terminal or meshed architectures, among others. The paper concludes that most of the development will be based on DC cable technology, potentially rising the future DC cable demand.*

## KEYWORDS

High power corridor; HVDC; multi-terminal; meshed; offshore development; onshore development; DC-DC converter.

## INTRODUCTION

The European Union (EU) has committed to becoming climate-neutral by 2050 [1]. The offshore renewable energy plays a key role in achieving this milestone with 12 GW of wind energy capacity installed offshore in the EU. The EU offshore renewable energy strategy has as objectives to increase the actual wind energy capacity to more than 60 GW by 2030 and reach 300 GW by 2050. A similar trend happens in the United States, where the Biden Administration has the target of deploying 30 GW of offshore wind by 2030. Achieving that target also will unlock a pathway to 110 GW by 2050 [2].

In Europe, there is a great wind potential in the North Sea that is envisaged to contribute to the previous energy targets [3]. This wind power needs to be integrated and then transmitted from offshore to the consumption points located onshore. As outlined in the European project eHighway2050, all the analyzed scenarios foresee that a significant extension of the transmission capacity will be required in order to integrate and transmit the power from the renewable sources into the consumption areas [4]. The traditional AC grid system must be updated to face this challenge and it is identified that high power corridors (HPC) will be required. The HPCs can be understood as the "highways" to transmit the energy coming from the offshore renewable power resources to the consumption areas onshore. They are meant to stretch long distances across several countries and transmission system operators (TSOs) [5], making convenient the use of high voltage direct current (HVDC) instead of high voltage alternating current (HVAC). An example can be found in Germany, where several HVDC links going from the north to the south are planned and will be used to distribute the offshore wind power throughout the territory [5]. Initially,

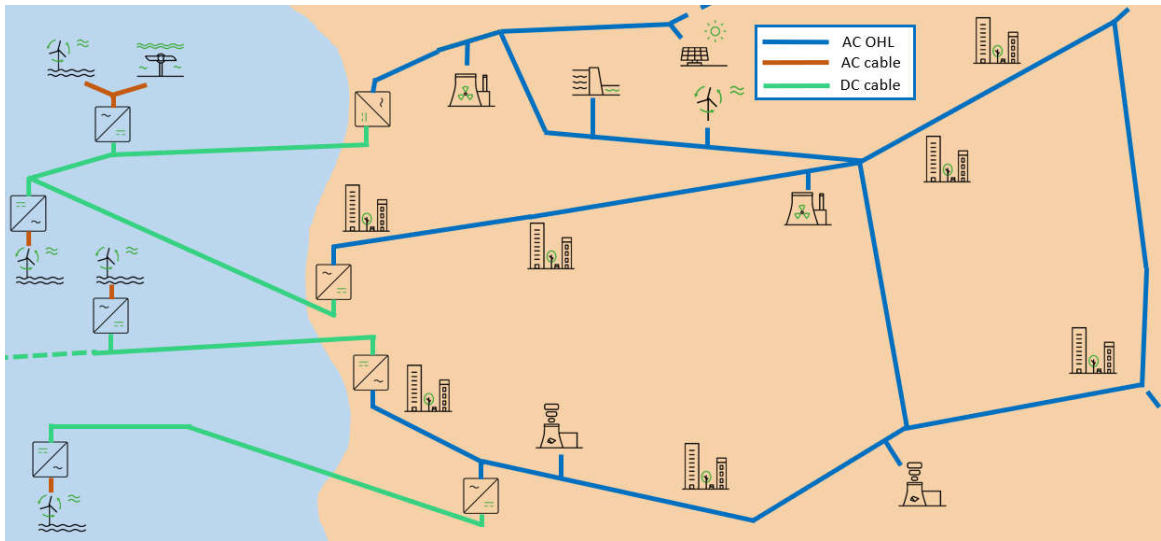
those HPCs are envisaged as HVDC point-to-point links. Nonetheless, due to the system evolution, its architecture can evolve in order to increase the flexibility and redundancy.

