ELECTRIC POWER
RESEARCH INSTITUTE

Integration of Offshore Wind Generation with HVDC

Considerations for Planning

2018 TECHNICAL UPDATE

Integration of Offshore Wind Generation with HVDC

Considerations for Planning

EPRI Project Manager
A. Del Rosso

ELECTRIC POWER
RESEARCH INSTITUTE

3420 Hillview Avenue
Palo Alto, CA 94304-1338
USA

PO Box 10412
Palo Alto, CA 94303-0813
USA

800.313.3774
650.855.2121

askepri@epri.com

www.epri.com

3002013674
Technical Update, August 2018

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or
e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2018 Electric Power Research Institute, Inc. All rights reserved.

Acknowledgments

The Electric Power Research Institute (EPRI) prepared this report.

Principal Investigators
J. Ruddy
R. Adapa

This publication is a corporate document that should be cited in the literature in the following manner:

Integration of Offshore Wind Generation with HVDC: Considerations for Planning. EPRI, Palo Alto, CA: 2018. 3002013674.

Abstract

In planning for offshore wind integration, the decision on how best to deliver the energy to the onshore grid is an important one for any utility. This technical update outlines considerations for utilities planning the integration of large offshore wind farms, with high-voltage direct current (HVDC) transmission through subsea cables. The report examines the differences between an offshore HVDC connection and an onshore HVDC link. Traditional planning techniques for conventional HVDC—although still applicable—may not be sufficient to identify all the challenges, such as sub-synchronous control interactions in the offshore alternating current (AC) collection network. Detailed three-phase models are recommended for use in planning to minimize problems during commissioning.

Keywords
HVDC cables
HVDC planning
Line-commutated converters
Offshore wind generation
Voltage-sourced converters

Table of Contents

List of Figures

List of Tables

Section 1: 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 governers have announced offshore wind policies with a goal of 2.4 GW and 3.5 GW respectively [24],[25]. 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.

The rest of this chapter provides a brief introduction to offshore wind with HVDC. Chapter 2 summarizes the high level planning considerations to be undertaken in the pre planning phase. Chapter 3 outlines the technical planning considerations with offshore wind connected HVDC. Chapter 4 provides a case study 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 1-1, adopted from [6]) 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 [6]. As the investment costs required to compensate for this reactive power and ensure appropriate active power transfer becomes less cost effective than using HVDC.

HVDC has other technical benefits over HVAC for the connection of offshore wind [1]. 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 [2] 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.

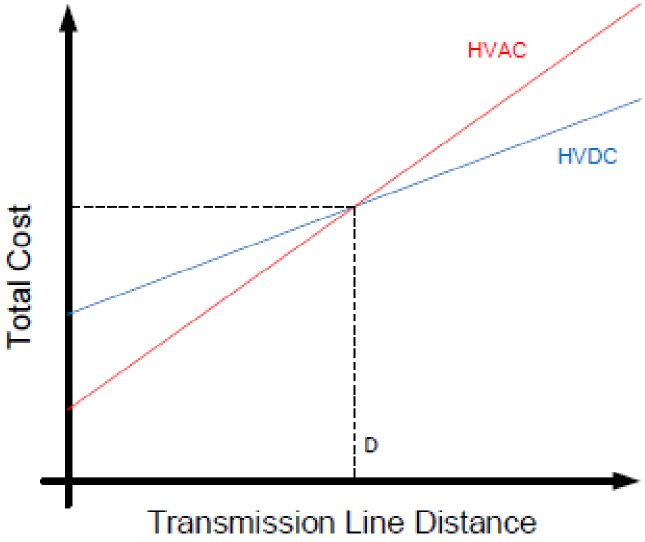

Figure 1-1
HVDC vs. HVAC break-even distance

Choice of HVDC Transmission

To date all offshore wind connected via HVDC has been done so 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 surrounding network
- Zero power operation possible – LCC requires a minimum power transfer to stay connected
- Ability to connect to weak AC grids
- Limited harmonics produced by the converters
- Black start capability
- More compact converter station – particularly advantageous offshore
- LCC requires extra equipment (STATCOM/SVC) offshore, and harmonic filtering which further increases the offshore station size

It can be seen that the controllability, compactness and reactive power considerations of VSC make it more desirable than LCC based HVDC. VSC-HVDC presents a more attractive option technically since with VSC voltage can be regulated on both sides quite easily and independently of the real power transfer, and with VSC connection to weak parts of the electric power system is technically less challenging.

Other options for connecting HVDC have been suggested recently in an attempt 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 [3]. Another option reducing complexity offshore is to use diode rectifier based HVDC [4]. 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.

