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HVDC Planning Considerations for Offshore Wind Integration

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SUMMARY

In planning for offshore wind integration, the decisions on how best to deliver the energy to the onshore grid is an important one for any utility. This paper outlines considerations for utilities planning the integration of large offshore wind farms, with High Voltage Direct Current (HVDC) transmission via subsea cables. The differences between an offshore HVDC connection and an onshore HVDC link are examined. Traditional planning techniques for conventional HVDC while still applicable, may not be sufficient to identify all the challenges such as Sub Synchronous Control Interactions in the offshore AC collection network. A small case study demonstrating the initial stages of the HVDC planning process with an offshore wind farm is provided.

KEYWORDS

HVDC, VSC, Offshore Wind, Transmission Planning

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INTRODUCTION

Offshore wind is becoming more important in the overall energy mix. Higher more consistent wind speeds offshore provide a more constant supply of energy than some onshore wind sites. Offshore wind can be located closer to large population centers than onshore wind. Europe is leading the way in the interconnection of offshore wind via HVDC, with a few operational projects in the North Sea. The USA's first offshore wind farm began operation in December 2016 – Block Island wind farm. With an AC cable connection to shore, the 30 MW offshore wind project features five 6 MW turbines. Many further installations are planned along the east coast in particular off the New York and New Jersey coasts where both State governors have announced offshore wind policies with a goal of 2.4 GW and 3.5 GW respectively [1],[2]. The need for utilities to understand the issues surrounding interconnection of remote resources, in particular offshore wind farms via HVDC in a planning context is growing worldwide as their implementation becomes more common. This paper provides a brief introduction to offshore wind with HVDC and summarizes the high level and technical planning considerations to be undertaken in the planning phase. Finally, a case study is provided comparing HVAC and HVDC options for a 200 MW offshore wind farm and a power flow example for a VSC based HVDC connection.

WHY HVDC TRANSMISSION FOR OFFSHORE WIND

For an onshore above ground transmission system, the break-even distance between HVAC and HVDC (Point D on Figure 1, adopted from [3]) is around 300-400 miles, depending on the cost of the HVDC converter stations. In an offshore system, subsea cables are required. Capacitive charging is much higher for AC cables than AC overhead lines. Thus, for long AC cables there is a need for reactive compensation, in the form of shunt reactors, to maintain an acceptable steady-state voltage profile along the cable. If the cable is so long that compensation on each end is not sufficient, then compensation becomes a significant technical and economic challenge. This fact forces the breakeven distance between HVAC and HVDC offshore to approximately 50 miles [3]. Because of the investment costs required to compensate for this reactive power to ensure appropriate active power transfer on AC cables, AC cable option becomes less cost effective than using HVDC.

HVDC has other technical benefits over HVAC for the connection of offshore wind [4]. The DC link limits fault propagation from the wind farm to the onshore grid, or vice versa. The HVDC system has lower losses than HVAC and there is no potential for resonance between the offshore cable and the onshore grid. It was reported in [5] that for wind power plant located more than 50 to 100 km offshore (roughly 30 to 60 miles), and larger than 200 MW, HVDC is a more economical solution.

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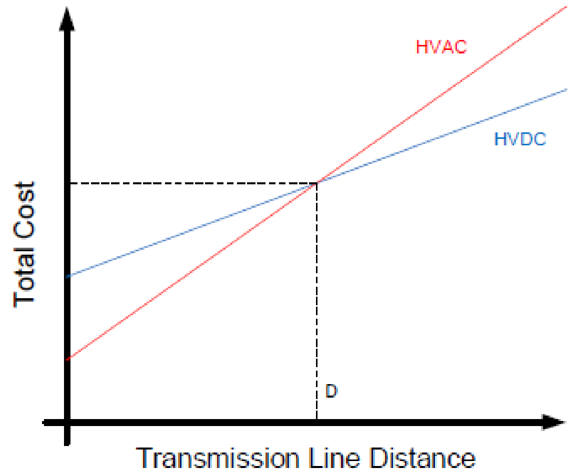

Figure 1: HVDC vs. HVAC break-even distance

To date all offshore wind connected via HVDC has been done with voltage source converter (VSC) technology. This is due to the multiple advantages of VSC over conventional line commutated converter (LCC) for offshore applications. These advantages include:

- Independent control of active and reactive power
- Reactive power consumption or generation can be controlled to meet the needs of the network
- Ability to connect to AC grids with low short circuit ratio
- Limited harmonics produced by the converters
- Black start capability
- More compact converter stations – particularly advantageous to offshore
- LCC requires extra equipment (STATCOM/SVC) offshore, and harmonic filtering which further increases the offshore station size

The controllability, compactness and reactive power considerations of VSC make it more desirable than LCC based HVDC for offshore wind applications. VSC-HVDC presents a more attractive option technically since with VSC voltage can be regulated on both sides easily and independently of the real power transfer.

The controllability, compactness and reactive power considerations of VSC make it more desirable than LCC based HVDC for offshore applications. Other options for connecting HVDC have been suggested to reduce complexity of the offshore substation. Low frequency AC transmission in which the offshore wind farm is connected to shore via a AC cable operated at lower frequency (~ 1/3 of fundamental), thereby reducing the capacitive charging current of the cable. Onshore the wind farm is connected to a back to back VSC to convert back to the grid frequency [6]. Another option reducing complexity offshore which has gained momentum in recent years is to use diode rectifier based HVDC [7]. The offshore VSC is replaced by a less complicated, modularized diode rectifier unit. These technologies are at a conceptual stage but it is not anticipated that there should be any unsurmountable technical challenge to their implementation.

OFFSHORE WIND INTEGRATION PLANNING CHALLENGES

In planning an offshore wind farm there are several considerations that a utility will have to decide on; including deciding whether the utility will own and operate the offshore transmission or whether an external developer will own and operate the offshore grid. From a transmission planning point of view, the EPRI HVDC planning guide [3] provides a comprehensive outline of the studies that should be performed by a utility and a vendor, prior to and during the installation of a HVDC transmission system. The studies include the following:

- Initial feasibility Studies
  - Power flow and stability analysis to assess basic feasibility
  - Reliability and availability studies
- Pre-specification Studies
  - Reactive Power Requirements and Dynamic Performance Studies[1]
  - AC Impedance Scans for Harmonic Filter Design
  - Sub Synchronous Torsional Interaction Screening Studies
- Building an AC 3-phase System Equivalent for EMTP studies
- Control system design
- Model development and verification for operational planning

These studies also need to be performed for an offshore wind based HVDC link, however, the scope of this document is to consider extra and alternative studies required for HVDC connected with offshore wind.

The most notable difference from a network planning point of view between an onshore HVDC link and an HVDC offshore connection is the control of the converters. In a regular point to point HVDC system, power is controlled from one station and the DC voltage is controlled by the second station, meaning the operator has full control over the power flow in the DC link, by controlling the converter. However, in an offshore system the offshore VSC station is tasked with controlling the offshore grid voltage amplitude and frequency. The onshore station must control the DC link voltage, since both converters are now controlling voltage (AC and DC), the HVDC link must pass through the power generated by the offshore wind power plant. The utility then must control the power flow by controlling the wind power plant output. In general, individual wind turbines should be configured to output maximum power, unless this causes mechanical stresses, or power is being curtailed for reserve purposes. Figure 2 and Figure 3 illustrate the differences in the control structure between an onshore point to point HVDC system and an HVDC link connecting offshore wind.

[1] The WECC HVDC Task Force in collaboration with EPRI have developed generic HVDC models for planning studies with HVDC available in most major vendors' software packages.

