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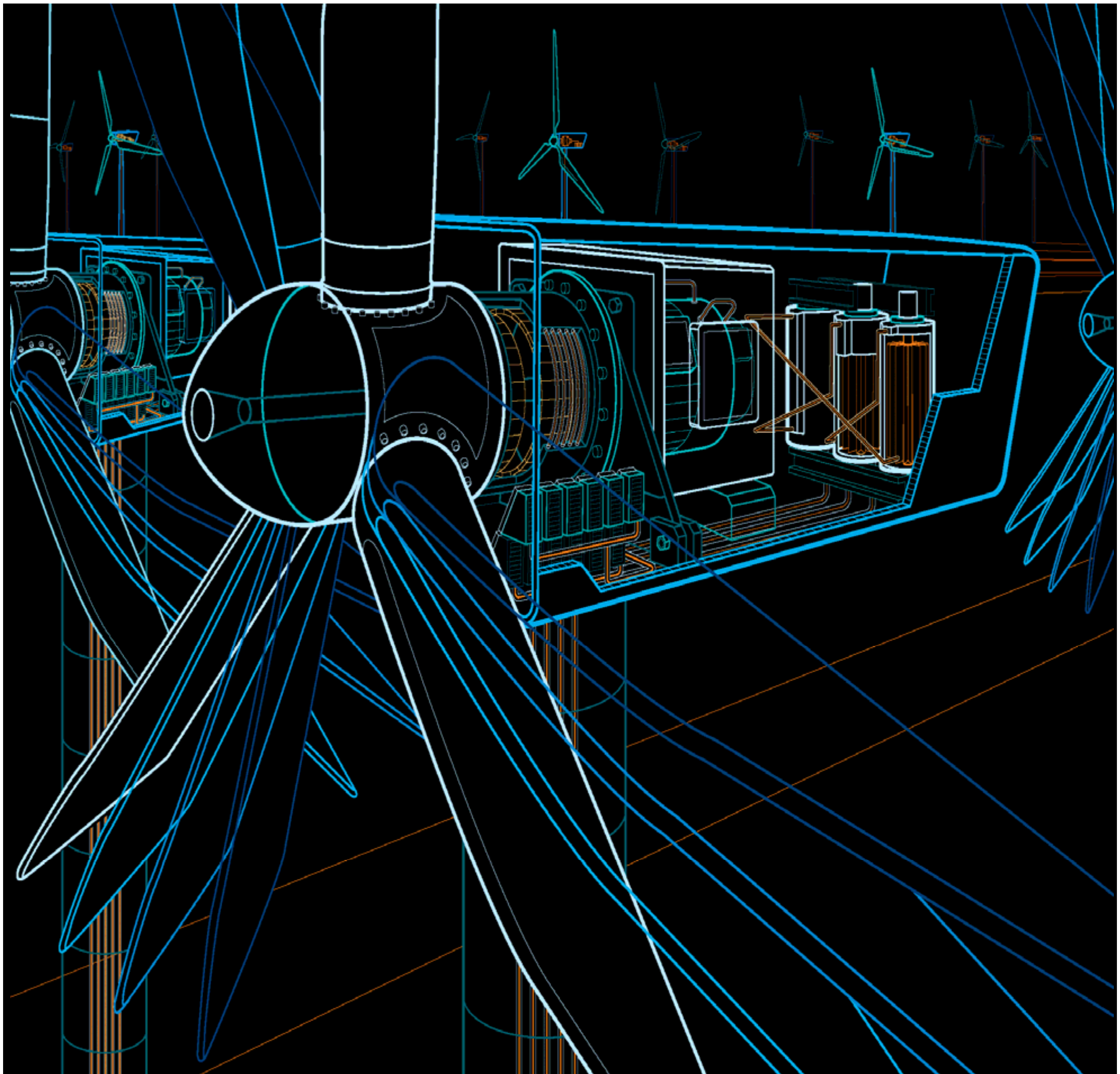

