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MEMO

OFFSHORE ENERGY HUBS - HIGH LEVEL SYSTEM DESCRIPTION AND REQUIREMENTS

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1. Introduction

In this document Energinet is presenting high-level conceptual descriptions of a generic offshore Energy Hub, without naming specific countries, detailed topologies, or specific solutions. The intention is to guide research projects which seek to investigate solutions for the future offshore development and integration of Offshore Energy Hubs.

2. Choice of electrical transmission type

One of the major design decisions to be made for Offshore Energy Hubs (OEH), is whether the HVDC-VSC interconnectors of the hub should be coupled on the AC or the DC of the offshore substation. This decision has impact on multiple aspects of the hub design, such as:

1. Cost of the electrical infrastructure
2. Transmission losses
3. Electrical system robustness
4. Market operation of the electrical components
5. The future expandability of the system

When the HVDC-VSC systems are coupled on the DC side, the technology is referred to as the so-called multi-terminal HVDC (MTDC). The alternative for MTDC for OEHs would be to couple the systems on the AC-side, which is comparable to *common* point-to-point HVDC systems, with the main distinction that all the offshore HVDC-VSC converters of the OEH in such case will be connected to the same offshore AC network while operating under extremely weak network conditions.

When considering the design and operation of OEHs and large offshore grids, there are two main benefits of a meshed MTDC system compared to a meshed point-to-point HVDC system:

1. Fewer HVDC converter terminals are needed when expanding the interconnector capacity as new HVDC cables can be installed without necessarily having to increase the converter capacity offshore.
2. Power losses are lower when utilizing the HVDC systems as interconnectors, as the power has to go through fewer AC/DC conversions.

Several international research programmes have identified the MTDC technology as the optimal technology of the future for large-scale renewable energy integration [1] [2].

The question may then be asked:

Why is a pure multi-terminal HVDC solution not the obvious design for the first phases of OEHs?

The answer to this question lies in technology readiness level of the technology, which is described in the following section.

2.1 Technology readiness level of multi-vendor HVDC

Globally there are a number of MTDC systems either under planning or already in operation. Examples of these are:

1. Zhangbei Flexible HVDC Grid project in China [3]
2. Shetland Caithness Moray HVDC link [4] [5]
3. Hydro-Québec New England interconnector [6]

However, common for projects such as these are that they are procured and executed by one single-vendor, or as in the Chinese case where the system operator, State Grid Corporation of China, has significantly reduced the technical scope of the private vendors to the extent that all system integration is handled by the system operator.

Hence, one remaining challenge of achieving commercially competitive multi-vendor HVDC systems is to realize the so-called *multi-vendor interoperability*.

The technical problem of multi-vendor interoperability will not be described in detail in this memo, as materials are publicly available [7]. However, in short-hand multi-vendor interoperability can be described as the capability to integrate systems from different vendors together now and in the future without having to do significant re-design of existing systems.

2.2 Advantages and disadvantages of the solutions

The advantages and disadvantages for AC and DC side coupling is shown in Table 1.

Table 1. Advantages and disadvantages of solutions for coupling the electrical components.

	Advantages	Disadvantages
AC-coupling	• DC cable voltage levels can be different if this is economically feasible • Technology is mature in regards to components	• High risk of AC side control and stability problems. • AC-interoperability is an issue, and HVDC vendors and wind power plant owners will have to cooperate. • If DC cable voltages aren't aligned, the system can only in a limited extent be expanded into a MTDC configuration in the future. • Higher losses when used as interconnector
DC-coupling	• Lower losses when used as interconnector • Lower control and stability risk and complexity on the AC-side due to coupling of fewer systems. The AC-side is similar to classical HVDC connected offshore wind. • Transmission capacity can be expanded in the future without constructing extra converters offshore	• Multi-terminal HVDC operation is less mature and no standards or grid-codes exist • Multi-vendor interoperability has not been demonstrated, and there is a high risk for vendor *lock-in* and significantly weakened negotiating position of the system operator • Depends on HVDC circuit breaker technology for which there is no operational experience in Europe • DC cable voltage must be aligned between parties • The expandability of the AC-side may be limited without the 400 kV AC bus, and the capacity for connecting large-scale consumption plants, such as PtX may be limited.
Both AC and DC coupling	The advantages for each solution above (depends on mode of operation) and: • Reduced control and stability risk, as the possibility to connect on either the DC or AC side provides redundancy. • The AC-side coupling can be commissioned and tested in the first step, while MTDC operation with testing of control	Will have the disadvantages for both solutions

	systems and HVDC circuit breaker is implemented at a later stage • More attractive as multi-vendor demonstrator for project owner due to risk mitigation through the fall back option of AC coupling	