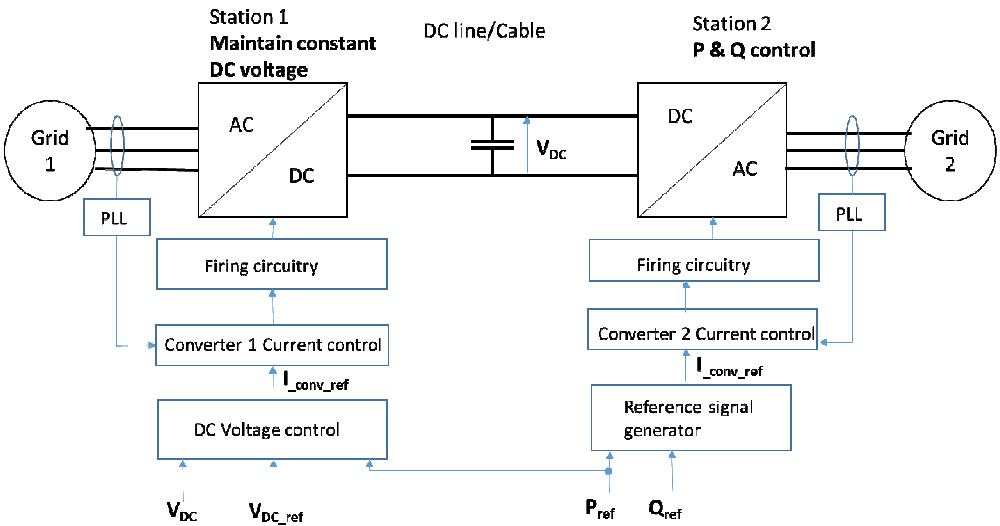

Figure 2: Control structure for HVDC point to point onshore connection

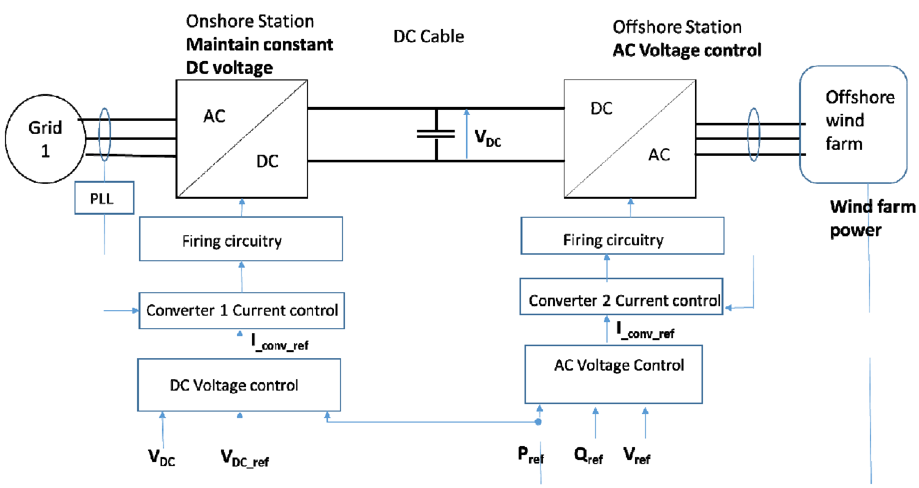

Figure 3: Control structure for point to point HVDC connecting an offshore wind farm

TECHNICAL PLANNING CONSIDERATIONS FOR OFFSHORE WIND

The following list of planning studies will be required for an offshore HVDC link beyond the typical planning studies mentioned in the previous section.

1. **Feasibility including offshore resource assessment.** Initial feasibility studies include a power flow model to ensure the AC network can receive the desired power level.
2. **DC cable voltage and power selection.** The offshore converter station platform is a limiting factor for offshore wind energy facilities that rely on HVDC technology to deliver the electricity to the grid. Currently VSC technology was applied with the size of the converter stations up to 1,000 MW with symmetrical monopole configuration, though the converter ratings could be increased in the future VSC based projects. XLPE based cables, commonly used with VSC HVDC installation have been type tested and planned installations exist for voltages up to 400 kV [8] and one supplier has type tested a 525 kV XLPE DC cable [9].

