CARBON TRUST

OFFSHORE WIND ACCELERATOR (OWA)

Novel Control and Energy Storage for Offshore Wind

Electrical Systems Working Group

January, 2022

The Offshore Wind Accelerator

The Offshore Wind Accelerator (OWA) is the Carbon Trust's flagship collaborative research, development and deployment programme. The joint initiative was set up between the Carbon Trust and nine offshore wind developers in 2008, with the aim to reduce the cost of offshore wind to be competitive with conventional energy generation, as well as provide insights regarding industry standard (and best practice) health and safety requirements. The current phase involves participation and funding from nine international energy companies: EnBW, Equinor, Ørsted, RWE, ScottishPower Renewables, Shell, SSE Renewables, Total Energies and Vattenfall Wind Power.

Acknowledgements

This report provides an executive summary of a recent project delivered by Frazer-Nash Consultancy and the University of Strathclyde for the Offshore Wind Accelerator.

The University of Strathclyde and Frazer-Nash worked closely with the Carbon Trust and the Electrical Systems Technical Working Group from the Offshore Wind Accelerator over the course of the project. During the project, Frazer-Nash and the University of Strathclyde also engaged a number of system operators, technology manufacturers, universities and regulators. We would like to thank all those who provided input.

1. Introduction

Power systems globally are seeing increasing penetration of power electronics interfaced generation. A report produced by the ENTSO-E[1] presents forecasts of the highest instantaneous percentage of renewable energy sources (including small hydroelectric power) penetration in relation to power demand occurring in any hour of the year in European countries in 2025. The forecasts highlight that eight countries (including Great Britain (GB), Ireland and Germany) will reach up to 100% of instantaneous demand available from renewable generation and 22 countries will reach at least 50% by 2025. A significant proportion of this generation will be converter interfaced, reducing the overall percentage of synchronous generation connected to the electricity system. This poses a stability challenge given that many stability requirements (including inertia and black start) have been traditionally provided by synchronous generation.

Motivated by this challenge, this Offshore Wind Accelerator (OWA) study investigated the addition of a storage system with innovative converter control to the onshore substation of an AC-connected offshore wind farm. The primary objectives of the study were to:

- Improve understanding of available technologies, control approaches and their ability to provide grid services.
- Use cost-benefit analysis to inform the investment case for installing these technologies at a range of typical sites.
- Understand the route to market for these systems including required Grid Code changes, ownership rules and dispatch considerations.
- Develop a roadmap for future investigation including potential simulation and demonstration projects.

This report summarises the key findings from the project.

2. The Technology

2.1. Hardware options and capability

Hardware technology options were selected based on commercial availability and the ability to provide both the wind farm's Grid Code requirements for dynamic reactive power compensation, as well as, other ancillary services.

The first architecture considered was a 2- or 3-level converter with a battery in the DC link of the converter, schematic diagram shown in Figure 1. This architecture is used in the majority of grid-connected battery systems.

[1] ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Power Sources , "Technical Report: High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters".

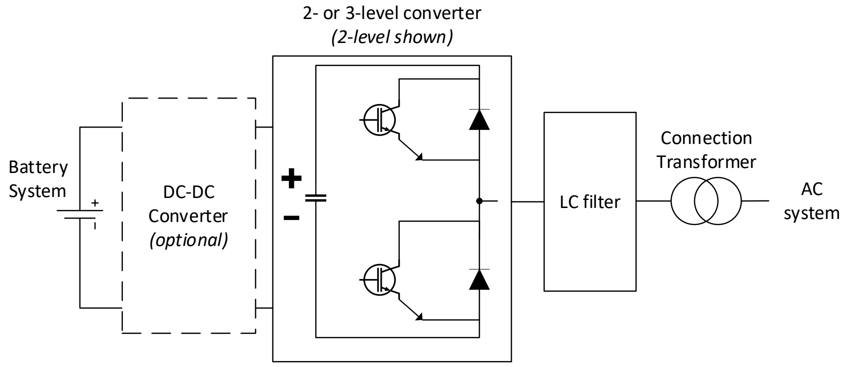

Figure 1: Simplified schematic of a 2- or 3-level converter with battery in the DC link

The second architecture considered was a modular multilevel converter (MMC). MMC converters stack multiple converter modules to enable higher power operation, and have been used in STATCOMs for offshore wind farms. In this hardware option, the energy storage is embedded in the individual sub-modules, as shown schematically in Figure 2. Ultracapacitors, also known as supercapacitors, are used instead of batteries due to the challenges of meeting insulation requirements with sub-module integrated batteries.