DOMINION VIRGINIA POWER
Offshore Wind Interconnection Study

2011-E7406-1 R1

Technical Report

Summary Report

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Summary Report

Introduction

ABB has been requested by Dominion Virginia Power to determine the feasibility of designing, constructing, operating, and maintaining submarine cable based interconnection facilities for offshore wind resources along the Atlantic coast so that electric power generation from offshore wind farms can be developed and used by Dominion customers. This report is a follow-up to Dominion's onshore connection study. The report for Dominion's onshore study can be found at http://www.dmme.virginia.gov/DE/VOWDA/DominionOffShoreWindStudyReport.pdf

The layout for the offshore area identified for wind development is shown in ***Figure S-1***. The total size of the offshore area is approximately 700 sq. km. (35 km x 20 km). An estimate of up to 3,000 MW of power has been proposed in this offshore area. The distance between the closest shore area and the beginning of the offshore area is approximately 45 km (28 miles). The offshore generated power is assumed to be interconnected to the Dominion power system at stations that are up to 15 km (9 miles) inshore from the coast.

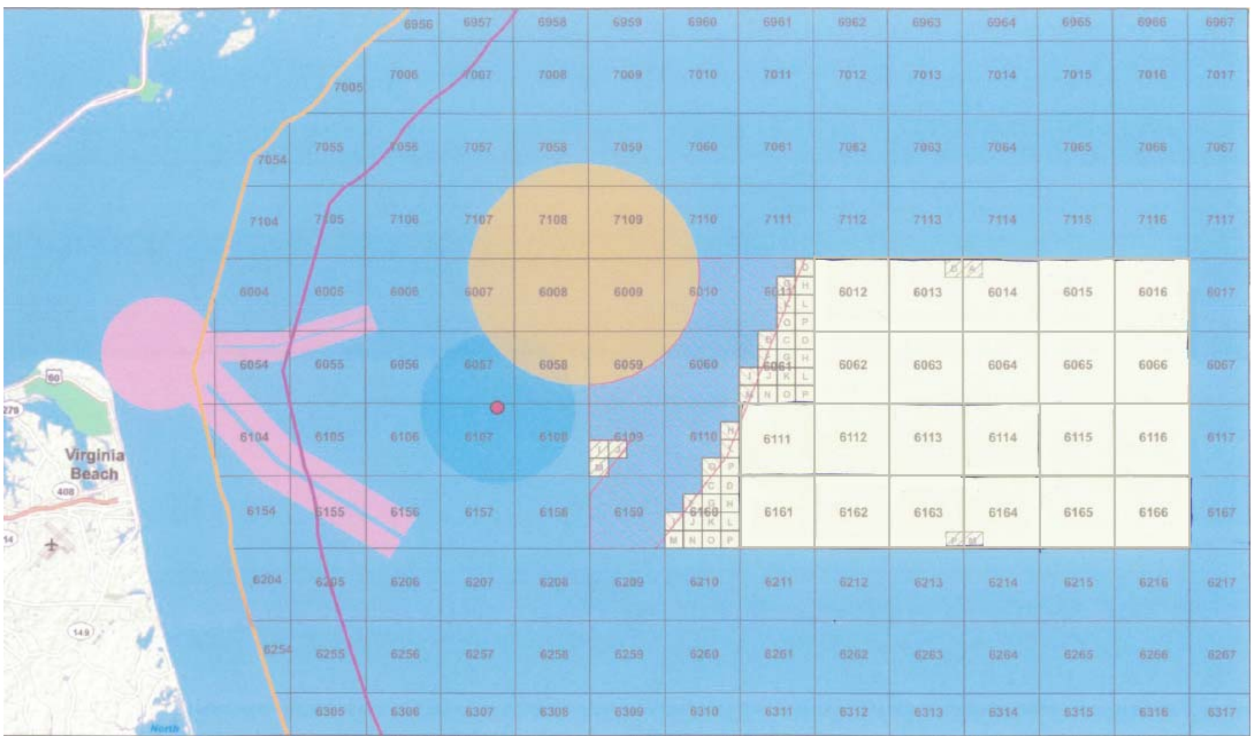

Figure S-1: Offshore wind area layout for Dominion Virginia Power

There are two types of cable system that have been used for submarine connections to offshore wind generation. Both AC and DC cable systems have been used for offshore wind connections to onshore. All cables have much higher capacitance than overhead lines. The high capacitance is due to the small distance from the energized conductor in the middle of the cable to the metallic sheath on the outer edge of the insulating medium. This makes a cable very similar to a capacitor. The longer the cable is the more total capacitance in the cable.

