WHITE PAPER

U.S. offshore wind: key considerations for reliable interconnection

Challenges and opportunities of interconnecting offshore wind power in the U.S.

Wind generation is already a favored and extensively used alternative-energy source in the U.S., but opportunities to fully utilize the potential of onshore wind resources in North America are hampered by the large geographical distances between favorable mid-western wind resources and the large population centers near the east and west coasts where much of the nation's electrical load is located.

Enter offshore wind generation. Although U.S. offshore wind projects are in their infancy compared with developments outside North America, energy firms are increasingly evaluating the potential of the offshore wind market. Key motives for the growing interest in offshore opportunities are clear:

- Offshore wind resources are more favorable than onshore with higher wind power density and generally higher wind speeds.
- Offshore wind resources are less intermittent compare to on land, resulting in higher energy generation levels per amount of installed capacity.
- Onshore wind farm development locations are limited near the major coastal population centers.

Of course, offshore wind generation is not without its challenges, especially regarding interconnection to the electrical transmission grid. The existing U.S. transmission system was developed based on large, centralized fossil-fuel and nuclear-based power stations, which are typically located away from the coast. The load centers near the coast are at the edges of the existing transmission grid and there are few existing substations that are capable of accepting power from major new offshore generation facilities for transmission to the loads. This means that the interconnection and integration of large new offshore facilities into the existing grid is one of the more critical aspects of the future success of offshore wind.

To reduce the risks associated with the interconnection of wind rich offshore areas, some key system and technology considerations must be assessed in order to ensure the most economic and reliable outcome. These include:

- **Power transmission type,** meaning high voltage AC or high voltage DC (HVDC).
- **Offshore substation systems,** including options such as Gas Insulated Switchgear (GIS), HVDC voltage source converters (VSC), and transformers.
- **Onshore substation systems,** such as air insulated switchgear (AIS) vs GIS.
- **Power Quality systems,** including HVDC VSC, shunt reactors, STATCOMs, SVCs, synchronous condensers, and hybrid solutions.
- **Protection & Control systems** such as SCADA, control and protection systems, and cyber security.

These issues are each discussed on the following pages.

Offshore and onshore substation systems

Understanding offshore substation systems
The offshore wind generated power is first collected at an offshore transformer substation, making it the heart of the wind farm and serving as a gathering point for the energy coming from any number of wind turbines. From this collector substation, the power is transmitted to shore via submarine cables where it may transition to either underground cables or overhead transmission lines to carry the power to the final interconnection point on the electric transmission grid.

Critical objectives at the early stage of project development are to select the optimal technology to make this interconnection of the planned offshore wind facility to the grid and to ensure that the power can be reliably delivered to the loads. Two options are available for the transmission system – AC and HVDC. AC transmission is often the economical solution for offshore wind facilities that are reasonably close to the final interconnection point (e.g. less than 30 to 50 miles). However, the cables generate reactive charging currents that use up a portion of the cable capacity needed to transmit the wind generated power. Longer cables use up more capacity with charging currents.

HVDC is a feasible alternative for wind facilities located far off the coast or when appropriate interconnection points to the onshore grid do not exist near the landing site of the submarine cables. The HVDC cable capacity is not used up by charging currents and is fully available for transmission of the offshore wind power.

Once the cables come onshore, the power must be transmitted to the interconnection point on the grid. If AC transmission is being used, this can be accomplished via underground cable or overhead line. Both will face right-of-way and permitting concerns and will likely face community opposition. Underground cables have low visual impact, but face the same charging current issue as the submarine cables. Overhead lines are generally faster to install and less expensive, but they have a high visual impact along their corridor and tend to face more opposition. If an HVDC technology is selected for the wind farm, the HVDC-to-AC converter station must be sited. If an appropriate converter location is available near the shore, AC transmission from the converter to the point of interconnection can be considered. Otherwise, the converter station will be located closer to the interconnection point and the power will be transmitted via underground DC cables before being converter to AC. The DC cables do not suffer from the charging issue, and can achieve the necessary high capacity ratings with fewer cables and a smaller right-of-way.

