WHITE PAPER / **OFFSHORE WIND PROJECT PLANNING**

CHARTING A COURSE TO GRID STABILITY: OFFSHORE WIND PROJECT CHALLENGES AND SOLUTIONS

BY **Joshua Crawford,** PE, **Scott Hodgdon** AND **Nicholas Matone,** PE

As the number of offshore wind projects continues to grow, addressing grid interconnection challenges is critical for these systems to successfully fit in the evolving power grid. Maintaining system frequency and voltage stability while supplying sufficient short circuit current is key for offshore wind projects to achieve grid stability.

The generation mix across the U.S. is changing as traditional synchronous baseload generation resources such as coal, oil and nuclear retire and renewable, non-dispatchable, nonsynchronous generation provides an increasingly large percentage of demand. The newest renewable juggernaut that will enter the generation mix in this country is offshore wind, a proven technology globally but relatively untested stateside. Proper integration of offshore wind energy into the U.S. electrical grid requires an understanding and consideration of the many unique and challenging characteristics of wind generation and its impact on the grid.

GALE-FORCE GROWTH

The offshore wind market is blowing away records for new power generation across the world. In 2017, a study by the Global Wind Energy Council showed that 4,331 megawatts (MW) of new offshore wind capacity was installed globally, representing an increase of 95% over the 2016 market. In 2018, the offshore wind market reached 23 gigawatts (GW) in total cumulative installations in 17 markets around the world.

The first U.S. commercial offshore wind farm came online in 2016, with a capacity of 30 MW. In 2020, it is still the country's only operating offshore wind farm, but there is roughly another 25 GW in the project pipeline, according to a U.S. Department of Energy market summary. Of this, approximately 2 GW is expected to come online by 2023.

With continued state-level activity and many projects under development, attention turns toward how to deal with complexities and challenges to most efficiently bring projects to fruition.

INHERENT CHALLENGES OF OFFSHORE WIND

Generating energy from offshore wind and transporting it inland to where it can be used is a complex technical challenge. Beyond the permitting, structural and logistical challenges for manufacturing, transportation and erection, offshore wind utilizes inverter-connected nonsynchronous turbines that require special consideration by grid operators to deliver smooth grid interconnection and stability.

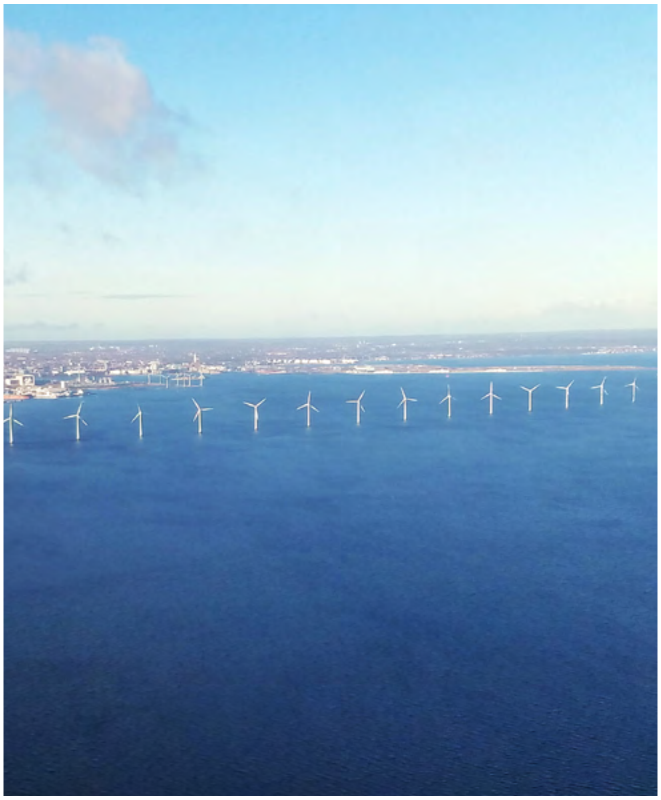
Historically, generation sources have been able to provide consistent, dispatchable and controllable energy to the grid via rotating synchronous machines.