This paper outlines technical solutions to step-wisely develop HPCs based on HVDC. Those HPC can be extended following the architecture of point-to-point links, by converting already built AC OHL into DC. The development of the HPCs can also lead to multi-terminal DC (MTDC) systems with a radial architecture to reduce the number of needed converters and increase the flexibility. A further step can be the meshed architectures with even higher flexibility and redundancy. Using DC cables combined with already existing OHL can be a solution to build a MTDC system when facing the opposition of building new OHL. If different voltage levels or configurations of the HVDC links coexist, DC/DC converters may be a solution to make the interconnection possible. The evolving of the power system may also demand a higher power rating in certain cables or OHL, thus, the installation of cables in parallel can be an option to increase the power capacity of existing interconnections.

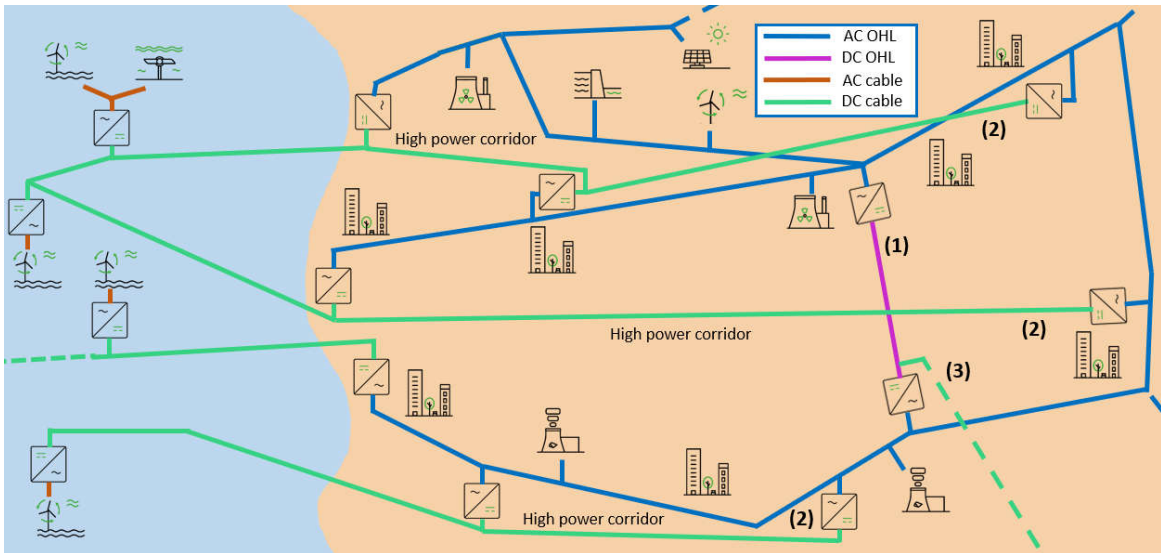
## HIGH POWER CORRIDORS

The power generated offshore needs to be transmitted onshore in order to reach the consumption areas. Fig. 1 shows a generic power system that is used to introduce the need of HPCs and their corresponding development. Fig. 2 and Fig. 3 will be introduced in the following sections and show the evolution and development of HPCs in the previous power system. In Fig. 1, there are several AC OHLs that form the power system onshore, interconnecting different generation sources with the consumption points. In the left part, the different offshore power sources (mainly offshore wind farms) that are expected to be built to achieve the climate targets are illustrated. Those offshore power sources are connected to the shore using HVDC transmission systems (cables), using point-to-point links or MTDC configurations. The HVDC converters at the shore are then connected to the HVAC power system. The increase in the transmission capacity can be theoretically achieved by new OHLs or cables. However, it is increasingly difficult to obtain the rights of way (ROW) to build new OHL and they also face a fierce opposition from citizens.

