

# Challenges Towards the Deployment of Offshore Grids: the OffshoreDC Project

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**Abstract**—This paper summarises challenges towards the deployment of offshore grids which are dealt with in the Nordic OffshoreDC project. The OffshoreDC project studies the techno-economic challenges related to assessment of the value and use of optimisation in the design of offshore grids. The project also studies the technical challenges related to control, protection and provision of ancillary services from HVDC grids with connected wind power plants. Finally, the transients in the DC grids are studied in the project.

*Offshore grids; HVDC; Offshore wind power plants; Grid design; Control; Protection; Transients*

## I. INTRODUCTION

The future wind power development in the Nordic region is likely to include a large fleet of offshore wind power plants [1]. At the same time, the high penetration of wind power will increase the need for balancing and reserves. The balancing capability of Nordic hydro power is highly useful, but transmission bottlenecks prevent their optimal use. Preliminary studies (e.g. the EU Tradewind and OffshoreGrid.eu) have indicated that it can be advantageous to combine the grid connection of offshore wind power plants with interconnections in large offshore grids. Such grids can also support other offshore power customers, e.g. wave power plants and oil platforms, possibly with gas power plants.

HVDC technology is already widely used for interconnection between power system areas, enabling power transmission over long distances without substations. To use HVDC for multi-terminal applications with large scale wind power connections, there is a need to develop solutions for a stable and secure design and operation of the grid.

The paper presents the main challenges in the deployment of offshore multi-terminal HVDC grids, classified into technological, operational (control) and market aspects, based on research done in the Nordic project DC Grids for Integration of Large Scale Wind Power - OffshoreDC. A broad picture of the challenges will be offered spanning time scales going from fractions of milliseconds (electromagnetic transients) to several hours and days (electricity market).

For short time scales, the control and operation of HVDC grids are of crucial importance. On the other hand, problems related to the interaction with existing and newly created AC grids should not be neglected. Also, integration of wind power in such a scenario must happen in the optimal way, as wind is expected to be the main chunk of the offshore generation portfolio: existing AC grids may require system services from the HVDC grids, while at the same time HVDC grids may demand new services to be delivered to them.

Moving to longer time scales, maximising the overall benefits of a possible HVDC grid is of utmost importance. This will be difficult due to uncertain and incremental deployment of offshore wind power and transmission connections. Hence, the biggest challenge in these terms is to achieve an optimal grid layout by quantifying its long-term benefits in advance, combining grid optimisation tools with market models.

Furthermore, it is apparent how the above aspects are intertwined, because the implementation of HVDC grids has to overcome the technological barriers. Moreover, the proper operation of power markets depends on the capability to tap system services from the generation facilities. At the same time, the deployment of an offshore HVDC grid should happen only if actually beneficial. This paper hence aims at linking the challenges, offering a wide overview of the research and development hurdles lying ahead.

## II. TECHNO-ECONOMIC CHALLENGES

### A. The value of offshore grids and wind power

Variability of wind power and PV may be the defining challenge for the European power grids in the coming decades. Another challenge will be the lack of available land in Central Europe to accommodate increasing amounts of wind power. Both of these issues can be mitigated by offshore DC grids. There are large areas of sparsely populated land with good wind resource in the Northern parts of Europe. Accessing those resources will require transmission lines. Overhead lines are often difficult to get built – therefore long distance DC sea cables are a relevant option. At the same time sea cables can help to connect offshore wind power plants to the onshore grids.

There is lot of research about offshore DC grids concentrating on the North Sea, but very little in the Baltic Sea. North Sea likely has more favorable characteristics toward first implementation of offshore DC grids: multiple planned wind power plants with long distance to shore, several countries with currently weak connections, probable benefits from sharing resources, and generally shorter distances between countries than in the Baltic Sea. However, there are also interesting factors in the Baltic Sea. It can serve as an access road to the far North with good wind resources and partially stranded hydro resources; there are relatively large islands that could be attractive locations for DC hubs; Baltic Sea is mostly shallow and could offer a large resource base after closer to shore projects are realized with radial AC connections.

The challenge in analyzing such grids is that there is a very high number of degrees of freedom when choosing how to layout the grid. The sizing of DC lines, possible connection points onshore, possible future offshore wind power plants, radial vs. meshed, location and size of DC hubs, etc. All this is strongly influenced by the onshore markets and grids. The approach taken in the OffshoreDC project is to link two models analyzing different aspects of this challenge (Figure 1). NTNU runs a grid topology optimization model which takes possible onshore connection points and power prices as input. VTT runs a unit commitment and dispatch model that estimates the power prices. These two models iterate through a soft link running over a FTP server. In addition, VTT analyses steady state security with PSS/E in order to estimate how the power can be evacuated from the onshore connection points and when the connection has to be taken deeper onshore. These results will also impact the iteration.