For AC cables, the alternating voltage results in capacitive current flowing into the cable to charge the cable alternating from positive to negative voltage. The longer the cable the more capacitive current or "charging current" in the cable. At longer distances, the charging current will use the entire current capability of the cable just to carry this charging current. Therefore, there are limits to the distance that AC submarine cables can be used.

DC cables have a constant voltage and only experience the charging current in the first few milliseconds that the cable is energized. This leaves the entire current capability of the cable to transmit power. DC cable systems have no limit on distance; however, they are generally not as practical at shorter distances because of the additional costs of the converter stations, one which must be mounted on a platform. The following section gives more details on these alternatives.

System Alternatives

The wind power generated offshore can be transported to the shore using both AC and DC cables. The performance characteristics and feasibility of both HVDC and AC transmission for the Virginia interconnection facilities are reviewed in this report for completeness. However, based on the characteristics and location of the Virginia offshore wind resources, AC transmission is a more economical and, therefore, the recommended alternative.

AC System

Possible AC export cable ratings considered to connect the offshore system to the onshore system are:

- 550-kV cable
- 345-kV cable
- 230-kV cable
- 115-kV cable

Higher cable voltages result in higher charging currents, which in turn result in more capacitive reactive power generated by the cable system. The charging current also increases with the length of the cable system. Due to the high level of charging current for 550-kV cables and the required length of the offshore interconnection system, the 550-kV export cable option is not practical for the Virginia interconnection facilities.

Another consideration for choosing an appropriate voltage rating is the number of cables that will need to be laid in parallel underwater. For export submarine cables, about half of the construction cost is typically in the freight and installation. If 115-kV cable circuits are used for this project, it will require sixteen cable circuits to transport 2.6 GW of this wind generation. If either 230-kV cables or 345-kV cables are used, eight circuits will be sufficient and the 230-kV cable was optimized for about 325 MW of power which results in the capability to transmit 2,600 MW with eight cables. More cables and platforms can be built to accommodate additional power if more wind generation is installed. The cost of 115-kV cable is not significantly cheaper than 230-kV cable, but the additional circuits will increase the cost of the 115-kV cable option well above the cost of the 230-kV option; therefore, the 115-kV cable option is not as economically feasible as 230-kV.

Comparison between the 230-kV and 345-kV cable alternatives

A more detailed look at the comparison between 230-kV cables and 345-kV cables:

- The 345-kV cable will have approximately 36% higher charging current than a 230-kV cable of the same length. (That is, approximately 393 MVAr versus 283 MVAr for the length of the Virginia system)
- The 345-kV cable option will require eight circuits totally, the same number as for the 230-kV cable option.
- The onshore station has 230-kV as an existing voltage. If 345-kV cable is used, transformers will be required to connect the offshore area to the onshore system.
- Another consideration in choosing a cable is the number of cables that will need to be laid underwater. If three single phase cables are installed as opposed to one tri-core cable, then the installation cost of the three single core cables will be almost two to three times higher than the one tri-core cable. The installation costs make tri-core cable the economical choice to consider. Both 345-kV and 230-kV cables are available as tri-core cables.

Based on the above considerations, the tri-core, 230-kV cable option appears to be the optimum cable design for the Virginia project.

For this study, the offshore area is divided into zones with one platform in each zone. Each platform is assumed to house one 34.5/230 kV wind farm collector system. With more platforms, there is more flexibility to phase the equipment installation. If the design was limited to fewer platforms, there would be less opportunity to phase the installation of the equipment. Even more important are the technical challenges with fewer platforms. The impact of having just one platform in the offshore area is listed below.

Impact of the One Platform Concept

- The length of some of the 34.5-kV collector system cables would exceed 25 km to reach the farthest wind turbines.
- The single platform would need to bring seventy-two 34.5-kV feeders and eight 230-kV cables onto the platform. Finding space to lay all of these cables and bringing them up to the platform would be very challenging even if it were possible.
- If an event on the platform were to shut down the platform, up to 2,600 MW of generation could be lost during one disturbance.
- If the one platform was built and only part of the wind generation was installed, the platform could be considerably overbuilt for the offshore wind generation.