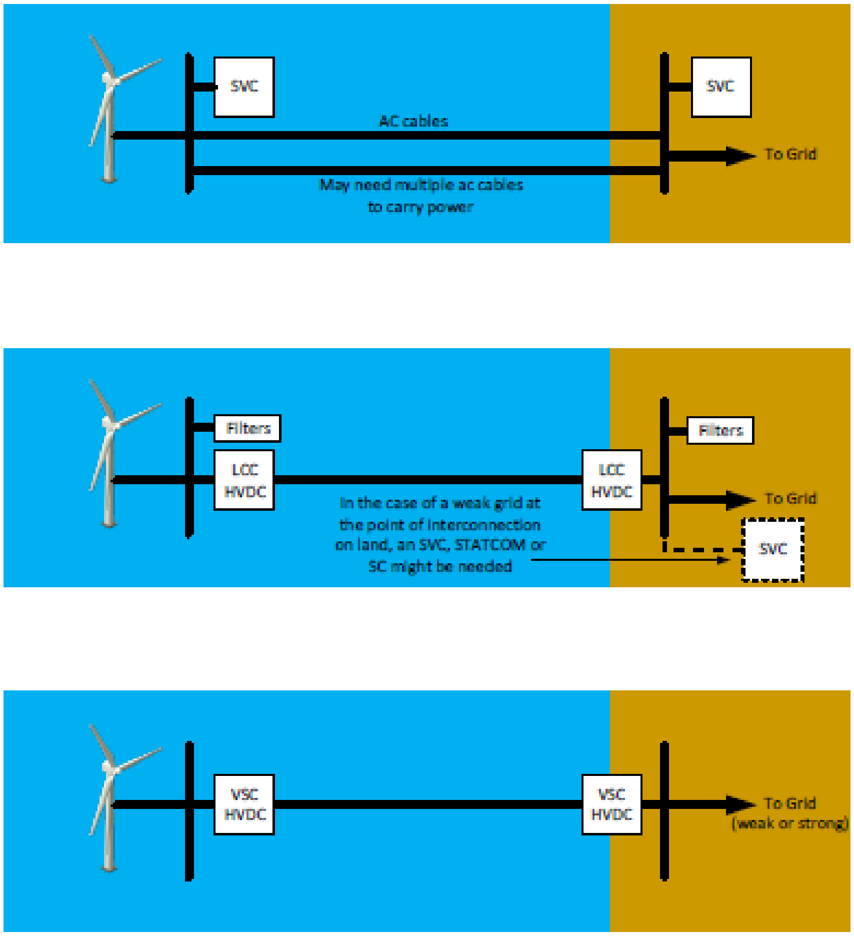

Figure 1-2
Transmission options for offshore wind [6]

Section 2: Offshore HVDC Connected Wind Farm Planning Challenges

In planning an offshore wind farm there are a number of considerations that a utility will have to decide on. The following items require consideration.

1. **Offshore transmission ownership and operation.** The utility may decide not to own and operate the offshore network and only operate from the point of connection. Advantages of this include the fact that a developer will own and build the offshore HVDC link. On the other hand, the utility may utilize an offshore grid for supplementing the onshore grid.
2. **Reliability.** In [5] it has been suggested to build one HVDC or HVAC link to offshore wind farm. Since there is no load offshore, it may not be cost effective to install two cables for N-1 redundancy. It is also suggested that a second AC transmission transformer is installed offshore due to the higher than normal failure rates of converter transformers and the repair time offshore.
3. **Offshore substation resource sharing.** If the utility owns the transmission offshore they have the choice whether to share the offshore platform resource with the developer who will require AC switchgear, transformers etc. on an offshore platform. The advantage of this is reduced overall cost and footprint, however it requires coordination between the offshore developer and the HVDC vendor to share a platform.
4. **Multi-terminal offshore grid.** It is likely that a utilities first offshore wind farm connected via HVDC will be a point to point link. The option of future interconnection of more offshore wind farms in a stage-wise manner should be considered. Depending on how far these wind farms are planned from the first farm, the connections may be on the AC side (< 30 miles) or connected in a multi terminal HVDC grid. Assuming both sets of wind farms have separate connections onshore, connecting offshore wind farms together will improve redundancy.

HVDC Planning Studies

The EPRI HVDC planning guide [6] 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 and are summarized in Figure 3:

- Initial feasibility Studies
  - Power flow and stability analysis to assess basic feasibility
- Pre-specification Studies
  - Reactive Power Requirements and Dynamic Performance Studies
  - AC Impedance Scans for Harmonic Filter Design
  - Sub Synchronous Torsional Interaction Screening Studies
- Building an AC 3-phase System Equivalent

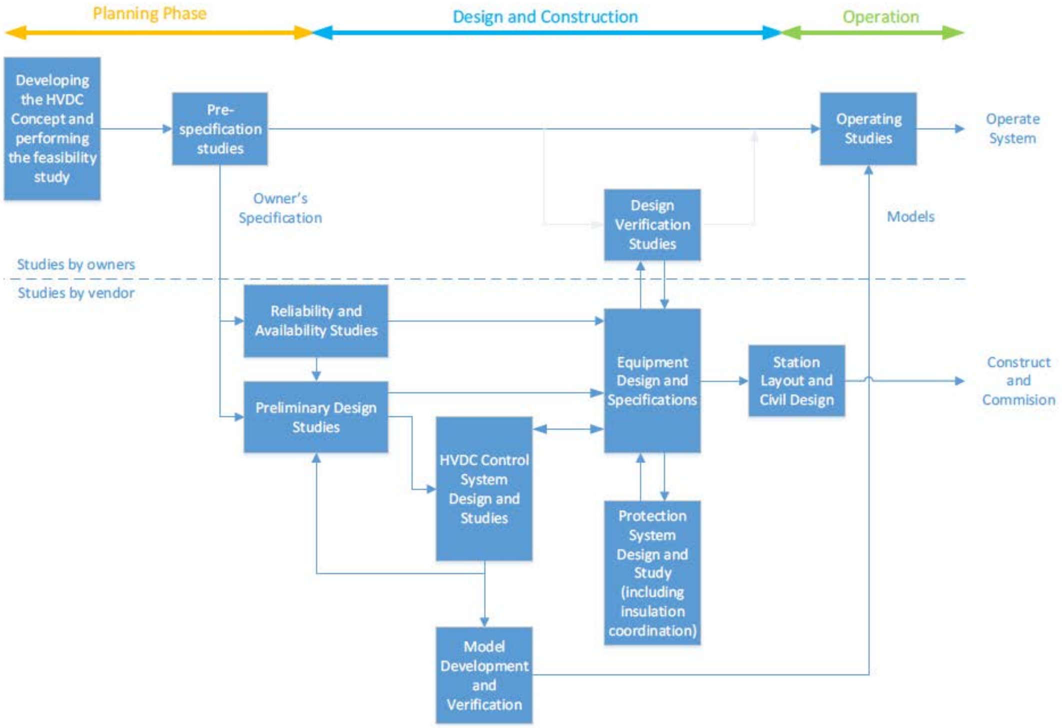

Figure 2-1
Range of studies done in the lifetime of a HVDC project [6]

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

Section 3: Technical Planning Considerations

Differences Between Onshore HVDC Links and HVDC Connected Offshore Wind

The most notable difference 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 turbine should be configured to output maximum power, unless this causes mechanical stresses, or power is being curtailed for reserve purposes. Figure 3-1 and Figure 3-2 illustrate the differences in the control structure between an onshore point to point HVDC system and an HVDC link connecting offshore wind.