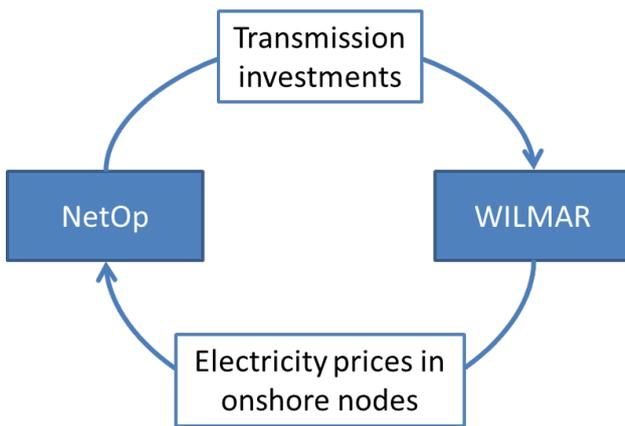


Figure 1. Optimisation flow when analysing offshore DC grids

### B. Overall grid optimisation

The overall grid design process flow is shown in Figure 2. Investment data and time series data for wind powers, load demands, power prices are needed as design input. In the early phase of the grid design, historical power price data is used in the optimisation calculation. The grid topology from the initial design is then used in conjunction with the market model tool to update the power prices for the second design loop. Finally, power system studies will

be performed on the grid topology from the second design loop to check for its feasibility.

According to the TWENTIES report [1], there exist plans for as many as 97 offshore wind power plants in the Baltic Sea. Ideally all wind power plants should be used in the optimization calculation. This, however, is not practical as the number of possible connections increases exponentially with the number of nodes (wind power plants, substations, and load centres) and eventually leads to an unsolvable case. Therefore, clustering or grouping of the wind power plants to reduce the number of nodes in the optimisation calculation is needed to reduce the excessive computational time. Criteria for wind power plants clustering are therefore also needed. This raises the questions whether a wind power plants in one country can or cannot be grouped with wind power plants of other countries and how big the size (in MW) a cluster should be. The more wind power plants are grouped into one cluster will increase the geographical distance between it and other clusters and eventually only radial connections are feasible.

An optimisation based on only one operational state is not sufficient in grid design as the state of power system is not stationary due to the fluctuations of the wind power and power consumption. Eventually this leads to the fluctuation of the power prices. To account for this variability, the optimisation has to be done with many operational states. Historical data of power consumption and power price at each load centre and simulation data of wind power have to be used to describe the system states. Ideally, the complete set of data should be used to describe the power system states but this could also lead to unsolvable case as there are too many unknowns involved in the calculation. To keep the number of states as low as possible in order to reduce the computational time, selection of smaller number of samples that can represent the whole data set has to be carried out. This involves the detail studies of the statistical distributions of the data.

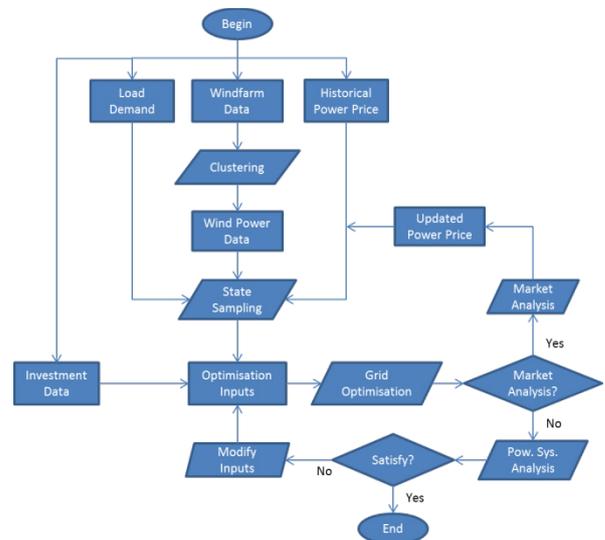


Figure 2. Grid design flow chart in OffshoreDC project.

### III. TECHNICAL CHALLENGES

#### A. Offshore grid control and protection

The backbone of a multiterminal HVDC grid realization is the control strategy of the interconnected power electronic converters, securing a robust performance and handling of the services requested by the system's operators such as precise power flow or a range of ancillary services. Additionally, the control strategy should ensure that the HVDC grid performs within its operational technical envelope and also that the system can remain stable during unexpected events e.g. faults on the AC or DC side of an HVDC grid or a station disconnection.