3. **Collection network voltage and power rating.** Increased collection network voltages reduce power losses in the offshore collection network. Standard voltage levels for offshore collection networks are 33kV and 66kV. Different cable ratings may be required at different points in the offshore wind farm layout, depending on the current carrying requirement of certain points in the offshore network. There has been a lot of experience and publications considering planning layouts for offshore wind power plants.
4. **Reactive compensation required offshore.** AC cables consume reactive power; in this case the collection network will require reactive compensation. Some of this reactive compensation may be provided from the converters. Power flow dynamic studies are required to determine the reactive compensation required both from the converter and from shunt reactors.
5. **Ancillary services from offshore wind.** The onshore converter station has the capability to provide voltage support to the onshore grid with reactive power control, and frequency support via coordinated controls with the offshore wind farm. Power flow and time domain analysis at the onshore point of common coupling (PCC) will determine the requirements for ancillary services.
6. **Black Start procedure.** VSC HVDC has potential to become a black start resource. Coordinated black start planning and simulation is required so that testing may take place during the commissioning stage of the HVDC link [10] [11].
7. **Issues related to weak grid connections:** Positive sequence stability models provide accurate results for inverter-based generation connected to strong grids. However, in the case that converters are connected to weaker grids, control interactions can occur, which require accurate 3 phase electro-magnetic transient (EMT) simulations to capture control interactions [12]. In an offshore grid this is particularly an important problem for utilities to understand. Since the offshore wind farm will be developed by a third-party developer and the offshore station by a vendor, it may be difficult to obtain accurate EMT simulation data, including sensitive control schemes to enable utilities to study this effect in the planning phase.
8. **Control Interactions:** The combination of the offshore wind power plant and the HVDC converter station in an offshore network may potentially lead to control interactions between the HVDC converter controls and the power-electronic controls of the wind turbines. For this reason, detailed EMT simulations may be needed, with vendor proprietary models of both the HVDC vendor and the wind turbine generator vendor to ensure proper coordination of all controls and avoidance of any negative control interactions. Such studies will require close coordination with all the involved equipment manufacturers.

A focus of recent attention has been the mitigation of control interactions and harmonic resonance in the offshore network. In Europe's first HVDC connected offshore wind farm, Borwin1, harmonic resonance interactions between the converter controls and the AC offshore cables caused over-voltages which resulted in failures and disconnections over an extended period from 2013 to 2015. The harmonic interactions between the converters were not uncovered in the planning, design or commissioning stages [13]. The most appropriate solution for reducing harmonic interaction between converters is tuning of the converter controls during planning to avoid issues. This requires adequate EMTP studies in the planning phase to identify possible interactions and tune converter controls appropriately [14]. To determine scenarios to study with 3 phase EMTP simulations, screening studies should be used. Such studies include impedance-based frequency scans to determine the ratio of the impedance of the HVDC converter (including controls) and the wind farm, determining frequency ranges where potential interactions can occur [15].

SAMPLE CASE STUDY – OFFSHORE INTEGRATION WITH HVDC

This case study is provided to illustrate the initial feasibility study for selection of HVDC system for offshore wind integration. Consider a 200 MW offshore wind farm which is 150 km from shore. Figure 4 illustrates the major issue in using HVAC cables to connect offshore wind farms: the reactive power production of the AC subsea cable. A 220 MW AC cable is shown connecting a 200 MW offshore wind farm. As the length of the cable increases it produces more and more reactive power, in the uncompensated case here, the cable has no capacity for active power export after 100 km. Reactive compensation at both ends may be used to improve the active power capacity. The red lines in Figure 4 display a case with 100 MVAR of reactive compensation. In this case the active power export capability is still at the maximum 200 MW at 80 km, reducing to zero after 135 km. Excess reactive compensation offshore is expensive and the magnitude required to offset the cable reactive power production explains the significant increase in cost of implementing HVAC cables for far offshore wind farms.

Significant work has been done comparing the different options for AC and HVDC offshore wind in the UK [16]. Dynamic studies investigating fault scenarios showed that large AC connected offshore wind farms which are far offshore may be detrimental to system stability, due to the large AC cable capacitance connected to the system. In comparison HVDC connection can be beneficial with the extra controllability offered by VSC HVDC transmission.