Synchronous generators offer a significant and swift frequency response due to inherent design and large rotating mass, frequently referred to as inertial response. Additionally, synchronous generator systems provide primary frequency response through governor controls and large dynamic reactive power range through automatic control of the field current. Through sophisticated control of the synchronous machine's quadrature response, the excitation system's power system stabilizer (PSS) can also dampen low-frequency oscillations.

Offshore wind turbines, like onshore wind and solar photovoltaic (PV) systems, are asynchronously connected to the grid using power electronic inverters. Wind generation and solar PV utilize advanced high-speed digital controls and are designed to run at maximum capacity to deliver improved performance. These technologies are not, however, intended to store significant energy or provide a large reactive power output without significant facility derating, which presents challenges and increases the risk to the stability of the grid.

The North American Electric Reliability Corp. is working to accommodate inverter-based generation with guidelines that protect grid reliability and stability. Recent examples include the Federal Energy Regulatory Commission (FERC) Order 842, which requires inverter-connected generation to provide primary frequency response capability; and FERC Order 827, which provides reactive power requirements for nonsynchronous generation.

As technology evolves and renewable generation programs develop, interconnection study methods must be developed in ways that capture all potential operating scenarios. Offshore wind developers need to understand the potential impacts to the grid and mitigation strategies that may be required; otherwise, unexpected project costs can result from inadequate planning and budgeting. It can be difficult in the study and development project phases to capture these costs and to understand the performance available from different technological solutions when the cost per megawatt hour is being determined for a proposed bid.



OFFSHORE WIND AND GRID STABILITY

The grid operates as a balanced system where generation and load must match at all times. Three primary considerations for grid stability (frequency, voltage and short circuit current) offer challenges but represent the basis of evaluation for interconnecting any new generation, including offshore wind:

- A significant and rapid change in demand, supply or network connectivity can cause changes to **grid frequency**, which result in unstable operation.
- Similarly, the grid requires maintenance of the **voltage** throughout the system within a nominal range for proper operation of equipment.
- A large amount of **charging current** is required to energize the connection of long lines, such as a buried or undersea cable for offshore wind power or long transmission lines, and this can cause changes to bus voltages and result in unstable operation. System faults, inrush current from the connection of large load centers or motors, and operation of large variable frequency drives all require significant levels of short circuit current. A lack of available short circuit current can result in system waveform distortion and improper operation of protective relaying.

Synchronous generation provides a meaningful contribution to grid stability through inertia and governor response (for frequency stability), voltage regulator response (for voltage stability), machine reactance, time constants and field forcing for short circuit current contribution.

Nonsynchronous generation from offshore wind provides limited frequency and voltage response through the power electronic controls and restricted short circuit current up to the limit of the inverter overload capacity.

DEVELOPING GRID STABILITY SOLUTIONS

For offshore wind operations, additional frequency, voltage and short circuit current capability are sometimes required to support the stability of the grid. Several systems can be put in place to address grid stability needs.

REACTIVE POWER

Electrical systems in the U.S. operate at 60 hertz (Hz), meaning the alternating voltage and current go through a cycle of positive and negative polarity approximately 60 times per second. Devices connected to this power grid require electric and magnetic fields to operate and transmission lines, transformers, motors, etc., all need electrical current to produce these fields. The power necessary to provide the currents for these fields is called reactive power and is measured in volt-ampere-reactive (VAR). Reactive power is stored in electric or magnetic fields, and this power is absorbed and resupplied back to the system every cycle. Reactive power results in the voltage and current waveforms being out of phase from each other as these electric and magnetic fields charge and discharge.