Based on providing a reasonable design that is technically feasible, the proposed solution is to divide the wind farm area into four zones with a central substation platform for the collection system in each zone. Each platform will have eighteen 34.5-kV feeders connected to it. This general arrangement will allow the collector system to use 34.5-kV submarine cables with reasonable lengths. It is proposed that two 230-kV export cable circuits will be used to connect each substation platform to the onshore Dominion power system. This proposed arrangement is illustrated in ***Figure S-2***.

Each zone represents one phase of construction. When a platform is built and installed, all of the offshore substation equipment needed for the development of that project phase must be installed with the platform. Each project phase will involve completing one platform entirely. Other platforms can be developed as needed.

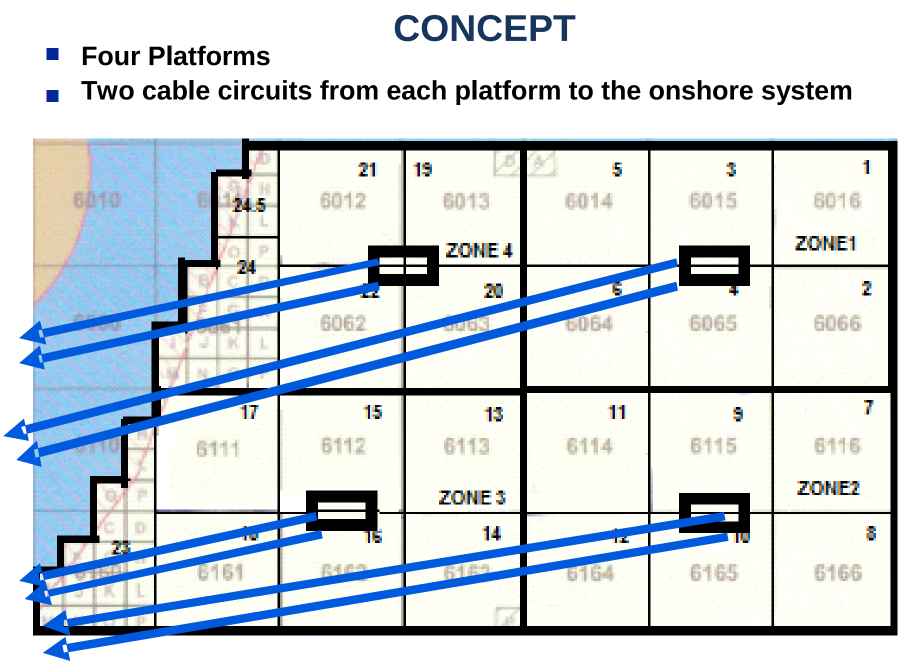

Figure S-2: Proposed Wind farm Zones

HVDC System

HVDC Light® is ABB's trade name for the voltage source converter technology. HVDC Light® systems have the ability to operate well with weak AC systems (low short circuit levels) and to provide black start support to the power grid.

Voltage source converter based HVDC (HVDC Light®) for this application is commercially available for circuit capacity ratings up to around 1,100MW using two cables, one +320 kV and one - 320 kV. ***Figure S-3*** shows the concept with three HVDC circuits with a combined capacity to transmit up to 3,000 MW from the offshore wind farms.