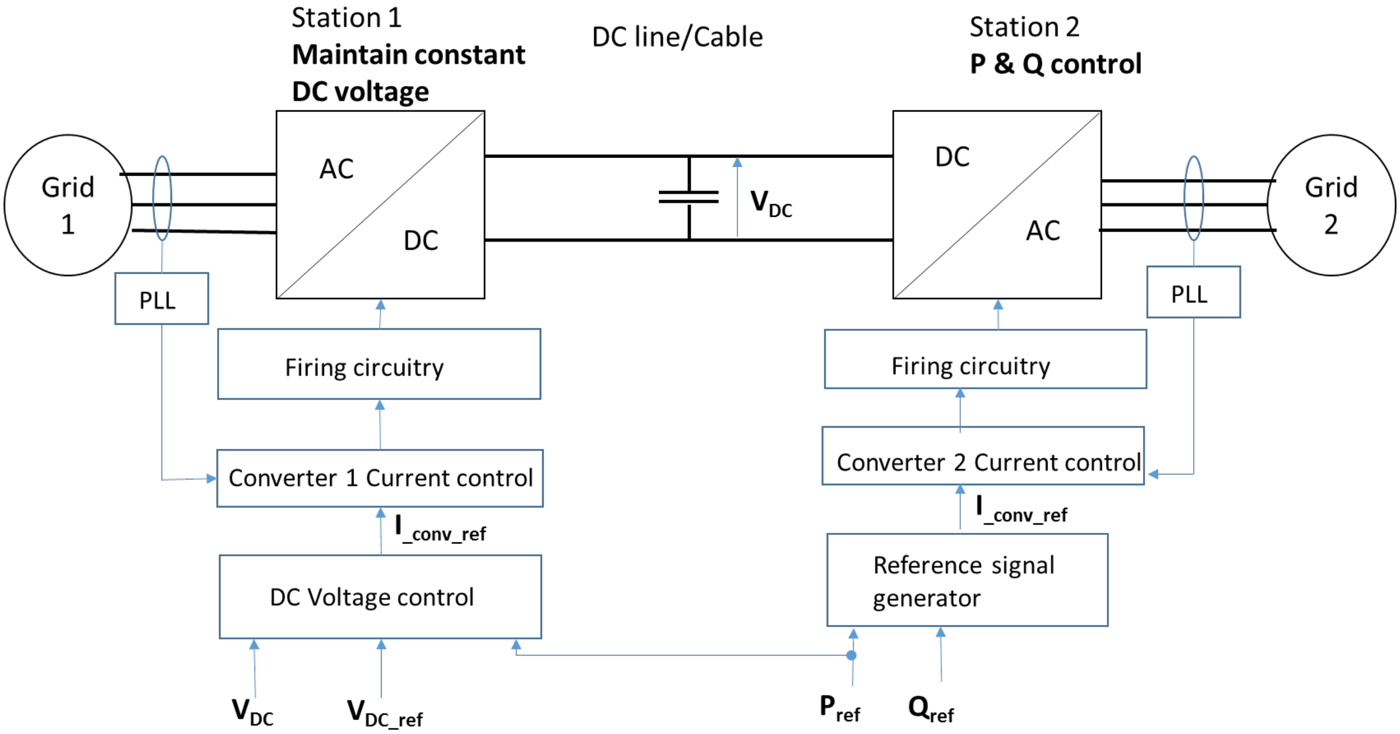

Figure 3-1
Control structure for HVDC point to point onshore connection

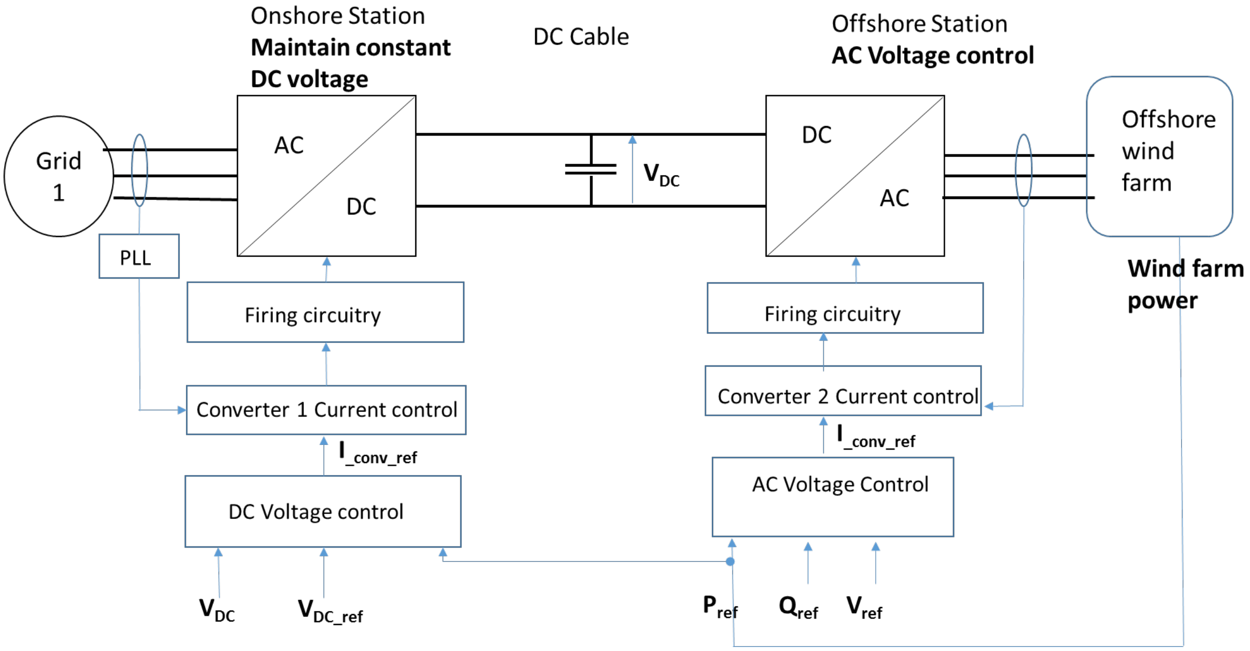

Figure 3-2
Control structure for point to point HVDC connecting an offshore wind farm

Technical Planning Considerations for Offshore Wind

1. **Feasibility including offshore resource assessment.** Initial feasibility studies include a power flow model to ensure the AC network is capable of receiving 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 [17] and ABB has presented a 525 kV XLPE DC cable [7].