Reactive power is produced by devices that either inherently, through fundamental physical properties, create a phase angle difference, or through devices that can control the phase angle difference between the current and the voltage. Most devices connected to the grid, such as motors and compressors, consume reactive power. A surplus of reactive power will result in an increased system voltage, and a shortage of reactive power will result in a decreased system voltage. System voltages need to remain within a certain operating range, which varies from region to region but generally must be within 0.95 pu to 1.05 pu.

Passive devices that produce or consume reactive power include capacitors and reactors, respectively. Capacitors serve as sources for reactive power and reactors serve as consumers of reactive power. Because of the nature of reactive power and its mathematical connection to phase angle difference, in terms of stability, both can be viewed as sources of reactive power. In this view, capacitors are sources of "leading" reactive power, where the current waveform peaks before (or leads) the voltage waveform. Reactors are sources of "lagging" reactive power, where the current waveform peaks after (or lags) the voltage waveform.

Active devices would include synchronous machines such as generators, large synchronous motors and synchronous condensers, all of which control the phase angle difference between the voltage and current by varying the strength of the machine field current.

Additionally active devices also include power electronics devices such as static VAR compensators (SVCs) and static synchronous compensators (STATCOMs), collectively known as flexible alternating current transmission system (FACTS) devices. These utilize complex control algorithms and thyristors or insulated-gate bipolar transistors (IGBTs) to control the phase angle difference between the voltage and current.

In offshore wind power systems, the long subsea transmission cables can act as large capacitors. The longer and larger the cables, the greater voltage and current will be out of phase and the more reactive power is consumed. This must be compensated for in the design of offshore wind systems, often with the use of compensation equipment onshore at the site of interconnection to the rest of the grid. Compensating for the reactive power consumption of the offshore cables will allow the cables to operate more efficiently and increase the amount of power that makes it onshore.

SYSTEM INERTIA

Large, rotating masses used in synchronous power generators naturally help to control power system frequency to deliver a balance between generation and demand on the grid. The rotational inertia of a synchronous generator minimizes the rate of change of grid frequency during times of changing conditions. Such inertia keeps power flowing for a period that allows for available response and reaction to faults and outages. Achieving a level of required stability for the grid is not so easy for offshore wind plants.

Inverter-based offshore wind power does not have rotational inertia equipped for energy storage. As offshore wind systems and other inverter-based renewable systems are added to the grid and replace synchronous generation, measures must be taken to reduce the risk of diminished frequency response and control.

REACTIVE POWER COMPENSATION EQUIPMENT

The electrical system challenges of offshore wind systems must be addressed and resolved to satisfy the local interconnection and U.S. grid code requirements. During interconnection planning studies, the needs of an offshore wind system will be evaluated, and equipment identified to help satisfy criteria and drive performance.