Developers must also consider a project's ability to produce and transmit energy to the grid without impairing grid stability and reliability. Knowledgeable solution providers can help developers conduct system impact studies to better understand how a wind installation and its transmission technology will affect the grid and assess the cost of upgrading the grid to accommodate the new offshore generating facility.

Once the transmission type is established, technologies must be selected that minimize the space requirements of the offshore collector substation because larger space demands can rapidly increase the costs for the facilities. If HVDC turns out to be the best option for the interconnection, the space and performance requirements dictate the use of voltage source converter (VSC) technology, which is more compact than earlier HVDC technologies and can operate better with the limited system strength provided by the offshore wind generators.

If AC is the best interconnection option, gas-insulated switchgear (GIS) is rapidly becoming the new norm. GIS is compact metal encapsulated switchgear consisting of high-voltage components such as circuit-breakers and disconnectors, which can be safely operated in confined spaces. The gas used in GIS, sulfur hexafluoride (SF_6), has a high dielectric strength and arc-quenching properties which allow the conductors and switchgear to be moved closer together. GIS excels in environments like offshore substations where space is limited with high associated costs, community permitting is important, and lower maintenance costs are vital.

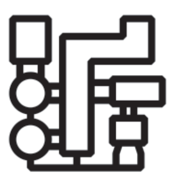
A critical consideration for both AC and HVDC options is the selection of transformer unit sizes that reasonably balance the conflicting requirements of construction cost, offshore space requirements and reliable delivery of power from the offshore wind facility during normal system operating conditions as well as during contingency conditions on the offshore platform.

Addressing onshore substation systems

The onshore interconnection substations, whether AC or HVDC, will likely be sited near load centers in densely populated areas, or in coastal areas with limited power transfer capability. Developers need to clearly understand the potential challenges and requirements in such locations.

AC substations for offshore wind power are often in areas near the end of the existing transmission grid where only sub-transmission or distribution level infrastructure exists. The existing transmission lines were not designed to transfer large amounts of power from the system extremities back to the loads. Significant transmission system reinforcements may be necessary in these areas, including the construction of new substations or new lines.

Soils and geologic conditions may vary and have significant environmental impact, especially in coastal areas, and understanding these conditions early in the development process helps avoid unnecessary risks. Breakers and components that minimize the footprint, such as AC GIS or HVDC VSC technologies, may be adopted to minimize the environmental impact and costs. Traditional air-insulated substations (AIS) and HVDC stations require large clearances necessitating substantial real estate for the installations. With GIS equipment, since all conductors are sealed in gas-filled vessels, the overall AC substation footprint can be reduced by as much as 85%. The smaller footprint of GIS substations reduces land requirements and increases options for site construction.



GIS approach
can reduce substation footprint up to
85%

Importance of power quality systems

Ensuring power quality and system reliability is key to the success of any offshore wind generation project. Flexible AC Transmission Systems (FACTS), energy storage systems, synchronous condensers, shunt reactors, and HVDC VSC technology all play instrumental roles in ensuring power quality. When the grid interconnection point is weak (i.e. the short-circuit strength is low), unacceptable voltage conditions may occur. To keep system voltages within acceptable operating limits, developers need to employ FACTS or HVDC VSC technology. FACTS are dynamic shunt compensation tools, such as Static Synchronous Compensators (STATCOM) or Static Var Compensators (SVCs), that have proven useful for increasing the power transmission capability of existing grids. These tools aid in congestion management and can help make room for additional power transfer from wind farms over existing grids.

When wind power generation increases to the point where it becomes a significant portion of the total generation on the grid, the requirement for resources with fast regulation increases. Such resources must quickly offset fluctuations in wind power generation and balance the real and reactive power requirements of the system in order to maintain grid reliability.