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 farms.

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 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 [8] [9].

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, these require accurate 3 phase EMT simulations to capture control interactions [10]. 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.

The next section includes an example from an offshore wind farm in Germany and suggestions on how utilities can approach this problem in the planning stage.

Harmonic Resonance in BorWin1 Offshore Network

The first offshore wind farm connected with HVDC was BorWin1, a 400 MW wind farm, 125 km off the coast of Germany. The commissioning uncovered harmonic issues which caused substantial outages of the HVDC link [11].

Offshore grids are very different to onshore grids. The substitution of an overhead line (OHL) for a cable leads to much higher shunt capacitance values and much lower series inductance per unit length leading to lower resonant frequencies in the offshore network than an equivalent OHL. Since all the generation is power electronic based there is no rotating mass and therefore the resonant damping of synchronous generation is not available. In addition, there is little or no load offshore, and therefore little to no resistive damping for resonant frequencies.

In 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 commissioning in 2013 to 2015. The harmonic interactions between the converters were not uncovered in the planning, design or commissioning stages.

A number of solutions exist to ensure that resonance issues do not occur [12].

- Addition of resistive elements,
- Active damping,
- Tuning of converter controls.

The addition of resistive elements has the impact of damping resonance, however these elements can be costly and difficult to install offshore. Active damping can be installed in the control of the VSC, which can be used to damp harmonics across a specific frequency range. The most appropriate solution for reducing harmonic interaction between converters is tuning of the converter controls during planning to avoid issues. This requires adequate planning studies to identify possible interactions and tune converter controls appropriately.

Harmonic Interaction Studies

In planning for HVDC systems it may not be sufficient to only consider positive sequence models to determine harmonic frequencies for harmonic filter design [6,23]. Typically, for harmonic filter design, the first step is to develop appropriate 3-phase model for the surrounding network using data and network topology information from a positive-sequence system model [6]. In this approach, the positive-sequence model is used as a guide to identify the boundaries of the 3-phase model, as it will typically not be practical to model the entire network in 3-phase, and then specific lines/cables may need to be modeled in 3-phase using detailed frequency dependent models (e.g. using line geometry), while others can be modeled as distributed parameter lines.

The three phase model is typically built in an EMT software platform and such studies require detailed knowledge of specific vendor control systems and complete knowledge of the converter and network. Assuming the required data and expertise is available, the simulations required are extremely time consuming as details of the control system and Pulse Width Modulation (PWM) must be modelled at a very small time-step. It is likely that these harmonic stability studies will be performed by the vendor, due to the unavailability of detailed control system models. Thus, as outlined in [6], the most typical course of action is for the utility to assist in the development of a suitable 3-phase model of the AC network to be supplied to the vendor.

For the utility to analyze the system in less time, an analytical stability criterion may be used [13]. This method requires only knowledge of the frequency dependent impedance of the converter and the offshore grid.

As explained in [12] in the simple system in Figure 3-3, the current depends on the frequency dependent impedances of the load and the source.

$$I_1 = \frac{V_s(s)}{Z_s(s) + Z_1(s)} = \frac{V_s(s)}{Z_1(s)} \frac{1}{1 + \frac{Z_s(s)}{Z_1(s)}}$$

For this system to be stable by the Nyquist stability criterion, the magnitude of $|\frac{Z_s(s)}{Z_1(s)}|$ must be below 1 for all frequencies.

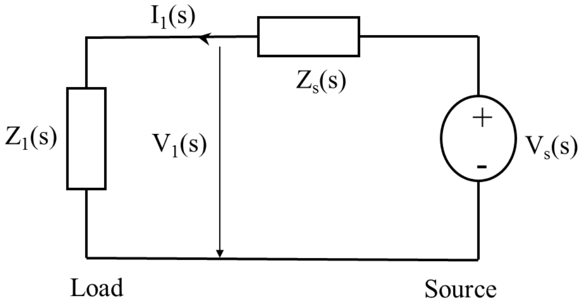

Figure 3-3
Source and load example for Nyquist stability criterion

In the case of a grid connected inverter the small signal representation is shown in Figure 3-4:

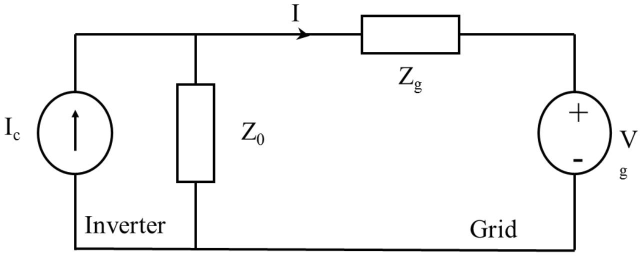

Figure 3-4
Small signal representation of an inverter-grid system

The output current of the inverter is

$$I = I_c(s) - \frac{V_g(s)}{Z_0(s) + Z_g(s)}$$

$$I = [I_c(s) - \frac{V_g(s)}{Z_0(s)}][\frac{1}{1+\frac{Z_g(s)}{Z_0(s)}}]$$

Similar to the simple example above, the system will be stable when $|\frac{Z_g(s)}{Z_0(s)}|$ satisfies the Nyquist criterion.

The Nyquist plots of the impedance ratio will give an illustrative system stability plot. Utilities could use this method to determine frequency ranges which cause issues, then request vendors to update and tune the control parameters to eliminate the harmonic interaction, and provide a new frequency dependent converter impedance model for further testing.