3. OEH generic electrical concept

An important criteria for Offshore Energy Hubs is that they should be expandable in phases, as the electrification of the energy system progresses.
The topology shown in Figure 1 represents a generic offshore energy hub, while:

1. Satisfies the requirement that the OEH should be expandable beyond the first stage, with the potential to add extra interconnectors to neighbouring countries or offshore systems as multi-terminal HVDC.
2. The coupling of the systems at the HVAC substation provides a fall-back solution, which helps mitigate control and stability risks at a low cost compared to the price of longer periods with outage, while also accommodating the connection of large-scale consumption, such as PtX on the HVAC busbar.

About the topology:

- As a starting point the first phase of an OEH can be assumed to be based on the 2 GW HVDC standard, similar to what German and Dutch TSO TenneT is planning[1]
- The DC cable system can be considered with dedicated metallic return (DMR) due to system operator requirements.
- The system can be connected either on the AC-side or on the DC-side.

[1] https://www.tennet.eu/2gw-program

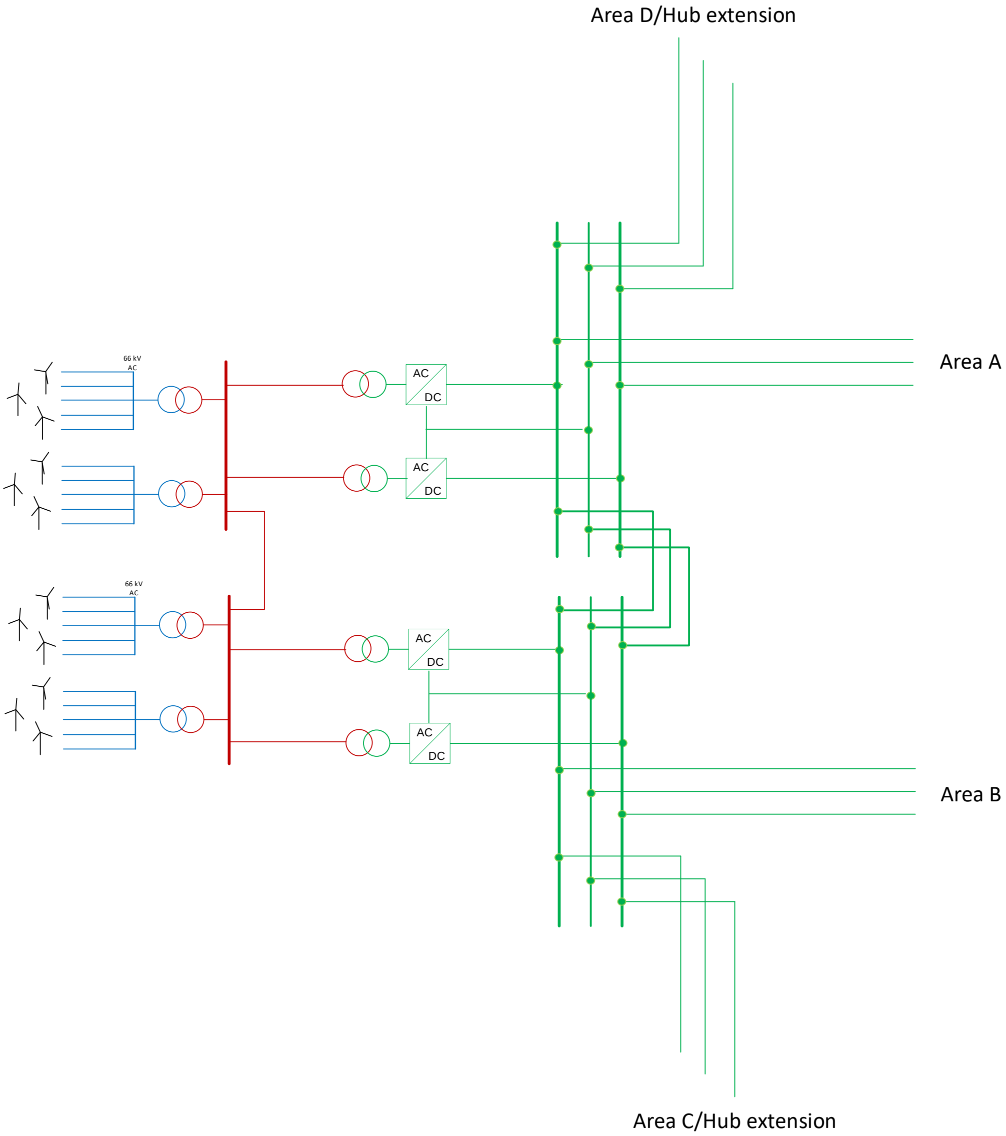

Figure 1 Electrical concept for the first phase of an offshore Energy Hub connecting 4 GW to two onshore areas, Area A and Area B, with potential extension to new hubs or areas.