The predominant grid control approach considers the notion of separating the control duties into distinct levels of different priority. The highest priority level receives requests from the power system operator and passes information to the next level in order of priority, until the final switching signals requested by the power electronic equipment are produced.

As such, the HVDC grid needs a master-controller which monitors all stations and receives regular feedback on their electrical properties and availability status. This controller receives direct information from the system's operator based on requests for the performance of the whole grid and passes necessary signals to each station whose local, lower-priority, independent controller will assume further action.

In the lower-priority level of control, two major control strategies to establish a power flow within an HVDC grid have been suggested; the voltage margin method and the DC voltage droop method. The voltage margin method implies that each station can switch between fixed power or fixed DC voltage operation, according to the voltage level in the grid and the stations' power rating [2]. Only one station in the whole grid can be a voltage regulating unit at a time. A loss of a voltage control unit is not detrimental since the temporary change of voltage in the grid will trigger another station to automatically take over the voltage controlling duties. This control strategy is viable in grids with low number of terminals (3-4), but inadequate for larger grids. Additionally, it presents the disadvantage of forcing the single voltage controlling unit to bear all the power variations in the system.

The DC voltage droop control concept is considered the most adequate solution when a large number of stations are used [3]. Each station features a modified proportional-integral (PI) controller, where a droop mechanism allows a loose action of the integrator on the error between reference and feedback signals. This principle is demonstrated in [4] (a), where a typical PI voltage controller normally operating on a reference  $V_{DC}^*$  is modified with a power set-point  $P^*$  and a droop characteristic  $\rho$ , so that different power levels cause a different steady state voltage to be imposed by the voltage controller. This control method can be used simultaneously on multiple stations of the HVDC grid. A distributed voltage control is thus achieved, where multiple stations attempt to control the DC grid voltage by changing their power flow accordingly. The master control provides each droop controlled station with customized  $V_{DC}^*$  and  $P^*$  set-points, such that in steady state the station will present DC voltage and power, equal to its assigned setpoints.

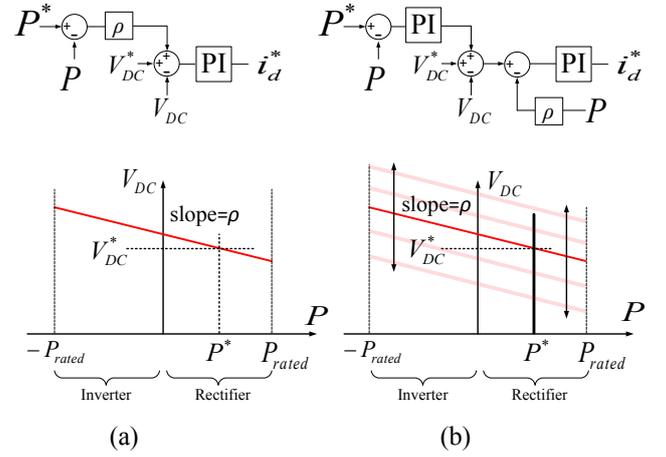


Figure 3. a) DC voltage droop controller b) Power controller with DC voltage support capabilities

In HVDC grids, not all stations are in droop control mode. However, during faults either on the AC side or the DC side of the DC grid, it would be beneficial if all stations could provide a support for DC voltage discrepancies. This challenge can be tackled if even the purely power controlled stations temporarily featured droop capabilities. As described in [4] and shown in simplified form in Figure 3, a modified droop controller can be used. The station normally follows precisely a power reference  $P^*$  but during fast occurring faults, the station follows a droop curve supporting the DC voltage just as a conventional droop controller would dictate.

In HVDC grids, the maintenance of the DC voltage within strict limits is required for the protection of the equipment and the minimization of losses. As a result, droop controlled stations which conform to this rule have conventionally such a droop curve slope  $\rho$  that for small deviations in DC voltage, a great variation of power is allowed, sacrificing the accurate power flow. A challenge is to design droop control mechanisms that prioritize on power flow requirements, retain the DC grid voltage close to its nominal value and still offer acceptable dynamic response during fault events or power scheduling changes.

Another control challenge appears in the connection of multiple stations on an AC islanded grid, such as a large offshore wind park. When a single station is connected to an offshore grid, the control strategy is simple and essentially sets an AC voltage which the wind turbines follow. The size of an offshore grid can be so large that multiple stations need to be connected to it and share the transfer of the produced power. In this case, special strategies must be followed where these stations simulate the connection of multiple synchronous generators on a typical AC grid, without the stations communicating with each other.