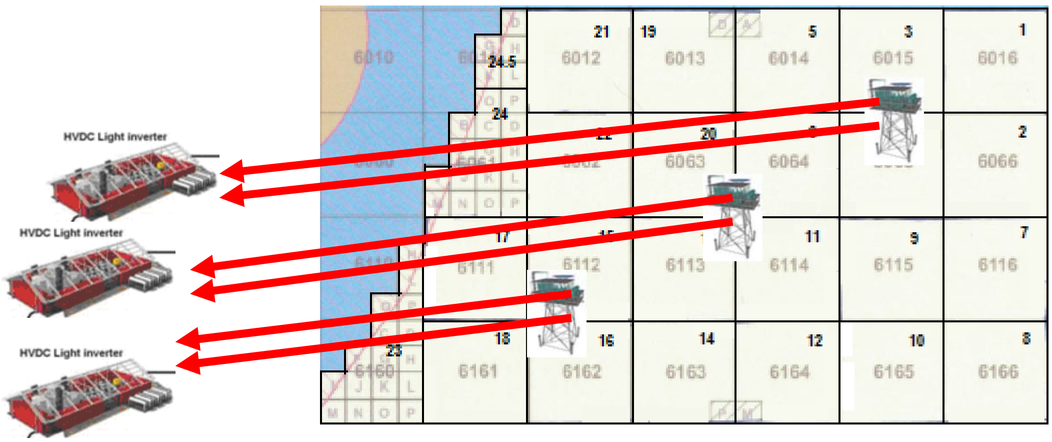

Figure S-3: HVDC Light Concept

The offshore wind interconnection point will require a platform to mount the HVDC Light® converter and AC cable collection station. ***Figure S-4*** shows the overall concept for HVDC based offshore wind interconnection.

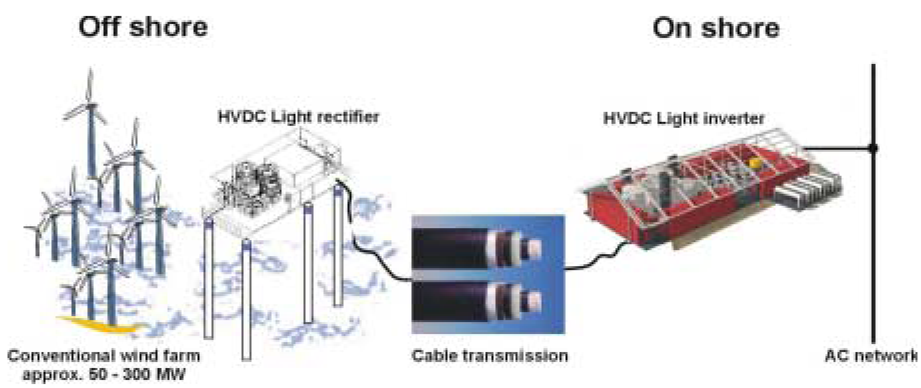

Figure S-4: Off-Shore HVDC LIGHT® Concept

Figure S-4: Multi-story converter designs for platform applications.

If an HVDC system was developed, the collector system would still be an AC system. The offshore wind would be collected using cable feeders at 34.5-kV or an equivalent voltage and would be brought to the platform and connected to an AC bus. The voltage would be stepped up to 138 kV, 230 kV or any other appropriate voltage and connected to the HVDC converter via AC transmission cables. The converter will be connected to the shore using DC cables. Both the AC and HVDC Light® equipment would be designed to be compact and as light weight as technically and economically feasible. A single line diagram for the HCDC Light® system is shown in ***Figure S-5.***

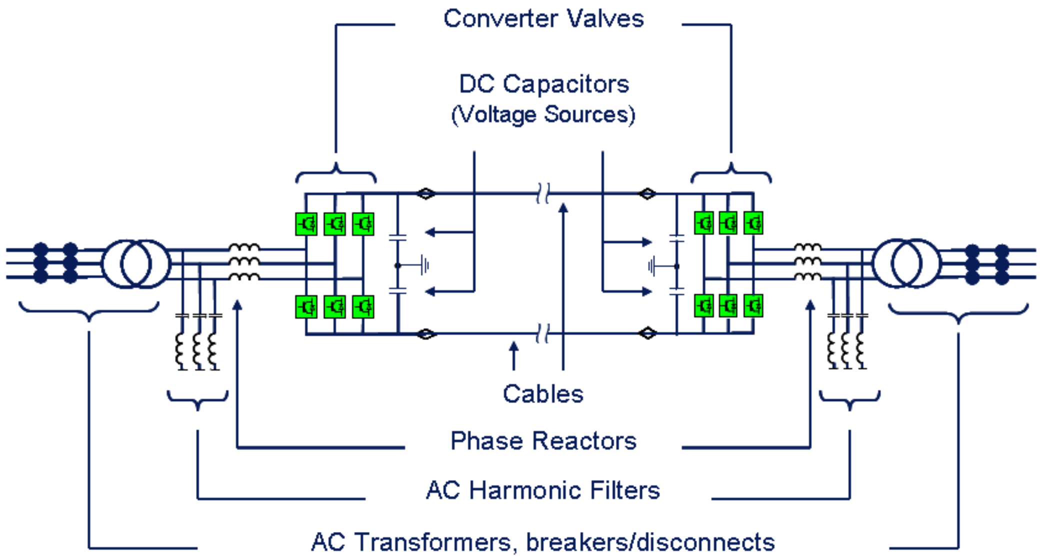

Figure S-5: Simplified Single-line Diagram for HVDC Light®

As shown in the figure above, an HVDC Light® system consist of two cables; one with a positive voltage and one with a negative voltage. Both cables are operated together as one circuit. There is no stray dc current or emergency earth return operation.