It is equally important to address various interconnection issues driven by grid codes, the North American Electric Reliability Corporation (NERC), and regional transmission owner (RTO) or independent system operation (ISO) requirements. The list of concerns for the developer includes:

- Addressing the reactive power and black-start capability needs of the grid when traditional thermal generation units are retired and replaced by intermittent wind resources.
- Defining the performance of their offshore wind system during normal and contingency conditions.
- Considering the effect of cable system energization, generator synchronization on system voltage, and any alternatives for meeting reactive power capabilities.

FACTS devices, battery energy storage systems, synchronous condensers, and HVDC VSC can provide voltage regulation and reactive power support to the grid at the interconnection point. Battery energy storage systems and synchronous condensers can also provide synthetic inertia to improve performance and frequency response of grids with a large proportion of wind generation and relatively low levels of traditional fossil-fuel based or hydro-based generation. Shunt reactors increase the energy efficiency of long AC cable systems by absorbing the reactive power (charging current) generated within the cable. A shunt reactor can be directly connected to the power circuit or to a tertiary winding of a three-winding transformer and can be permanently connected or switched via a circuit breaker. To optimize the consumption of reactive power the reactor can have a variable rating. If the load variation is slow, which it normally is (seasonal, daily, or hourly), a variable shunt reactor (VSR) could be an economical solution for some customer applications.

Identifying the need for and type of FACTS shunt devices is addressed as part of the system studies during the conceptual and design phases of the offshore wind facility development.

Understanding protection and control systems

A successful offshore wind project will ensure the optimal deliverability, availability and reliability of the power. Automatic and remote-monitoring capabilities are critical to accomplish this. The introduction of remote-monitoring capabilities is part of a digitalization effort in the electric power industry, often referred to as “the digital substation.”

Utilities must be able to understand, predict and optimize system performance to help avoid shutdowns. For example, a fault could damage a transformer, which is typically one of the more expensive assets in an AC or HVDC substation. Effectively monitoring potential faults starts with the use of protective relays, modern versions of which are intelligent electronic devices. These are real-time embedded systems that monitor power system conditions including the amount of current moving from the offshore substation through the cables. Control systems and protective relays send information about the currents they are measuring and if the system detects a fault, it can isolate the transmission cable by ordering the cable breakers to open.

Embracing solutions with digitalization capabilities is crucial when building an offshore wind system because device intelligence helps to enhance safety, ensure compliance, and drive reliability, performance and efficiencies. For instance, remote monitoring enables experienced operators to view real-time feeds and make decisions without the inherent costs or dangers commonly associated with on-site troubleshooting. Digitalization can also provide real-time, actionable notifications of system health and device failures before they cause extensive issues. This information enables operators to remotely take equipment offline or even make remote modifications to optimize equipment life.

As with any new power generating infrastructure, developers should pay close attention to the demands associated with the NERC critical infrastructure protection plan (NERC-CIP), which consists of nine standards and 45 requirements covering the security of electronic perimeters and the protection of critical cyber assets, as well as personnel and training, security management and disaster recovery planning.

Cybersecurity is a key component of NERC-CIP compliance, especially when leveraging digitalized assets because connected systems can be especially vulnerable without proper protection. As such, developers need to plan for multiple layers of defense embedded in substation automation and control system architecture.

Cybersecurity approaches include grid automation systems that follow industrial best practice guidelines outline in such standards as IEC 62443, IEC 62351, IEEE 1686, as well as support and compliance to NERC-CIP regulatory standards. There are several key technologies and strategies that have a meaningful role in addressing cybersecurity concerns. Firewalls (including next-generation firewalls), patch management, access control and detailed audit trails of all security-relevant user activities are prime examples.