Development of Converter Control Specifications

It is important for utilities to understand the capability of voltage source converters and provide detailed control objectives to the vendor for application in the design of the VSC-HVDC link. These HVDC planning studies have the ability to uncover issues which may be solved by control of the HVDC converter. For example, the required reactive power capability of the VSC converters, etc. Thus, the utility can present the required performance of the HVDC terminals and other issues/concerns to the vendor. The vendor can then work with the utility to perform detailed EMT simulations to illustrate the capabilities of the converters meet the needs of the system.

As mentioned previously controls are key to mitigating issues with harmonic resonance, control interactions and other such problems. Different voltage source converter topologies and vendor types offer inherently different control capabilities. The topology may be a 2-level, 3-level or Modular Multilevel Converter (MMC). The MMC has increased controllability over the output of the VSC, coordinating the switching of each sub module to synthesize an AC output. The 2 and 3 level VSCs are the simpler and least expensive topologies. They require larger AC filters than the MMC which requires almost no AC filtering. Today's technology, from all the major vendors are leaning more towards the MMC type designs since MMC topologies have increased controllability and produce less harmonics. The control of both these converters has limitations with respect to bandwidth available for current control. In normal operation this is not an issue, but where harmonic resonances or control interactions exist, extra controls may be required on the 2-level and 3-level VSC to mitigate these issues.

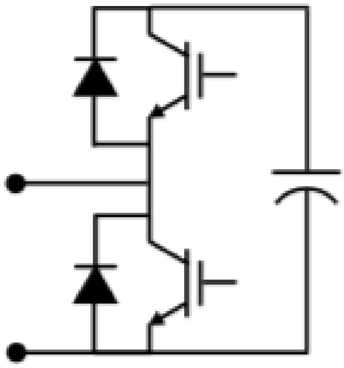

Figure 3-5
Half Bridge MMC

An overview of the different submodule types for MMC is given in the EPRI report on “Design and Operational Challenges of DC Grids and Requirements for DC Circuit Breakers and DC/DC Transformers” [15]. The main options are a half bridge topology with two switches in each submodule and a full bridge topology, with 4 switches in each submodule.

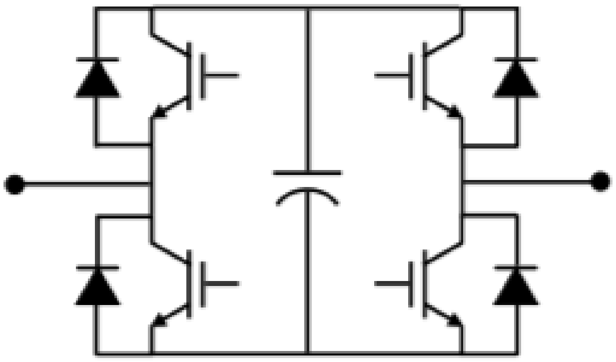

Figure 3-6
Full Bridge MMC

The full bridge option is more expensive and has lower efficiency than the half bridge option due to the extra switches, however it has advantages in terms of DC fault handling capability. A detailed description of the behavior of these topologies is available in [15]. In short, the full bridge MMC reverse capacitor voltage can block the fault current after a fault is detected. Since the half bridge cells are all connected in the positive direction, the reverse voltage does not exist to block the fault current.

Section 4: Renewable Integration with HVDC Case Study

Consider a 200 MW offshore wind farm which is 150 km from shore. A simple cost comparison for the transmission system comparing AC transmission and VSC HVDC transmission shows that the VSC HVDC solution is the most economical.

Figure 1-2 displays the transmission options for offshore wind. The LCC based solution is not a viable one due to the advantages that VSC transmission for HVDC has over LCC, in terms of commutation failures, ability to control AC voltage offshore and space required offshore. No LCC installations for offshore wind exist.

Comparison Between AC and DC Options

Figure 4-1 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 10 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 [19]. 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.