HVDC Light® becomes the preferred option to transmit offshore wind power when the distances become too long for AC cables to be feasible. For example, the 230-kV AC cable produces 9.4 amps of charging current per kilometer. The current rating of the cable to the farthest platform is 876 amps. A cable about 90 km long would use the entire ampacity rating of the cable for charging current. This limits the practical distance for AC cable transmission.

Although an HVDC Light® alternative requires only 6 export cables to be laid instead of 8 cables for the 230-kV AC alternative, there are significant additional costs in the offshore and onshore converter stations. There will be one converter station at each end of the three circuits and the offshore converter must be completely installed on a platform. For shorter distances where AC cables are feasible, the converter costs of HVDC Light® systems generally make the HVDC offshore option significantly more expensive than an AC option. Therefore, since the Virginia offshore zones are relatively close to the shore and feasible to interconnect with 230-kV AC export cables, HVDC is not an economical option for radial connection of the offshore wind farms to Dominion's onshore substations, which are located relatively close to the coast.

Note that HVDC Light® could become a feasible option if the Virginia system was to be networked to other offshore wind systems. HVDC would permit long cables and also control of the power flow. Such power flow control would be needed if low impedance offshore cables were paralleled with higher impedance onshore overhead lines and would permit the system operator to appropriately balance power transfer over the cables and the onshore overhead lines.

Offshore collector system modeling

Figure S-6 shows the anticipated basic feeder configuration for the offshore collection system. The following assumptions were used for the development of the system:

- Each zone is divided into a number of smaller areas with dimensions approximately 5 km x 5 km each.
- Each wind turbine generator (WTG) is assumed to be rated 6 MW at 0.95 pf (±1.972 MVAr). It is assumed that the WTG has the capability to supply/absorb all of the ±1.972 MVAr when generating different levels of power.
- Each WTG is assumed to have a 0.69/34.5-kV, 8.33 MVA, 11% impedance transformer to transform the generator voltages to the 34.5-kV level.
- Every six wind turbine generators in each area form **one collector circuit** (36 MW, ± 11.8 MVAr capacity). This lumped output of the six generators is connected to the collector system using a 3 x 1750 kcmil cable with 42 MVA capacity at 34.5-kV.
- Collector systems in each zone are assumed to be connected to a **maximum of 18 circuits.**
- As seen in ***Figure S-6***, the output of every three generators is collected by one cable in each circuit. Hence, each such cable carries up to 18 MW. A 3 x 250 kcmil cable with 20 MVA capacity at 34.5-kV is used to interconnect the WTGs.