The role of expert insights

A full understanding of the requirements and challenges of any offshore wind installation can help to mitigate risks and lower design, construction and operating costs. The development of an offshore wind facility requires numerous phases, with various types of evaluations being prudent or necessary for each phase. The U.S. Bureau of Ocean Energy Management's (BOEM) offshore wind energy program identifies four phases: planning and analysis, leasing, site assessment and construction and operations. These phases can overlap and feed into each other. Plans from each phase are necessary to ensure a properly designed and operated offshore wind facility.

Siting of a facility is dependent upon the wind resources available at the potential sites. Experts on wind resources can provide input early in the process to help determine which of the BOEM lease sites should be pursued. In addition, a review of local governmental requirements, regulations and grid codes is necessary to ensure compliance from both a design and operation perspective. For example, state regulations may require that the offshore wind turbines be placed sufficiently far from shore to minimize visual impacts, adding to the distance the facilities must transmit power. Consideration of environmental impacts and exclusion zones – such as fisheries, shipping lanes and military exclusions – may also result in longer transmission cables, changing the economics between AC and HVDC interconnections and altering the technology selection.

Planning for offshore wind

Power consulting solutions

Renewable energy studies

- Grid integration
- Power evacuation
- Stability studies

- Grid code studies
- Insulation coordination
- Other EMTP studies

- Reactive power requirement
- Fault ride through
- Harmonic, flicker

Expertise in grid integration analysis – Ensure that system reliability and performance are not compromised while getting an understanding of system costs from experts that have performed hundreds of system integrations.

Grid interconnection planning – Maximize power into the transmission grid at various sites without the need for additional system upgrades. Understanding up front what issues could occur downstream will be better for the lifecycle of your project.

Grid code compliance – Analysis to determine grid code compliance and reactive power handling. Includes: fatal flaw studies, conceptual design of transmission systems to evaluate wind energy, and cost and risk management.

System impact studies – Consider a range of system operating scenarios, as well as dynamic simulations on the network. Identification and prioritization of issues can be leveraged when investigating in upgrades or unexpected system impacts. Identify any transient overvoltages that can cause system failures which are traditionally not covered by the developers and/or OEMs.

Economic feasibility analysis – Evaluation of cash flows of specific renewable projects taking into account market conditions and regulatory framework and assessing potential impacts under different regulatory scenarios.

Advisory services – Identifying potential problems of transmitting power and leveraging solutions like HVDC cables. Understand project costs and system impacts early on and learn what options are available from the industry leaders.

Analysis of regulatory frameworks and electricity markets – Market and regulatory international benchmarks, identification of potential business opportunities in international markets and evaluation of regulatory risks. Economic and regulatory analysis to support the decision making process.

Preliminary interconnection and grid compliance issues can be evaluated early in the process to ensure understanding of potential onshore transmission constraints that may be found by the RTO or ISO. A developer typically needs to perform preliminary studies to identify the points of interconnection (POI) for their projects. RTOs and ISOs will perform feasibility studies, full system impact studies, or both using the POI and initial design of the offshore wind facilities submitted by the developer. If the studies by the RTO/ISO identify issues that require changing the POI or the rating and design of the project, the developer will need to resubmit revised information. This may lead to a loss in the RTO/ISO queue position for the interconnection and significantly delay the project. This means that the preliminary studies by the developers should be performed with the support of experts familiar with the RTO/ISO system, requirements and operating practices to reduce the risk of a project delay.

Specialized studies are conducted during the design process to evaluate various design and operation aspects and confirm the performance of the electrical and civil designs. Logistical aspects of the construction phase, such as the transportation and erection of massive turbine components, short seasonal installation windows, and limited availability of vessels capable of supporting the installations, must be accounted for as well.

In all of the areas discussed, assistance from industry consultants and other experts can help a developer navigate the complex site selection and design process, and better understand the planning, compliance and construction requirements. A comprehensive approach helps to ensure a smooth and timely implementation of the offshore wind facilities.