One way of connecting innovative solutions is by the interconnected HVAC substation on the OEH. By interconnecting via an HVAC substation in the AC coupled mode, all wind turbines, HVDC connections and PtX/electricity storage facilities will be able to exchange energy with each other through the AC substation. In the case of multi-terminal HVDC, the exchange of Energy between individual wind farms and PtX plants may be limited by the DC configuration. In the event of reduced wind power generation, future electricity storage facilities can supply onshore facilities via the HVDC connections.

3.1 Offshore wind assumptions

Today, wind turbines can have a voltage level of maximum 66 kV. A fundamental motivator for OEHs is to bring the transmission systems close to the wind energy sites. Thus, for the first phases of OEHs it can be assumed that the wind power can be connected to the hub directly at 66 kV.

In connection with the future expansion of wind energy, it may be necessary to connect the wind turbines with a higher voltage due to longer distances between the OEH and the wind power. By connecting the offshore wind farm (OWF) via an offshore platform (OSS), the voltage level can be increased to, for example, 220 kV AC. The technology of the future is expected to develop so that wind turbine voltage level can be increased to 110 kV, 132 kV or 150 kV. These voltage levels are expected to make it possible to connect OWFs directly to the OEH, thus eliminating the need for OSSs, which will ultimately reduce the total construction costs.

The OWF owner is responsible for building, maintaining and operating all components on the OWF side of the Point of Connection. The Point of Connection is not yet fixed. The OWF owner is expected to optimize its solution, including how many cables are used and include reactive power compensation in order to meet the requirements in the point of connection.

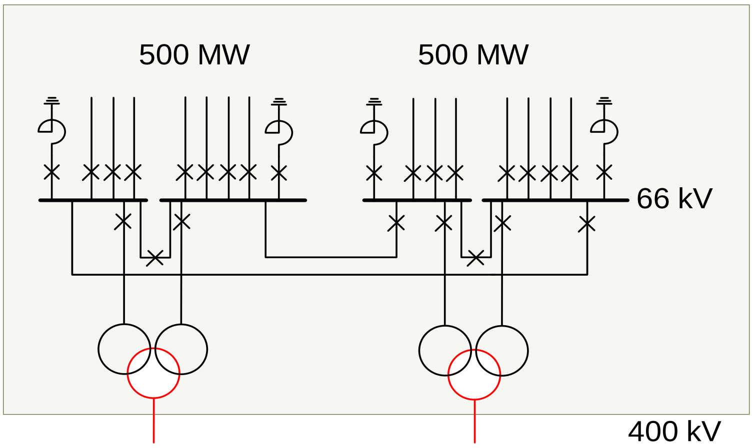

Figure 2. Example of the topology of the OWF owner on the OEH.

Figure 2 shows an example of the topology of the OWF owner on the OEH. In order to increase system flexibility, the 66 kV busbars are connected in a ring. During normal operation, however, the circuit breakers connecting the busbars are open. The reactive power compensation is only shown as an indication: the volume and location of the shunt reactors may vary.

4. System requirements

The following subsections states a number of high-level requirements for the electrical system of the Energy Hubs.

4.1 Grid-codes

The HVDC converters connected to Denmark must comply with the European network codes NC HVDC[2], which states properties such as reactive power capabilities.

The offshore wind power plants are categorized as DC connected power park modules (DC PPM), and are similarly covered by the NC HVDC. However, for several articles the NC HVDC refers to the requirement for generators NC RfG.

4.2 System operation requirements

A master controller must enable flexible and dynamic handling and distribution of wind imbalances on the OEH, aswell as coordinated downward regulation of wind power on OEH. The DC

[2] https://en.energinet.dk/electricity/rules-and-regulations/regulations-for-new-facilities/

master controller must be flexible by design, such that topology changes related to expansions can be facilitated, and that all HVDC converters can be controlled by this unit.