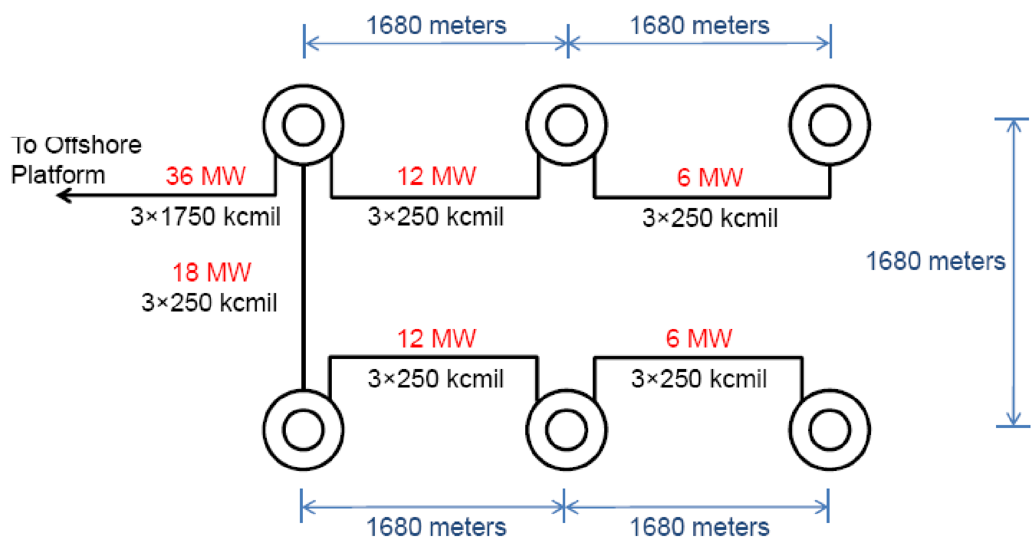

Figure S-6: Off-Shore Feeder Concept

Steady state simulation results

Capacitance of underground/submarine cables is typically much higher per mile than that of overhead transmission lines because in overhead lines, the capacitance is between phases and between each phase and earth, while in cables the capacitance is between each phase conductor and its shield. Capacitance causes charging currents to flow through the cable. As the cable length increases, more charging current is generated by the cable as capacitance is distributed along the cable. Capacitive charging current also increases with the voltage. Thus, along with the load current, the cable also has to carry charging current. This puts a voltage and length dependent limit on the load carrying capability of an AC cable circuit.

Steady-state powerflow simulations were run under different generation conditions to evaluate the loading on the cables. For different generation conditions, the cable loading and the amount of reactive power to be absorbed at the shore end to maintain 1 p.u. at the onshore end are shown in the table below:

CASE	WTG V_{term} (p.u.)	MVAr absorbed onshore	Line loading	Highest voltage at 230-kV side of platforms (p.u.)
All generators disconnected	N.A.	2,544.20	Uneven; cables heavily loaded at shore end with reactive power.	1.0386
Maximum generation	1	1,171.60	Almost even split of reactive power to shore and platform; cables heavily loaded.	1.0260
	0.95	1,030.40		1.0230
Zero generation	1	2,099.50	Uneven; medium loading on cables.	1.0260
	0.95	1,620.50		1.0140

From the above table, it can seen that if the WTG terminal voltage is lowered to 0.95 p.u. from 1 p.u., the reactive power to be absorbed at the shore end reduces as more reactive power is now absorbed by the WTGs. The voltages at the 230-kV platform end are seen to lie within limits even in the case with all generators disconnected. On an open ended cable, the charging current can cause the voltage at the open end to rise due to Ferranti effect.

Conclusions and Recommendations

- The proposed concept with four (4) offshore substation platforms and two 230-kV cables per platform can be developed in phases with each substation platform and associated collection and export cables representing one phase of 648 MW.
- When a platform is built and installed, all of the equipment needed for the total development should be installed with the platform. There is no easy or economical way to add substation equipment to the platform at a later time. This limits the development phase to completing one platform at a time as needed. Submarine cables are then added to the platform as the development of the wind farms in the associated wind zone progresses.
- Since the Ferranti effect which raises the voltage on an open-ended circuit is low for 3-core submarine cables (the circuit inductance is low because of the close proximity of the conductors), the study results demonstrated that all of the shunt reactors needed to absorb the cable charging can be put on shore. This will reduce the weight and therefore the cost of the offshore substation platforms.
- In the maximum generation cases, the reactive power absorbed onshore can be reduced by lowering the terminal voltage of the WTG.
- Steady-state simulations show that with the 230-kV cable open-ended, the maximum voltage on the offshore platform system due to Ferranti effect goes up to 1.044 p.u. on the 34.5-kV collector system.

- Under maximum generation conditions, the MVA loading on the cables was high but it was within limits. The generators are absorbing reactive power at or close to their reactive power limit. The wind turbine units help to absorb the reactive power generated by the cables under all generation conditions unless they're disconnected. The onshore system would need to absorb the remaining MVAr generated by the cables. If the onshore system doesn't have the capability of absorbing the MVAr, reactors will need to be connected to the system.