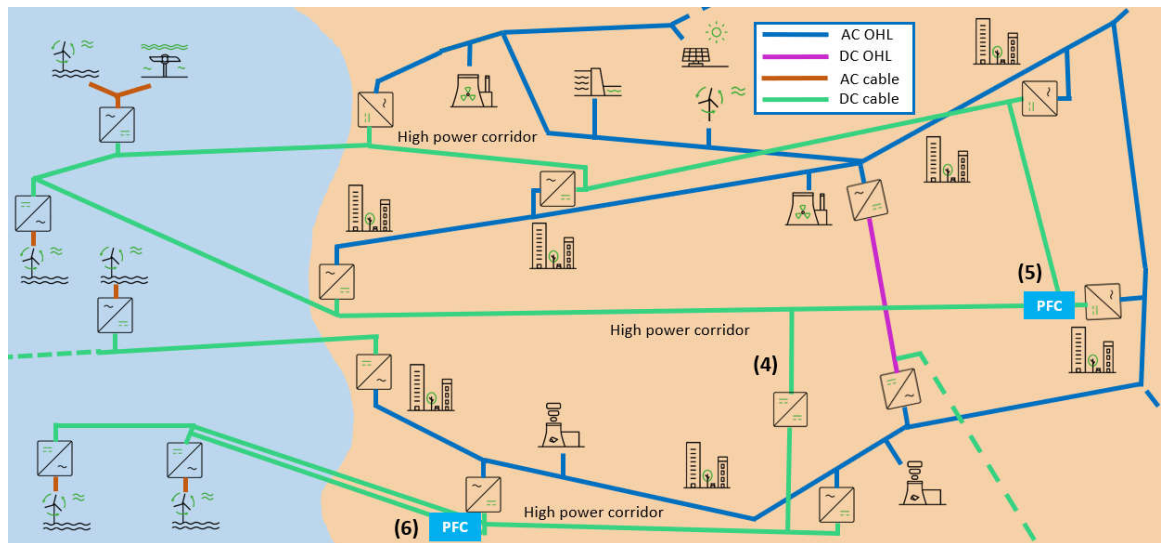
Then, the first alternative is to make use of underground cables for the new transmission projects. The HPCs may require distances of hundreds of km (e.g. the case in Germany [5]). In such a situation, if the OHLs are not an option, the choice lies between HVAC and HVDC cables. The cables have an important capacitance/km, which in HVAC is translated in reactive power that limits the power transmission.



**Fig. 1. Power system with offshore power sources connected by HVDC links and MTDC systems.**



**Fig. 2. HPCs running from the offshore power sources into the consumption areas forming multi-terminal systems in a radial configuration.**



**Fig. 3. HPCs development by connecting them together in a meshed architecture**

Besides, in HVAC, the cables suffer from the skin effect and proximity effect, which increase the losses. On the contrary, HVDC has always a fix investment cost which is the two converter stations at each end of the transmission link. However, after this initial cost, the cost/km increases slowly for HVDC compared to HVAC. HVDC also brings additional features, such as the possibility to perform asynchronous interconnections and better controllability. The break-even distance at which the HVDC technology becomes economically interesting over HVAC is around 40-100 km for cables (for OHLs, it is much higher, around 500 km) [6]. HVDC cables are a sound option when high powers and long distances are concerned, which is the case, for instance, of the offshore wind farms located far from the shore.

The second alternative to the construction of new OHL is to convert existing AC OHLs to DC OHLs, making use of the already build towers (no need of new ROW). This brings several benefits such as an increased power transmission capability and an enhanced controllability that are discussed in the following section.

There is not a standard voltage level to build the HPCs. At the moment, there exist HVDC links with different voltage levels that depend on the selected technology and power of the transmission link. OHLs may reach higher voltages than cables but their use in the HPCs is less probable due to the aforementioned permission issues (unless they are converted from AC to DC). Underground and submarine cables can reach voltages up to  $\pm 600$  kV [7]. One example is the Nordlink project (interconnecting Norway and Germany) with a DC voltage level of  $\pm 525$  kV, mainly built with mass-impregnated (MI) submarine cable [8]. On the contrary, several recent HVDC projects have been constructed using extruded XLPE cables with voltage levels up to  $\pm 320$  kV [9]. Thus, different voltage levels are expected to coexist in the power system, meaning that the HPCs will need to deal with this voltage disparity.

Fig. 2 presents the development of the power system introduced in Fig. 1 by adding HPCs to transmit the power generated offshore into the consumption points onshore. These HPCs are based on HVDC cables and consider some of the solutions that are presented in the following section.