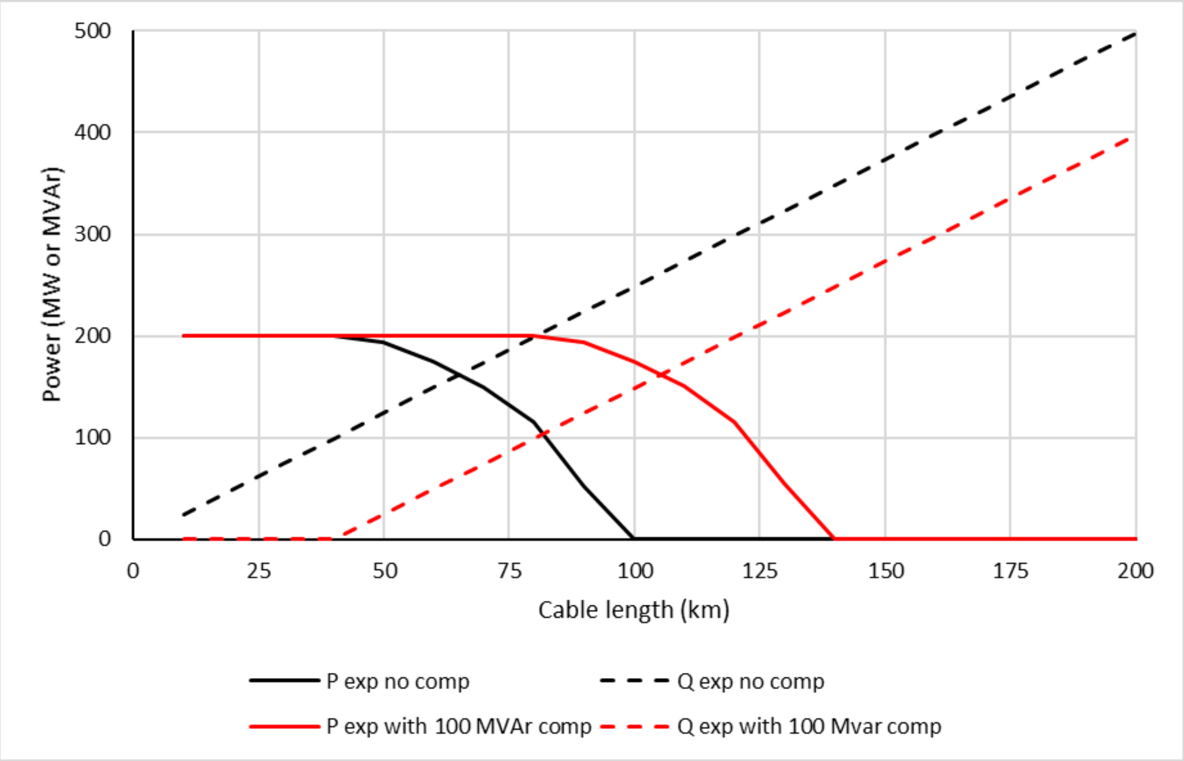

Figure 4-1
Active and reactive power exported to onshore grid for AC cable connected 200 MW offshore wind farm

Figure 4-2 displays the crossover distance between HVAC transmission and VSC - HVDC transmission in terms of capital costs. This information has been taken from recent research by Imperial College London [20], 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.

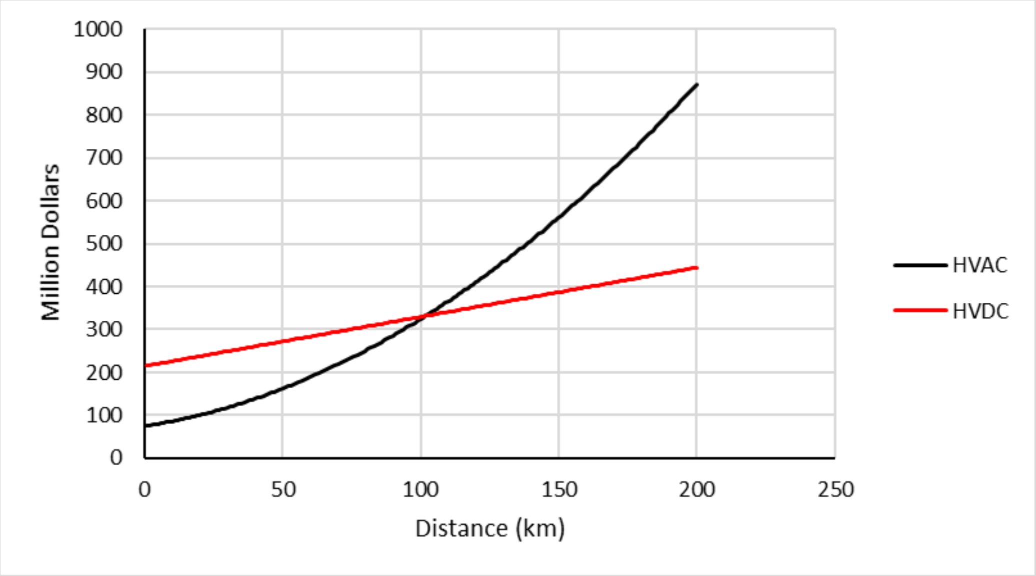

Figure 4-2
Cost of HVAC transmission and HVDC transmission for offshore wind

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 4-2 is obtained from [22]. 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 4-1 [21]. 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 4-3 shows the layout of the PSS/E power flow and Figure 4-4 displays the offshore wind farm area.

The choice of DC cable rating and voltage depends on the available cable sizes from vendors. Using XLPE 200 kV cables requires a current rating of at least 1000 A.

At the onshore point of connection up to 200 MW will be feeding in through the PCC (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 4-1
DC cable data

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

Table 4-2
33 kV collection AC cable data

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

The power flow dispatch when VSC HVDC transmitting 200 MW are displayed in Table 4-3.

Table 4-3
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 4-4 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. 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 at above 211 MVA.

Table 4-4
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. Since the power flow will always be from offshore to onshore, the offshore rectifier should be rated higher than the onshore inverter to compensate for the cable losses.