Generally, the system must also be able to operate and survive faults without being dependent on tele-communication between plants or the master controller.
It must be investigated how ramping down of wind after faults on HVDC cables can be implemented without dependence on slow communication equipment, but rather direct measured voltages and frequencies, or fast protection systems.

It must be possible to bypass the master controller for set-points directly to the HVDC converter. This applies to active power set points, but also to other settings, such as control of the DC voltage. Appropriate control hierarchy must be developed.

It must be investigated which measurements and other information the DC/AC master controller needs to operate the grid.

4.3 N-1 definition and dimensioning incident

The N-1 dimensioning incident will be equivalent to the size of one HVDC pole, that is 1 GW. Simultaneous faults on both poles in a bipole HVDC system are defined as 'exceptional contingecy' on an equal footing with, for example, busbar faults and faults in double system OHL towers.
How this event is handled can be a combination of purchasing reserves, disconnection of electricity consumers, large industrial loads or similar.

The electrical topology and the number of circuit breakers for the multi-terminal HVDC substation on the OEH must be designed in such a way that normal electrical faults do not cause permanent power loss higher than corresponding to the largest HVDC converter pole (e.g. 1 GW). After a busbar fault, it must be possible to reconnect the substation so that the lost power can be restored within 15 minutes. If there is sufficient capacity, it is allowed to redistribute the power to another subsystem.

4.4 Choppers for excess energy handling

Different strategies can be considered for handling the surplus power feeding into the transmission system when a HVDC converter is blocked or tripped. DC or AC side choppers can be used to burn the energy, and different designs can be made as to how fast the wind farms should either be disconnected or ramped down.
DC choppers can be installed at the onshore substations for handling short-term power surplus due to faults in the onshore AC grids.
For the AC coupled modes, AC choppers at the offshore substation for handling short-term power surplus due to blocking or trip of HVDC converters and cables from the OEH to the onshore system should be considered.

4.5 Voltage and frequency control on the OEH

Offshore HVDC converters must be capable of operating in "v/f"-control mode in order to control the voltage and frequency of each offshore connected WPP. This requirement applies to all operational scenarios, where WPPs are either connected to individual pole converter, in DC connection configuration, or in parallel “grid forming” mode in AC connection configuration, or when both poles on the bi-pole converters are connected.

Each HVDC converter pole connected to the OEH must be capable of operating in island operation with wind connected corresponding to the size of converter. Each HVDC converter pole must be able to control the voltage of frequency in the isolated AC grid (V/f control mode).

4.6 Ancillary services

4.6.1 Frequency services

Via the OEH, HVDC converters must be able to supply ancillary services for active power between the different areas. It must as a minimum be possible to exchange FSM, LFSM and EPC (external activation signal or frequency measurement).

4.6.2 System restoration

It must be possible to black start between the areas through the OEH.
The possibility of supplying black start from the third party systems on the OEH (e.g. wind power plants) to the surrounding synchronous areas must be investigated.

4.7 Sectionalizing of the offshore AC substation

In order to comply with the system operational requirements the HVAC substation on the OEH is proposed as

- double busbar, double circuit breaker with sectionizing for each HVDC converter (pole)
- for each section offshore wind is connected correspondingly to the converter(pole) size
- if PtX is to be connected, it must be distributed across each section.

5. References

[1] Best Paths, [Online]. Available: http://www.bestpaths-project.eu/.

[2] PROMOTioN, »Progress on Meshed HVDC Offshore Transmission Networks,« 2020. [Online]. Available: https://www.promotion-offshore.net/.

[3] »NS Energy,« [Online]. Available: https://www.nsenergybusiness.com/projects/zhangbei-vsc-hvdc-power-transmission-project/.

[4] H. ABB. [Online]. Available: https://www.hitachienergy.com/news/press-releases/2020/08/hitachi-abb-power-grids-wins-major-hvdc-order-linking-shetland-i.

[5] Scottish and Southern Electricity Networks, »Caithness HVDC switching station,« [Online]. Available: https://www.ssen.co.uk/CaithnessHVDC/.

[6] H. Quebec. [Online]. Available: https://www.hydroquebec.com/clean-energy-provider/markets/new-england.html.

[7] ENTSO-E, »ENTSO-E Position on Offshore Development - Interoperability,« [Online]. Available: https://www.entsoe.eu/news/2021/01/25/third-entso-e-position-paper-on-offshore-development-focuses-on-interoperability/.