## SOLUTIONS

This section presents the different technical solutions to further develop the HPCs, detailing their benefits and challenges.

### Point-to-point links

#### Conversion AC OHL to DC OHL

As mentioned in the previous section, the conversion of an already built AC OHL into a DC OHL can be a way to further develop the HPC. This brings several benefits, such as advanced power flow, protection, and stability control features. The main advantage is that the new line can make use of the already built towers and conductors utilizing the same ROW, which represents a faster timeframe for the project. The conversion to DC also brings an increase in the power transfer considering the use of the same conductors. The insulators in the towers must be changed to be adapted to the new DC voltage and an HVDC converter station must be constructed at each end of the transmission line. One interest is that the insulator change

can be done live working, so that the grid operator continues to benefit from the line power transfer capability during the conversion process.

The insulators are the only component that needs to be changed since for DC, the main DC insulation criteria is the pollution. Thus, one of the challenges is the insulation coordination of this type of conversion. Moreover, the ground level electric field must be verified. Another possibility can be that in an OHL with two conductors per phase, only one circuit is converted to DC (hybrid AC/DC OHL), what is being done in ULTRANET project [10]. In such cases, the added challenge is to ensure that the AC magnetic field is not disturbing the DC line and that there are no coupling effects between the AC and the DC. Fig. 4 shows a conceptual scheme of the conversion of an AC OHL into a hybrid AC/DC OHL [11].

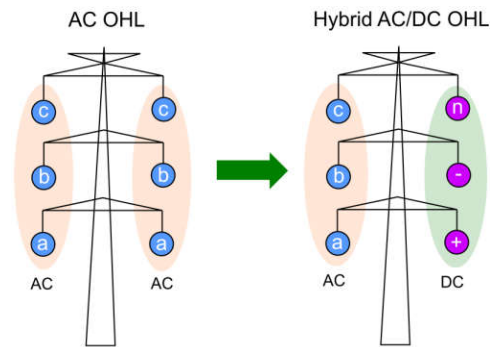


Fig. 4. Conversion of an AC OHL into a hybrid AC/DC OHL.

The conversion of an AC OHL into DC OHL is shown in the power system evolution from Fig. 1 to Fig. 2 by installing two HVDC converter stations while reusing the towers and ROW of the previous AC OHL (1).

### Multi-terminal DC systems

Another solution to develop the HPCs is to move from a point-to-point architecture to an MTDC architecture. This can be done by interconnecting different HVDC links between them or extending the existing ones with new interconnections through the DC side. The first benefit of this approach is that the number of AC/DC conversion stages decreases (less HVDC converters), thus, less losses during the conversion stages. In some cases, it can increase the power flow flexibility and modularity of the system. Fig. 5 presents a HPC made of two options: multiple point-to-point HVDC and a multi-terminal HVDC.

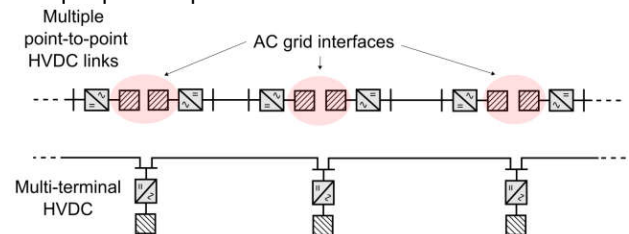


Fig. 5. HPC made of multiple point-to-point HVDC links and a multi-terminal HVDC system.

As it can be seen, the multi-terminal provides a reduction in the number of needed HVDC converters. An example of this is the EUROBAR initiative [3], where several European TSOs aim to standardize the integration of the North Sea offshore wind power into European power grids,

prospectively evolving to an interlinked offshore network or “busbar alike system” (MTDC system). Such initiative would maximize the utilization of wind capacities and could provide an optimization of the electrical system.