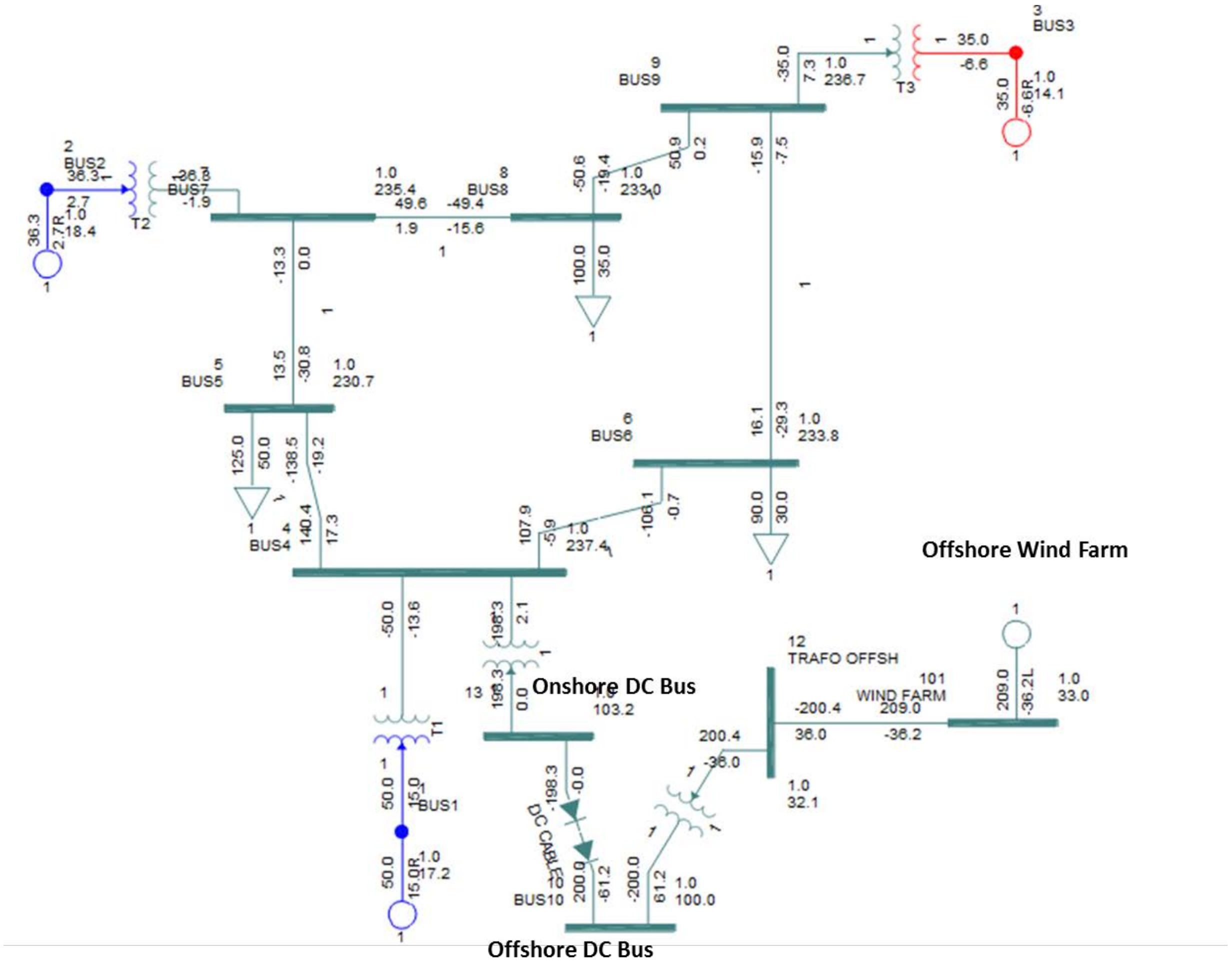

Figure 4-3
9 bus system with offshore wind farm connected via VSC-HVDC

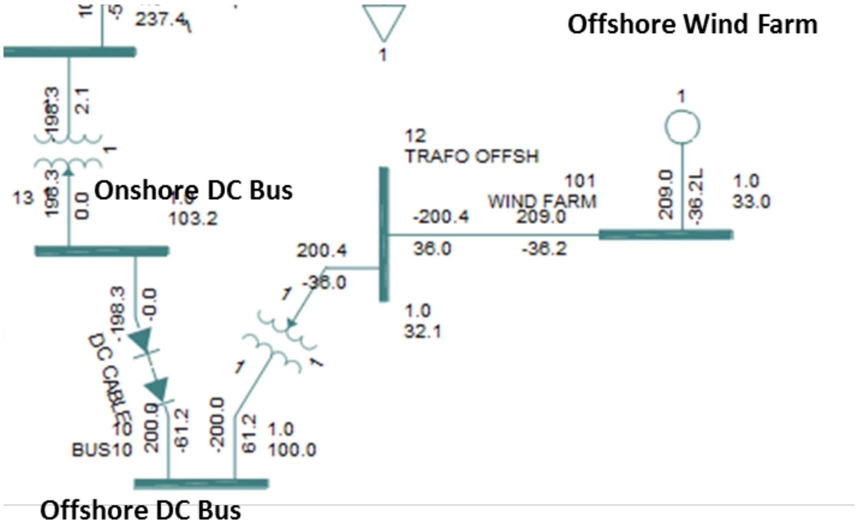

Figure 4-4
Zoomed in on Offshore wind farm

Section 5: Summary

HVDC planning is important for utilities to consider when planning future installations to the grid. This report has outlined some of the studies utilities should consider when implementing HVDC connected offshore wind farms. The report has outlined the reasons for selecting VSC HVDC for offshore wind, primarily because of the technological advantages over LCC based HVDC.

Chapter 2 describes high level pre planning decisions that need to be made by the utility in conjunction with the offshore wind farm developer, and the offshore transmission developer. Chapter 3 outlines 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 interaction. It is concluded that 3 phase planning models should be required to examine control and resonance interactions accurately.

Chapter 4 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.

Table 5-1 summarizes some of the studies which should be performed in the planning phase of designing offshore wind farms connected with HVDC.

Table 5-1
Studies to be performed in planning for HVDC connected offshore wind farms

Offshore Wind HVDC Planning	
Initial Feasibility Studies	**Study Type**
Offshore site resource assessment	Analytical
Onshore point of connection selection	Power flow models connecting at potential busses
Onshore AC system enhancement requirements	Power flow and dynamic model of AC system to determine if AC enhancements are required
Future offshore grid considerations	High level planning decisions, basic power flow models

Table 5-1 (continued)
Studies to be performed in planning for HVDC connected offshore wind farms

Offshore Wind HVDC Planning	
Techno-Economic Based Planning Studies	**Study Type**
Reliability of offshore resource	Reliability based study to determine extent of redundancy offshore - Standard is N-1 but for offshore this may not be desirable (Failure rates, Mean time to repair etc.)
Type of HVDC converter station	Techno-economic study comparing converter characteristics, costs, and environmental footprint
DC transmission voltage optimization	Limited by cable voltage, converter requirements, overall losses
Collection network (AC offshore grid) voltage selection	Limited by cable voltage, transformer size offshore, wind turbine transformers, collection network losses. Load flow/analytical loss study
Technical Planning Studies	**Study Type**
Wind Variability	Determine response of AC system to extreme variations of power/loss of HVDC infeed.
Reactive Power requirements	Power flow to determine reactive power support required offshore and onshore. Depends on converter characteristics and capability, offshore reactive power requirement and strength of onshore grid
Onshore frequency and Voltage support requirements	determination of requirements from offshore resources to provide ancillary services
Black Start Procedure	Possible to use offshore wind HVDC for black start - coordinated black start planning is necessary

Table 5-1 (continued)
Studies to be performed in planning for HVDC connected offshore wind farms