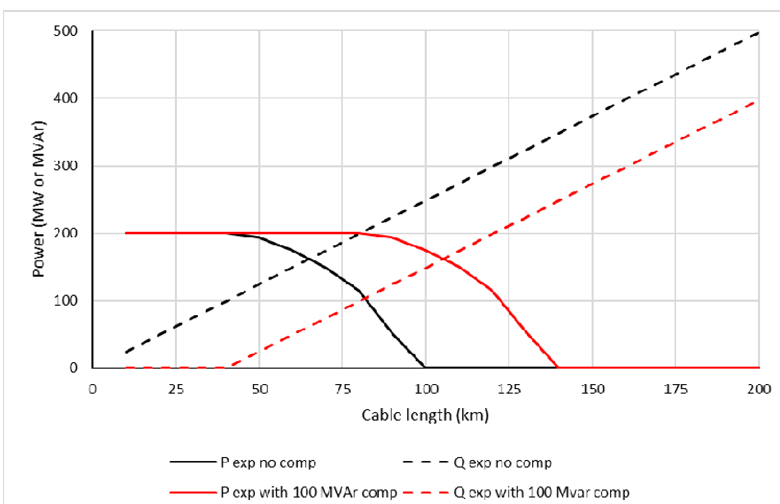

Figure 4: Active and reactive power exported to onshore grid for AC cable connected 200 MW offshore wind farm

Figure 5 displays the crossover distance between HVAC transmission and VSC - HVDC transmission in terms of capital costs. This information has been taken from research by Imperial College London [17], where they compared the cost of transmission for 600 MW offshore wind farm for HVAC, HVDC and Low Frequency AC for different distances at 10 km increases and applied a curve fit. Each individual offshore wind case will be a bespoke design which will require detailed costing and analysis before deciding on a transmission option, however this provides a reasonable basis for the assumption of the crossover distance.

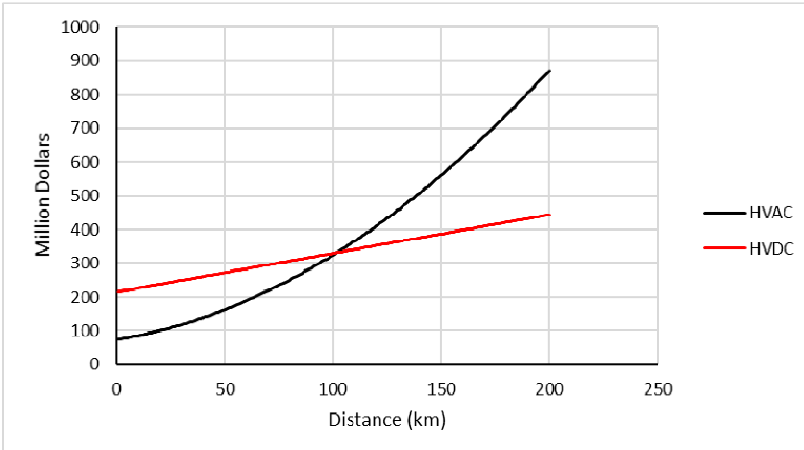

Figure 5: Cost of HVAC transmission and HVDC transmission for offshore wind

Sample Power Flow in PSS/E

The AC collection network of the offshore wind farm is selected to have 33 kV inter array cables connecting an offshore wind farm modeled as a lumped wind turbine with a maximum output of 200 MW, collection network cable data in Table 1 is obtained from [18]. A transformer steps up from 33 kV to the converter terminal voltage. The DC cable is modeled in PSS/E as a total resistance. DC cable data is outlined in Table 2 [19]. For a 150 km cable the total DC resistance is modelled as 2.1 Ω. For an illustrative power flow, the WSCC 9 bus system is used with a 200 MW VSC HVDC offshore wind farm connected to Bus 4. The offshore wind farm is modeled as a wind generator at 33 kV. The VSC HVDC link has a DC voltage of 220 kV. Figure 6 provides a diagram of the system for reference.

The choice of DC cable rating and voltage depends on the available cable sizes from vendors. Using XLPE 200 kV cables require a current rating of at least 1000 A. At the onshore point of connection up to 200 MW will be feeding in through the Point of Common Coupling. Depending on the strength of the grid that the HVDC system is connecting to, there may be requirements for voltage support and frequency support from the offshore system.

Table 1: 33 kV collection AC cable data

Rated Voltage	Resistance	Inductance	Capacitance
33 kV	0.73 Ω/km	0.113 Ω/km	298 nF/km

Table 2: DC cable data

Rated Power	Nominal Current	Cable Cross Section	DC Resistance
220 MW	0.793 kA	1300 mm^2	0.014 Ω/km

The power flow dispatch when VSC HVDC transmitting 200 MW are displayed in Table 3. It is important to note in power flow analysis of an offshore system, assuming the offshore wind farm is only connected to the grid via DC transmission, it must be modeled as a slack bus.