The MTDC architecture brings several associated challenges. Firstly, the control and operation become more complex than for the point-to-point links. Partly because the different substations and protection devices may be produced by different manufacturers (multi-vendor system), the control and protection interoperability is a key point to consider. Secondly, the transmission system security must be ensured. For the point-to-point links it may be acceptable to lose one link, but for large MTDC systems it is not acceptable to lose the whole system. In case of a DC fault or a severe contingency, the MTDC system must quickly and securely be restarted. The MTDC system should be also easily expandable to take advantage of its modularity. This means that the switches, busbars and other elements should be prepared for the evolution of the system and for future new terminals. One example is the Caithness Moray HVDC link that was designed and constructed to accommodate an additional connection (third terminal) with the Shetland Islands, creating an MTDC system [12]. The standardization of different elements of the system is something that can help to ease the path to build this MTDC architecture. Finally, the regulatory frame gathers several challenges that must be addressed before the construction of such a system. The ownership of the MTDC system must be defined, along with the operation responsibility and the allocation of costs and benefits.

The expansion of the HPCs as radial MTDC systems is depicted in in Fig. 2 to transmit the offshore power into the mainland using a minimum number of converters (2).

### DC Cable as an extension of a DC OHL

A particular case of the MTDC system expansion is when both cable and OHL are combined in the same system. There are already real point-to-point projects running partly with OHL and cables (e.g. South West HVDC link [13]).

Considering that some DC OHLs may be present in the power system, either because they have been converted to DC or were originally built like that, it may be difficult to extend them further due to the previously mentioned opposition to construct new OHLs. In such situations, it may be possible to make this extension by connecting a DC cable with the DC OHL (in the DC busbar of a converter station), leading to an MTDC system. This alternative is expected to have less opposition and can extend the power transmission of the HPC.

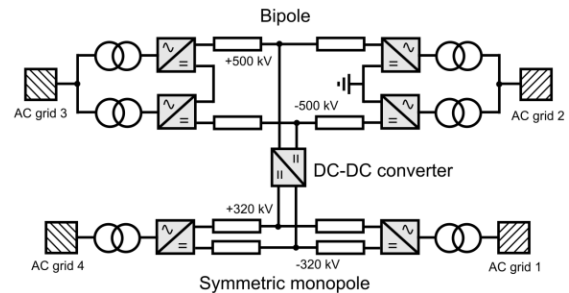
Apart from the previous MTDC system challenges, this approach brings additional ones regarding the protection, since two different systems (DC OHL and a DC cable) with different parameters, constraints and dynamics are connected together. This could affect the protection strategy of the whole system. Additionally, the voltage level of the DC OHL must be compatible with the voltage level of the DC cable to install.

An example of a DC cable connected to a DC OHL is shown in Fig. 2 (3) as an expansion of the previously converted DC OHL.

### DC-DC converter

In some cases, it may be interesting to interconnect different HPCs between them in order to increase the power flow flexibility. However, those HPCs may have different voltage levels; they may use different converter technology (voltage source converter (VSC) or line-commutated converter (LCC)); or a different transmission scheme (symmetric monopole, asymmetric monopole, bipole, etc.). In that case, it is necessary to install an HVDC DC-DC converter to make the interconnection possible. DC-DC converters can also act as firewalls (meaning that one fault in one HPC does not propagate to the other).

Nevertheless, there are not yet commercial products for DC-DC converters for HVDC applications. They are expected to use the same technologies as modern VSCs. The control and operation of the DC-DC should be compatible with the HPCs where it is connected. Fig. 6 shows a diagram of a DC-DC converter that interconnects two HVDC links with different transmission schemes and voltage levels.



**Fig. 6. DC-DC converter to interconnect a bipole HVDC link with a symmetric monopole HVDC link with different voltage levels.**

Fig. 3 presents a further development of the HPCs of Fig. 2 by adding additional interconnections between them to increase the flexibility of the power flows and the redundancy in case of contingencies. Specifically, (4) shows the interconnection of two HPCs with different voltage level by means of an HVDC DC-DC converter.