Offshore Wind HVDC Planning	
Stability Studies	**Study Type**
AC impedance scans	Determine resonant points both onshore and offshore
Onshore stability in steady state	Positive sequence stability as initial basis (only if connecting to strong grid), 3 phase stability analysis including converter controls and detailed switching models may be needed for weak grid connections.
Onshore stability during an event	Changing SCR at different wind penetration levels may affect stability, loss of generation/load nearby. Power flow and 3 phase modelling may be needed to sudy such scenarios in more detail
Offshore grid control interactions	Resonances, converter control interactions. Detailed 3 phase models should be used where available, with accurate control schemes represented to develop control interactions. Utilities can use an impedance based stability criteria assuming an accurate converter impedance is provided by the vendor

Section 6: References

1. P. Bresesti, W. L. Kling, R. L. Hendriks, and R. Vailati, "HVDC Connection of Offshore Wind Farms to the Transmission System," *IEEE Transactions on Energy Conversion*, vol. 22, no. 1, pp. 37-43, March 2007. doi: 10.1109/TEC.2006.889624.
2. CIGRE Technical Brochure 483, "Guidelines for the Design and Construction of AC Offshore Substations for Wind Power Plants," December 2011.
3. J. Ruddy, R. Meere, and T. O'Donnell, "Low Frequency AC transmission for offshore wind power: A review," Renewable and Sustainable Energy Reviews, Volume 56, April 2016, Pages 75-86, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2015.11.033.
4. P. Menke, R. Zurowski, T. Christ, S. Seman, G. Giering, T. Hammer, W. Zink, F. Hacker, D. Imamovic, J. Thisted, P. Brogan, and N. Goldenbaum, "Breakthrough in DC grid access technology for large scale offshore wind farms," *EWEA Offshore,* 2015.
5. K.R.W. Bell, L. Xu, and T. Houghton, "Considerations in design of an offshore network," *Cigre Science & Engineering, Innovation in the Power Industry,* 2015.
6. "HVDC Planning Guide," EPRI, Palo Alto, California. Product ID 3002005600, December 2015.
7. ABB Group, "525 kV extruded HVDC cable system: Doubling power transmission over longer distances." https://library.e.abb.com/public/db10262e14b5414099c9ca721964adb1/150909_525kV%20broschure%20(v%209).pdf
8. T. Midtsund, A. Becker, J. Karlsson, and K. A. Egeland, "A Live Black-start Capability test of a Voltage Source HVDC Converter," CIGRE Science & Engineering, No 4 February 2016.
9. N. Macleod, N. Cowton, and J. Egan, "System restoration using the "black" start capability of the 500 MW EIRGRID East- West VSC-HVDC interconnector," *IET International Conference on Resilience of Transmission and Distribution Networks (RTDN) 2015*, Birmingham, 2015, pp. 1-5.
10. CIGRE Technical Brochure 671, "Connection of wind farms to weak AC networks," December 2016.
11. [Online]. Available: www.4coffshore.com/windfarms/offshore-converter-events-borwin1-converter-cid1.html.
12. C. Buchhagen, C. Rauscher, A. Menze, and J. Jung, "BorWin1 - First Experiences with harmonic interactions in converter dominated grids," *International ETG Congress 2015; Die Energiewende - Blueprints for the new energy age*, Bonn, Germany, 2015, pp. 1-7.
13. J. Sun, "Impedance - Based Stability Criterion for Grid-Connected Inverters," *IEEE Transactions on Power Electronics,* vol. 26, no. 11, 2011.
14. CIGRE Technical Report 619, "HVDC Connection of Offshore Wind," May 2015.
15. "Design and Operational Challenges of DC Grids and Requirements for DC Circuit Breakers and DC/DC Transformers," EPRI, Palo Alto, California, Product ID 3002007635, November 2016.
16. Y. Murata, M. Sakamaki, K. Abe, Y. Inoue, S. Mashio, S. Kashiyama, O. Matsunaga, T. Igi, M. Watanabe, S. Asai, and S. Katakai "Development of High Voltage DC-XLPE Cable System," SEI Tech. Rev. 2013, Pages 55–62.
17. D. Elliott, K. R. W. Bell, S. J. Finney, R. Adapa, C. Borozio, J. Yu, and K. Hussain, "A Comparison of AC and HVDC Options for the Connection of Offshore Wind Generation in Great Britain," *IEEE Transactions on Power Delivery*, vol. 31, no. 2, pp. 798-809, April 2016.
18. X. Xiang, M. M. C. Merlin, and T. C. Green "Cost Analysis and Comparison of HVAC, LFAC and HVDC for Offshore Wind Power Connection," *AC and DC Power Transmission (ACDC 2016), 12th IET International Conference on*. IET, 2016.

19. N. Barberis Negra, J. Todorovic, and T. Ackermann, "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms," *Electric power systems research* 76.11 (2006): Pages 916-927.

20. R. Meere, J. Ruddy, and T. O'Donnell ,"Variable Frequency Operation for Future Offshore Wind Farm Design: A Comparison with Conventional Wind Turbines," *Energy Procedia* 53 (2014): Pages 280-289.

21. "Wide-Area Transmission Grid Harmonics Studies," EPRI, Palo Alto, California, Product ID 3002008361, December 2016.

22. NYSERDA Report 17-25 "New York State Offshore Wind Master Plan, Charting a Course to 2400 Megawatts of Offshore Wind Energy" [Online], Available: https://www.nyserda.ny.gov/-/media/Files/Publications/Research/Biomass-Solar-Wind/Master-Plan/Offshore-Wind-Master-Plan.pdf

23. [online] Available: http://nj.gov/governor/news/news/562018/approved/20180131a_eo.shtml

Export Control Restrictions

Access to and use of this EPRI product is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or U.S. permanent resident is permitted access under applicable U.S. and foreign export laws and regulations.

In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI product, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI products, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes.

Your obligations regarding U.S. export control requirements apply during and after you and your company's engagement with EPRI. To be clear, the obligations continue after your retirement or other departure from your company, and include any knowledge retained after gaining access to EPRI products.

You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of this EPRI product hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

3002013674

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com