Conclusion

Despite the challenges, the opportunities for offshore wind generation are clear. Technology advancements combined with proven successes across the globe are making offshore wind projects not only feasible, but attractive. The key to overcoming the obstacles is having the right mix of today’s technology, an ability to embrace proven strategies, and an expert partner who can draw upon real world experiences to help navigate the path through the complexities inherent in achieving success.

Results from the field

Customer: C-Power's Thornton Bank Wind Farm

Customer needs:
- To build the grid connection for C-Power's Thornton Bank Wind Farm, one of Europe's largest offshore wind sites 30 km off the Belgian coast near Ostend
- Project delivered in several phases

ABB solution:
- Electrical system studies, static and dynamic studies, grid compliance and system dimensioning
- Offshore and onshore substation
  - 170 and 200 MVA 33/155 kV power transformers
  - 36 kV GIS for the incoming feeders from the wind turbines
  - 170 kV GIS for the outgoing feeders to land
  - 36 kV shunt reactors to deliver reactive power compensation
  - Neutral grounding reactors for grounding the main electrical system
  - Protection and control systems and reactive power control

Benefits:
- Full compliance with Grid Code requirements
- True partnership to ensure a free issue project and with very limited impact on the community
- Full scope to integrate the energy produced

Customer: CREZ, USA

Customer needs:
- Reliable operation of new CREZ transmission for large amounts of wind generation (20,375 MW)
- Evaluation of reactive power needs for new transmission system.
- Understanding of system response to series compensation

ABB solution:
- Perform extensive study of ERCOT transmission system including evaluating both steady-state and dynamics performance
- Identify static and dynamic shunt reactive requirements. Confirm appropriate levels of series compensation
- Preliminary evaluation of subsynchronous issues

Benefits:
- Improved transfer capability of renewable energy to large load centers
- Addressed fast voltage collapse conditions prior to system completion
- Early understanding of SSR issues requiring further study

Customer: DOE – National Offshore Wind Energy Grid Integration Study (NOWEGIS)

Customer needs:
- Identify the capability of the U.S. transmission grid of integrating up to 54GW of offshore wind
- Determine regulatory and technical hurdles that hinder the adoption of offshore wind

ABB solution:
- Build a coalition of industry experts from government, utility, academia, and industry
- Perform a multi-pronged study evaluating wind resources, technologies, regulatory issues, and transmission grid capabilities

Benefits:
- Study results provide insights into the feasibility of integrating large amounts of offshore wind energy into the U.S. transmission grid
- Study results provide insights into regulatory issues that may impede the path to integration of offshore wind

Customer: E.ON, UK

Customer needs:
- Target capacity of 400 MW (116 x Vestas V112-3.45 MW), minimum distance of 750 m between turbines

ABB solution:
- Offshore and onshore substation automation
- Project grid connection:
  - Generation: 33 kV
  - Offshore substation: 33/150 kV
  - Onshore substation: 150/400 kV (Bolney 400 kV substation)
  - Connection offshore-onshore: 150 kV AC

Benefits:
- Covering consumption of 300,000 households in the UK and saving 600,000 tons of CO_2

Customer: Ørsted (former DONG Energy), 89 km off the UK east-coast

Customer needs:
Project wind assets: Target capacity of 1,400 MW (165 x SG 8.0-167 DD)
Project grid connection:
- Generation: 66 kV
- Offshore substation: 66/220 kV
- Offshore reactive power compensation substation (220 kV)
- Onshore substation: 220/400 kV (400 kV substation)
- Connection offshore-onshore: 220 kV AC

ABB solution:
- MicroSCADA Pro for substation monitoring and control
- Protection (ABB Relion® series) and gateways/ interface (ABB RTUs)
- Wired communications: Switches, routers, firewalls, FOX615 multiplexers, fully IEC 61850 compliant (GOOSE and MMC)
- Services for framework agreement standardization, engineering, testing, commissioning

Benefits:
- Framework agreement covering other projects (globally) for increased efficiency

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