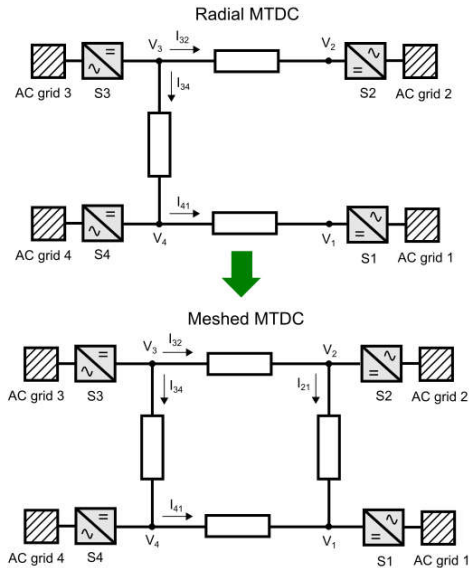
### Meshed MTDC systems

A radial MTDC system provides only one path for the power from a certain converter station to another. By adding additional connections between the existing stations, the radial MTDC system can evolve into a meshed DC system (or DC grid). The DC grid offers more than one path to transmit the power from one station to another. Thus, it provides a higher flexibility of power flows and redundancy (in case of faults) than a radial system. Fig. 7 illustrates a 4-terminal radial MTDC system that evolves into a DC grid by installing a connection between S1 and S2.

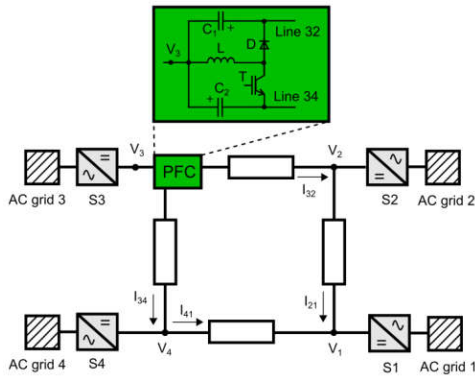
The challenges of the radial MTDC systems are also present in the DC grid. The cost of the latter is expected to be higher due to the additional connections, which would be compensated from higher flexibility benefit. Additionally, managing the current distribution within the mesh becomes a concern since the converter stations at each terminal can only control the current in their terminals but not the internal currents in the mesh. The current distribution depends on the resistance relation between the conductors [14].

In certain cases, additional devices may need to be installed to regulate the power flows and avoid the overload

of certain lines. These devices are called power flow controllers (PFCs) or current flow controllers (CFCs) and they are the equivalent to the flexible AC transmission systems (FACTS) but applied to DC. They are expected to be medium voltage converters (no commercial product available) that will insert a voltage in series with the conductors in order to actively control the current circulating through those conductors [14]. Fig. 8 illustrates a DC grid with a PFC in node 3.



**Fig. 7. Evolution of a radial MTDC system to a DC grid by adding a connection between S1 and S2.**



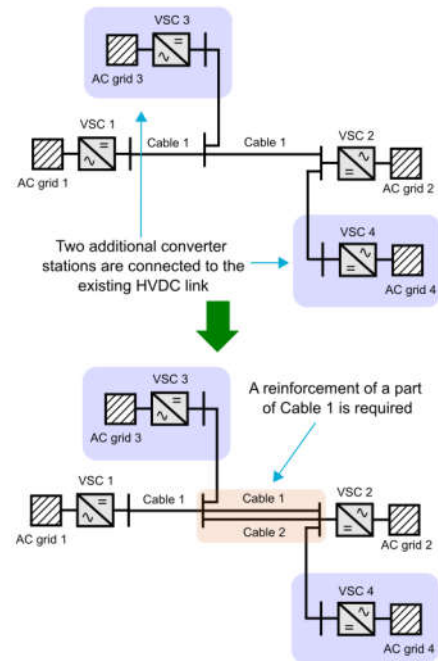
**Fig. 8. DC grid with a PFC suggested in [15].**

The evolution of two HPCs into a DC grid is shown in Fig. 3. The addition of a connection at the right of the map creates a mesh and allows to transmit easily the power through the two HPCs without needing to convert it to AC (it includes also a PFC) (5). With this extension, if one of the cables is disconnected after a fault, there is still a path for the power to be exchanged between any two converter terminals.