An important issue is raised when it comes to the protection of the HVDC grid. Unlike the AC breaker which can be compact and cost effective, an HVDC breaker, as in [5], needs a considerable amount of power electronics whose size (due to insulation complications) and consequent cost can hinder the wide use of DC breakers in a large DC grid. Therefore, under the contemporary conditions, an HVDC grid should be designed without the provision for DC breakers or a very limited use of them in key positions.

## B. Transient phenomena

Transient Overvoltage's (TOV's) in electrical transmission and distribution networks result from the unavoidable effects of lightning strikes and network switching operations. A TOV can be defined as the response of an electrical network to a sudden change in network conditions, either intended or accidental, (e.g. a switching operation or a fault) or network stimuli (e.g. a lightning strike). A switching overvoltage or as they sometimes are called switching transients is generated due to the interaction between the breaker or fault and the inherent elements (inductance, capacitance and resistance) associated with an electric power system. These transients have been studied in detail in pure AC system, however in this section we will shortly show the effects of them on the DC lines when voltage source converters (VSC's) are connected to the transmission system.

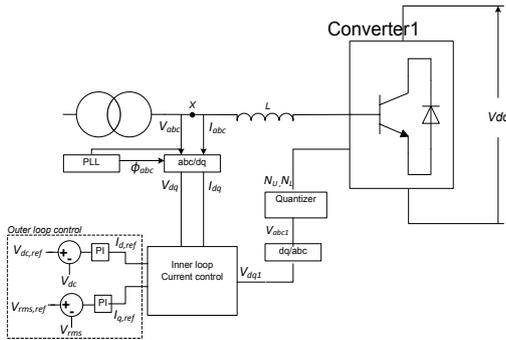


Figure 4. Converter control scheme.  $V_{dc}$  and  $V_{rms}$  used in the outer loop

As seen from Figure 4 the VSC is using a simple  $V_{DC}$  and  $V_{rms}$  control, hence active and reactive power flows are controlled to maintain a stable DC and AC voltage. When the AC side is subjected to a transient the effects on the DC side depends on various elements, most importantly the state of the converter. If the converter is blocked the only way the current is able to pass, is through the parasitic capacitances of the IGBT's and diodes, provided that the current frequency is relatively high since the capacitance is in the nF range. In a situation where the converter is on, the switching frequency is of great importance among several other things. As higher the frequency as faster the control is able to correct the current error due to small steps. From figure 4 we can see that we have integrators in both the inner and outer loop, hence when the step is large they will integrate to a large value before the next sample. Nevertheless, the increase in frequency will solve some of the transient problems but will increase the losses proportionally and introduce new ones. If the control is to fast it will react to short disturbances that don't cause any harm.

If a fault is generated and interrupted on the AC side of the converter will it evoke a transient recovery voltage (TRV) which causes further discharge of the DC cables adding to the fault current.

The location of the fault is actually very important for the outcome, since it determines the total resistance, inductance and capacitance between the fault and the converter. The total amount of energy discharged from the DC cables is dependent on the disturbance caused by the fault current and the TRV. The TRV is defined as follows [6]:

$$V_c = V_m \left[ 1 - e^{-\alpha \cdot t} (\cos(\omega_d \cdot t) + \frac{\alpha}{\omega_d} \sin(\omega_d \cdot t)) \right]$$

where  $\alpha=1/(2RC)$  and  $\omega_d = \sqrt{\omega_0^2 - \alpha^2}$ , accordingly the damping depends on R and C. The inductance L will influence the TRV frequency and voltage peak. To investigate how this will affect the system, a simulation is done for three different medium voltage cable types where the resistance and capacitance are comparable nonetheless with different inductance sizes. The total length of the cables is 2 km, the cables emulate the connection between the converter reactor and the low voltage side of the transformer. The fault location seen as 'x' in Figure 4 is then varied to find the optimum fault location.

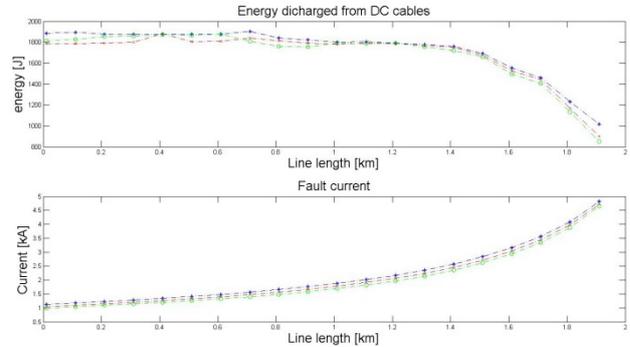


Figure 5. Upper: energy discharged from the cables as function of AC line length. Lower: fault current as function of line length.