Cost Estimate for Recommended 230-kV AC System

The preliminary construction cost for the 230-kV AC interconnection system was estimated for each platform. The indicative estimate for one 648 MW platform system is as follows:

I. Offshore platform (topside and offshore substation) -- $250 million
II. 230-kV cable system, 2×72 km – $389 million
III. 230-kV onshore variable shunt reactors (2 x 300 MVARs) including installation, -- $9 million
IV. Two three-breaker bays in a breaker and a half scheme to terminate two cables and two shunt reactors -- $ 4 million

Thus, the total indicative estimate for one 648 MW platform and 230-kV cable installation is $652 million.

Note: The above indicative estimate is for planning, conceptual engineering and study purposes only and neither the data, its associated commercial terms nor any past or future action, course of conduct or failure to act by either ABB or Dominion Virginia Power (the "Parties") regarding the proposed offshore wind integration project will give rise to or serve as a basis for any obligation or other liability on the part of the Parties or any of their affiliates. Neither Party shall be obligated to enter into any further agreement with the other Party. Any commitment, agreement or binding obligation with respect to the proposed offshore wind integration project would only arise and would be subject to, among other things, the negotiation, due execution and delivery by the Parties of a Definitive Agreement regarding the project.

Typical Schedule for Offshore Installations

The typical time to complete an offshore project with a platform and cables is shown in Figure S-7 on the next page. Prior to the start of Project Execution there will be some period of developing some conceptual and preliminary designs to help define the project and project requirements. This preliminary work leads up to the award of the project. The manufacturing schedule of the cable will depend on the total length of cable to be provided and the factory loading. If several platforms are done simultaneously this could affect the schedule. It might take longer to manufacture the cable, but all of the cable can be transported and laid at one time.

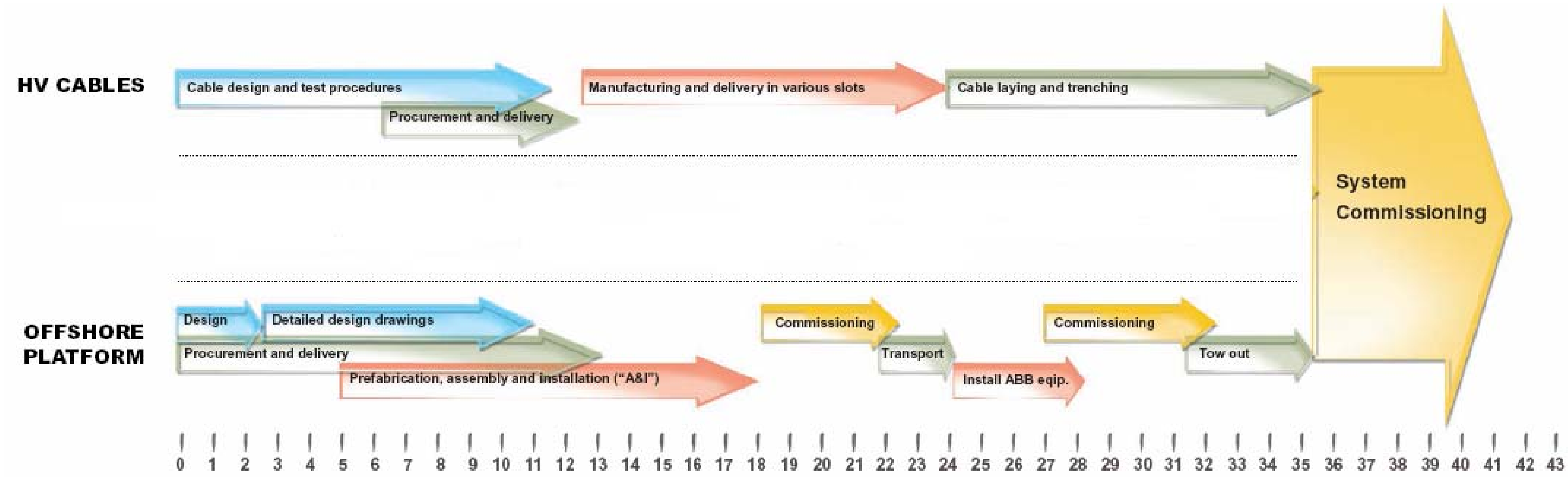

Figure S-7 - Typical Schedule in Months for Offshore System