### DC cables in parallel

The development of HPCs can lead to situations where the installation of new conductors and converter terminals provokes new power flows overloading the capability of the existing conductors. In those cases, a second DC cable can be installed in parallel with the overloaded conductor (either a DC cable or a DC OHL) to increase the power capacity. If the conductors have the same characteristics

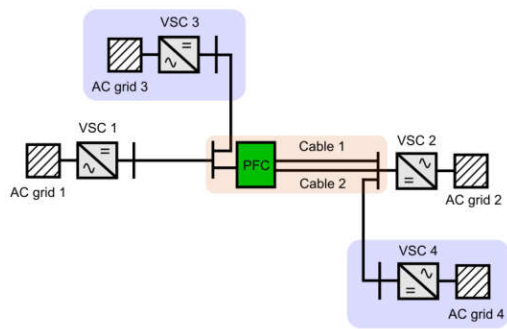
(type of conductors, cross-section, thermal resistances, etc.), the current will be equally shared between the two conductors. This can be applied when upgrading point-to-point links to MTDC systems, or MTDC upgrades. Fig. 9 presents an example with an upgrade of a point-to-point link into a radial MTDC system (by adding two additional terminals). In that case, the needed power flow of a part of Cable 1 is increased, which may require the installation of a second cable in parallel to reinforce the existing one.



**Fig. 9. Upgrading a point-to-point link into a radial MTDC system and installing a DC cable in parallel to reinforce the existing cable.**

The challenges of this approach are that the two conductors in parallel may have different characteristics. Then the current distribution will depend on the relation between the electric resistance of Cable 1 and Cable 2 (considering the example in Fig. 9). The cable with lower resistance will conduct more current, and for similar thermal resistances (which is true for cables), it will achieve the highest temperature. It means that this conductor will operate at the maximum current rating while the other conductor is underused. At that point, it is not possible to increase the power transmission since the converter terminals have no direct control of the current distribution.

A solution to overcome this can be to install a PFC between the two cables (see Fig. 10). This allows to actively control the current distribution, what guaranties that both conductors can be operated at the maximum rating for the maximum power transmission. It allows to perform a better utilization of the assets (conductors). Due to the capability to control the current distribution, it is possible to install a second conductor with a reduced cross-section compared to the case of two cables in parallel and no PFC. This implies that when needing to install a second conductor different from the first one, if installing a PFC, the cross-section of the second conductor can be lower, thus, reducing the cost. An example of this solution (6) is shown in Fig. 3, where the installation of a new wind farm leads to an increase of the offshore power, requiring the installation of a second DC cable in parallel and a PFC.



**Fig. 10. Installation of a PFC between two parallel cables to control the current distribution.**

Another application of this concept can be when two HVDC links use the same ROW. This might be the case in some corridors where the new HVDC cables are routed along the way of existing OHLs to make use of the same ROW [16]. A further development can be to interconnect the two links (having two parallel conductors) which would lead to a radial MTDC system, with the corresponding advantages and challenges that this brings. In case of installing a second conductor with different characteristics of the first one, the option to include a PFC could be envisaged in order to reduce the cost of the second conductor.

## CONCLUSIONS

This work has introduced several solutions based on HVDC systems to build HPCs step by step with the objective of transmitting the offshore power to the onshore consumption areas. Most of the solutions are expected to employ DC cables and HVDC converter stations embedded within the AC system. Building new DC OHL is not envisaged as a widely used option due to the difficulty to obtain the required project permissions in many countries. A large quantity of DC cable is expected to be needed to make the interconnections possible, which can lead to an increase of the DC cable demand. DC cables are expected to be major components in future grids.

Since DC cables will be a very common element in the development of HPCs, their associated challenges must be well addressed. Being part of the power system, as any other grid components, the installed DC cables must be highly reliable. It is necessary to guarantee high mean time to failure (MTTF) and low mean time to repair (MTTR). A proper monitoring of the cable systems can help to increase the MTTF. It should be accompanied by a good management of the operating constraints (specific protection, dynamic rating), such as overcurrent, overvoltage and temperature. Also, the ageing assessment can increase the MTTF by providing an estimation of the remaining useful life of the cable. Finally, a better identification of the fault location can allow to take faster corrective actions and reduce the MTTR.

## Acknowledgments

This work was supported by a grant overseen by the French National Research Agency (ANR) as part of the "Investissements d'Avenir" Program ANE-ITE-002-01.

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