SYNCHRONOUS CONDENSERS	STATIC VAR COMPENSATOR	STATIC SYNCHRONOUS COMPENSATOR
Considered a motor that spins freely without any connected load, a synchronous condenser is controlled by a voltage regulator to produce or absorb reactive power. Similar to a traditional generator, this equipment is also referred to as a synchronous capacitor or synchronous compensator. Put simply, a synchronous condenser is a synchronous generator that does not provide real (MW) power to the grid.	The static VAR compensator (SVC) effectively regulates network voltage to keep it constant at a set reference point with the use of a thyristor-controlled capacitor and thyristor-controlled reactor. An SVC monitors and controls voltage at a set point under normal operating conditions and provides fast response reactive power in the event of system changes by using thyristors to control how long the reactor or capacitor remains connected to the network during each cycle.	Like the SVC, the static synchronous compensator (STATCOM) regulates voltage by controlling the amount of reactive power supplied or absorbed by the system. A STATCOM uses many modular voltage source converters (VSCs), which switch capacitors on and off independently. By controlling when each capacitor is connected or disconnected from the circuit, the STATCOM can either supply or absorb reactive power with extreme granularity.
ADVANTAGES		
• Well-proven technology that can control the magnetic field and adjust the reactive power as needed. • Synchronous condensers create system inertia via a spinning rotor, which can be augmented through the addition of a flywheel, and can provide short circuit support in the event of a fault.	• Near-instantaneous response time for transient system stability. • Absorption and supply capabilities of reactive power can be independently selected depending on specific application needs. • Minimal moving parts and low maintenance requirements. • Less expensive than larger mechanical machines. • Lower electrical losses compared to synchronous condensers.	• Faster insulated-gate bipolar transistor (IGBT) firing achieves quicker response time for transient system stability compared to other reactive compensation technologies. • Provides more capacitive reactive power than the SVC during faults or when system voltage decreases. • Many fast-firing IGBTs damp out high frequency noise and eliminate the need for additional harmonic filters. • Lower electrical losses compared to synchronous condensers.
DISADVANTAGES		
• Large and more expensive than other equipment options. • Rotating machinery with moving parts increases maintenance requirements. • Loud operation and cooling systems can require noise mitigation measures. • Higher electrical losses due to the mechanical equipment and field current system.	• Lack of fault duty or short circuit support. • Lack of inertia contributions. • Harmonic filters are typically required to minimize the high-frequency noise caused by the thyristor switching.	• Lack of fault duty or short circuit support. • Leading and lagging power capacity are typically limited to being symmetrical. • Lack of inertia contributions.

FERC Order 842 has begun to address this new dynamic and requires newly interconnecting generating facilities to install, maintain and operate equipment that can provide primary frequency response as a condition of interconnection.

Planning and analyses are required to create offshore wind systems that compensate for frequency instability. Designing frequency protection and control schemes include the evaluation of alternatives such as synthetic inertial control to provide grid protection and optimal wind generation performance.

SHORT CIRCUIT CURRENT

To keep the grid stable and maintain proper voltage, enough short circuit capability is required from generating sources. In the event of a fault on the grid, generation equipment must be able to provide sufficient short circuit current to maintain voltage and frequency, so that protection systems can detect and clear the fault from the grid. If a fault remains for too long, or if there isn't enough short circuit current, the grid could become unstable and cause cascading blackouts as frequency and voltage deviate too far from their nominal operating ranges.

For reliable and safe operation of electrical power, systems must be able to predict and model the generating sources that produce fault current.

Offshore wind farms typically have many turbines, inverters, transformers, reactors and cables associated with the system, as well as additional compensating equipment onshore. Wind turbine generators can operate singly or be networked to deliver varying amounts of power. Turbines must be able to perform at variable speeds that can handle rapid wind speed fluctuations, optimize turbine blade speed and handle power swings.

The short circuit ratio (SCR) at a point on the system is a metric used to determine the voltage "stiffness" or electrical strength at that point. The SCR can be summarized as the short circuit capacity at a location on the grid divided by the MW capacity of the machine seeking to interconnect at that location. The higher the short circuit ratio, the greater the electrical strength of the system. If offshore wind farms are seeking to interconnect to an onshore transmission substation with a low short circuit ratio, studies must address the fact that inverter based generation does not significantly contribute to the total short circuit capacity at a station, and other onshore compensation equipment may be required to support the strength of the system after the interconnection is made.

Careful analysis, study and modeling of short circuit current conditions, fault risks and protection systems is needed for each type of offshore wind generator type being considered. This can be a challenging process given the many different wind generator manufacturer types, commercial software and proprietary software and operating systems used.

OFFSHORE WIND PROJECT ACTIVITY AND COMPLEXITY

Coupled with the challenges of designing an optimal offshore wind facility, developers need to navigate the unique challenges of a growing offshore wind market in the U.S.

With increased project activity and investment, developers must coordinate — or at least be aware of — the actions and complexities between the many federal agencies and regional, state and local laws. To assist, the Department of Energy (DOE) and the Department of Interior (DOI) Bureau of Ocean Energy Management (BOEM) have worked to create a National Offshore Wind Strategy.