From the upper plot in figure 5 it can be seen, that moving the fault away from the converter itself will bring down lower the effect of the fault on the DC side. Consequently, when the cable becomes longer, the capacitance and resistance will increase causing more damping of the TRV, although the fault current is increased as seen from the bottom lower plot. This is due to sum of the two disturbances, if the TRV washere infinitely small, the charge flowing into the fault would be the only contributor to discharging the DC side. Looking at the increase in inductance, we see that it makes only a small difference to the discharging but it is not the main element when looking medium voltage cables. Furthermore, the increase in inductance will give a higher voltage peak and higher frequencies [6] but which is outshone by the damping. This picture will of course change, if we look at high voltage cables since the resistance becomes much smaller thereby decreasing the damping while the inductance and capacitance would be more dominating.

## C. Integration of wind power plants

The deployment of offshore grids and Wind Power Plants (WPPs) will go hand in hand and are certainly interdependent on each other, considering that (i) the implementation of large scale offshore grids will happen only if reduced cost of offshore WPPs will be achieved, (ii) at the same time offshore grids may help lower the total cost of wind power and (iii) active support from WPPs to the operation and control of offshore grids can boost their chance to eventually be built.

General control and protection issues for offshore grids have been partly addressed by the research community – see e.g., but not limited to [7], [8]. However, more work is

needed, especially in terms of integrating wind power into large offshore grids taking into account actual limitations posed by modern commercial WPPs. This requires a classification of well-known and new control features and derivation of requirements for both WPPs and offshore grids.

Within the OffshoreDC project, these issues are being addressed for WPPs connected to land via simple VSC-HVDC connections and focusing on power system services. Preliminary results were presented e.g. in [9]. Conclusions and challenges can be summarized as follows:

- For services which dynamic range falls within a usual AC power system spectrum (e.g. frequency control and power oscillation damping), state-of-art WPPs can contribute provided that a proper overall control paradigm is deployed over the offshore grid. Power oscillation damping is more demanding but its implementation should still be possible.
- For services regarding voltage control, offshore grids involving VSC-HVDC potentially lower the burden on WPPs, since the extension of offshore AC islands will be limited and voltage control at onshore nodes can be done seamlessly for the WPPs, provided that the onshore HVDC stations are properly rated.
- For services directly regarding the dynamics of the DC part of the offshore grid, the available contribution from WPPs is more limited. This is due to the much faster dynamics in DC networks than in AC grids [8]. Looking at state-of-the-art WPPs, it seems unlikely they would be able to provide the needed support during e.g. the first instants after loss of an onshore converter station. For this, supplementary storage devices or added contribution from other onshore stations may be needed, while WPPs can take over as the system approaches steady-state again. This issue will be particularly critical if the amount of wind generation compared to the size of the offshore grid will be very significant. A possibility to increase the usage of WPP during fault conditions is to expand the DC-grid all the way up in the nacelle of the wind turbine and thereby increase the controllability from the WPP [10].

Another aspect that is worth mentioning is how to integrate WPPs from different developers and manufacturers and one or more offshore HVDC converters in offshore AC islands – see also Section III.A. The inertia-less nature of the network gives more control freedom but also poses possible new challenges to guarantee stability, due to converter interactions. At the same time, the proximity of WPPs from different vendors is a factor that must be taken into account in the design and tuning phase. Some work has been done on the issue, e.g. [11], but more research is needed to offer complete and robust treatment of the topic.

#### IV. DISCUSSION AND OUTLOOK

This paper has dealt with some of the many technical and economic challenges related to development of large scale offshore HVDC grids interconnecting AC power systems and connecting a large volume of offshore wind power plants.

The driver for development of offshore grids is the economic benefits which such grids will have on the cost of energy in future power systems, where the large scale development of offshore and onshore renewable energy calls for more flexible power systems. Strong offshore grids interconnecting the existing onshore systems have a potential to increase the flexibility significantly, and thus lower the cost of energy.

The main technical barriers are related to the control and protection of large offshore grids and the connected wind power plants. This includes the control issues, which are dealt with in the OffshoreDC project, but also the development of DC breakers which are feasible for large scale offshore deployment.

Also transients in the HVDC grids must be investigated. This work in OffshoreDC will contribute to ensure the lifetime and minimise maintenance costs of the offshore electrical equipment.

Besides these issues, there are several other challenges which are not dealt with in OffshoreDC. For instance the need for compatibility between HVDC grid components (converters, cables, breakers etc.) from different suppliers is very important. This issue must be solved before the offshore grids can develop into large interconnected solutions.

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