Table 3: Power dispatch for power flow with wind farm at maximum output

BUS	Power (MW)
BUS1	50.0000
BUS2	36.2703 (Slack bus on main grid)
BUS3	35.0000
Wind Farm	208.9613 (Modeled as slack bus offshore)

Reactive power requirement of Converter

The selected system parameters can be tested in the power flow. Once the voltage and power levels are decided, the reactive power requirement of the VSCs at each side of the HVDC link can be determined. Table 4 shows the voltage at bus 4 when no reactive power is supplied to the bus from the VSC, and the reactive power required to control that voltage to 1 per unit. The objective of this example is to control the voltage to 1 pu for illustration purposes, however the converter must have the reactive power capability to control the voltage as defined in the connecting grid code (generally 0.95 to 1.05 pu).

Knowing the reactive power requirement, the rated power of the converter is calculated as the square root of the sum of the squares of maximum active and reactive power required, which in this case is:

$$S = \sqrt{200^2 + 64.9^2} = 210.26\ MVA$$

Similarly, the offshore VSC HVDC converter has a maximum reactive power requirement of 61.2 MVAR, therefore both converters should be rated above 211 MVA.

Table 4: Reactive power requirement of onshore VSC

Bus 4	Voltage with no Q	Power from VSC	Q required to control Voltage to 1 pu
	1.0320	200	62.8
	1.0334	150	64.9
	1.0318	100	62.8
	1.0281	50	56
	1.0221	0	44.1

The converter should be rated to have some excess reactive power capability for voltage support during contingency events. The next step in the planning phase would be to perform a dynamic simulation to determine the extent of excess converter ratings for voltage control during grid contingency events.

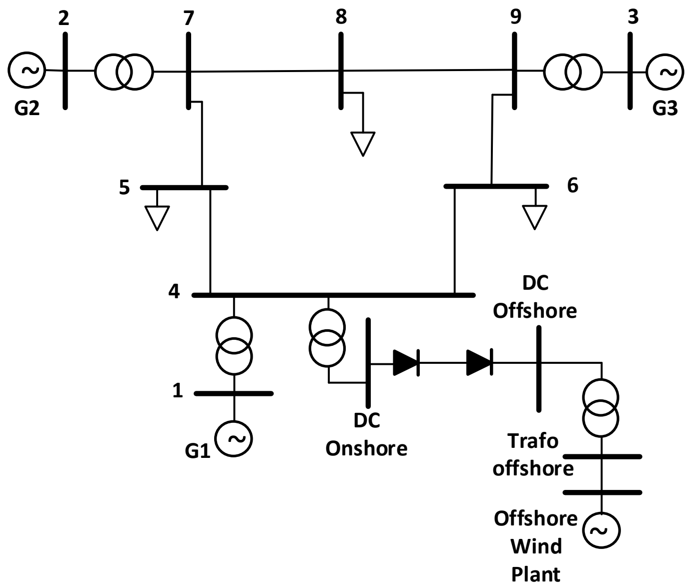

Figure 6: Diagram of 9 bus system edited to include offshore wind connected via HVDC

SUMMARY

HVDC planning is important for utilities to consider when planning future installations to the grid. This paper has outlined some of the studies utilities should consider when implementing HVDC connected offshore wind farms. The paper has outlined the reasons for selecting VSC HVDC for offshore wind, primarily because of the technological advantages over LCC based HVDC. The technical planning considerations specifically for offshore wind farms connected with HVDC, including initial feasibility studies, voltage and power ratings, reactive power requirements, requirements for ancillary services and issues with resonance and harmonic interactions are outlined. It is stated that 3 phase planning models should be required to examine control and resonance interactions accurately. The final section provides a case study for the integration of offshore renewables with HVDC. After 50-60 km the reactive power consumption of an HVAC cable becomes an issue for efficient transfer of real power. It is found that an approximate crossover distance between HVDC and HVAC transmission is 100 km for offshore wind applications.

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