The strategy identifies the challenges within the regulatory process to deliver the stewardship of projects and helps to identify the regulatory agencies leading distinct efforts. Offshore wind design, planning, implementation and permitting continues, however, to be a complex and changing dynamic for projects.

COMPREHENSIVE INTEGRATION AND INTERCONNECTION PLANNING

For offshore wind developers and transmission operators striving to deliver new generation that can reliably contribute to the grid, all roads lead to the criticality of producing comprehensive planning studies.

Consistent with Independent System Operator (ISO) and Regional Transmission Organization (RTO) policies and procedures, the integration of offshore wind to the nation's grid must do no harm. As such, high-quality transmission planning and interconnection studies are required that provide insight from analyses and models to guide the planning, development, design and implementation of offshore wind projects.

Offshore wind planning studies must consider more permutations of analyses and provide more robust screening and evaluation to assure integration to the grid:

- Siting and location analysis confirming suitability of turbine size, total installed capacity, power extracted and wind production profiles.
- System sizing analysis to address performance requirements and output, required equipment ratings, lease area space and regulatory requirements.
- Pre- and post-interconnection testing under a range of assumptions and variables to determine reactive power, and short circuit needs under different scenarios.
- Thermal, voltage, stability and transient stability impacts of interconnection using diverse contingency scenarios.
- Evaluation of connection point options including electrical characteristics of the connection bus, constructability for interconnection, local areas and the surrounding municipality.
- Cost and system performance analysis to identify optimal interconnection points, minimal systemside upgrades, maintenance needs and system balance.
- Shoreside grid impact analysis, retrofit needs, system upgrades and co-optimization requirements.
- Cost analyses to identify life cycle maintenance schedules and determine redundancy level requirements.
- Assessment of environmental and ecological impact analysis and development of mitigation strategies.

Comprehensive planning studies can help identify suitable offshore wind interconnection requirements upfront and avoid late design changes, which increase project costs and impact schedules.

CONCLUSION

The accelerated growth of offshore wind and renewable generation is challenging the country's already evolving power grid and its many stakeholders. To guide U.S. offshore wind projects, developers and public operators need to thoroughly understand the potential impacts, risks and needed compensation for successful grid integration of this new generation source.

This will require the skilled application of diverse technical resources and strategies to develop comprehensive solutions that minimize grid impact onshore. Projects in all phases of development will benefit, but it is especially crucial to projects earlier in the development pipeline.

BIOGRAPHIES

JOSHUA CRAWFORD, PE, BURNS & McDONNELL, is a senior electrical engineer in the Energy Group. He supports clients through all project phases of generator protective relaying upgrades and excitation system upgrades. Recently the renewable revolution has further focused his attention on the interaction of generation resources with the bulk electric system, and his project specialty has shifted toward synchronous condenser conversions and battery energy storage systems. Joshua has a master's degree in electrical engineering from the University of Missouri-Kansas City and is a registered professional engineer in Missouri, Pennsylvania and Texas.

SCOTT HODGDON, 1898 & CO, part of Burns & McDonnell, serves as a project manager. He has extensive experience in the power industry, holding various roles within system planning and wholesale power market analysis departments. He earned a Bachelor of Science in electrical engineering from Clarkson University and an MBA from Western New England University.

NICHOLAS MATONE, PE, BURNS & McDONNELL, is a staff electrical engineer in the Transmission & Distribution Group's Substation Department. His utility industry experience involves substation conceptual engineering, detailed substation physical design, grounding and lightning protection studies, construction details, standards development, gas insulated switchgear, and major equipment specification and purchasing. He also serves on the IEEE PES Gas Insulated Switchgear Committee. He earned a Bachelor of Science in electrical engineering from Pennsylvania State University and is a registered professional engineer in Connecticut.

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