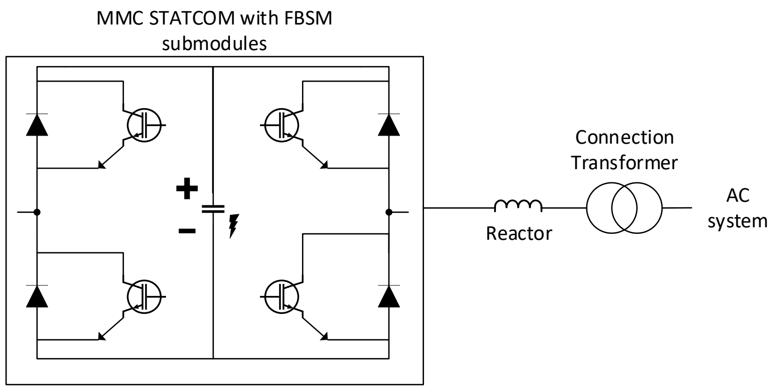

Figure 2: Simplified schematic of a MMC submodule with embedded energy storage

The capability of the two hardware architectures to provide a range of grid services[2] was evaluated (Table 1). Both design options are capable of inertia response, with the power requirements driving the sizing of the batteries or ultracapacitors. For fault level contribution, both systems are capable but will be limited by the current capacity of the converter. The 2-level/3-level design option is more capable than the MMC design option considered in this study for longer-duration frequency response, energy storage and some black start services due to the easier integration of larger energy capacity. Both systems are inherently capable of oscillation damping. Overall, the systems are strongly capable of providing ancillary services in addition to reactive power compensation.

[2] See glossary for definitions of these services.

Table 1: Design options evaluation against key grid services

Service	2 or 3- level converter with battery in DC link	MMC with ultracapacitors in submodule
Inertia response	Yes	Yes
Fault level contribution	Limited	Limited
Oscillation damping	Yes	Yes
Reactive power compensation	Yes	Yes
Energy storage	Yes	Limited
Frequency regulation / Primary control	Yes	No
Scheduling and dispatch of active power	Yes	No
Part of Black Start capability solution	Yes	No
Active Harmonic Filtering	Yes (development required)	Yes (existing option)

2.2. Control options and capability

Two converter control options were considered in this project based on technology readiness and functionality. These are defined below and their capabilities are summarised in Table 2.

- **Grid following control** is the approach applied in most power converter interfaced systems, consisting of an inner current loop and a phase locked loop (PLL) for measuring grid frequency. A grid following converter synchronises to the grid waveform and the converter output is adjusted to track an external voltage reference.
- **Grid forming control** approaches do not require an external voltage source to operate and can provide grid synchronisation without a PLL. The grid forming control approach considered for this study consists of virtual synchronous machine (VSM), emulation and a current loop.

Table 2: Control options evaluations against key grid services

Capability	Grid following	Grid forming
Inertia response	**Not capable** (existing control approaches). Can be modified to include inertia emulation but poses stability issues.	**Very capable**, limited by the available active power.
Fault level contribution	**Moderately capable** of delivering fault current (limited by semiconductor hardware) and effective at protecting converter hardware.	**Moderately capable** at delivering fault current (limited by semiconductor hardware) but not effective at protecting converter hardware without transition to current limiting mode.
Voltage and frequency regulation	**Very capable**, particularly with the addition of droop control.	**Very capable**, particularly with addition of droop control.
Islanding and black start	**Not capable**, requires external voltage source to operate.	**Very capable**, does not require external voltage source. Requires energy storage and switching between control modes.
Active harmonic filtering	**Very capable**, can be added to control approach.	**Very capable**, can be added to control approach.

3. Building the investment case

A cost benefit analysis study was completed to consider the financial, and non-financial, benefits of the different technology architectures.

The two hardware options were analysed and compared with the business case for a conventional STATCOM under baseline, pessimistic and optimistic scenarios reflecting different market conditions and system cost assumptions. Markets in Great Britain (GB), Ireland and Denmark were considered for both the current market (2021) and the potential market in 2030. Figure 3 provides an illustrative example for a GB site installed in 2030, with comparison to a conventional technology solution (a separate MMC STATCOM) and synchronous condenser (SynCon).

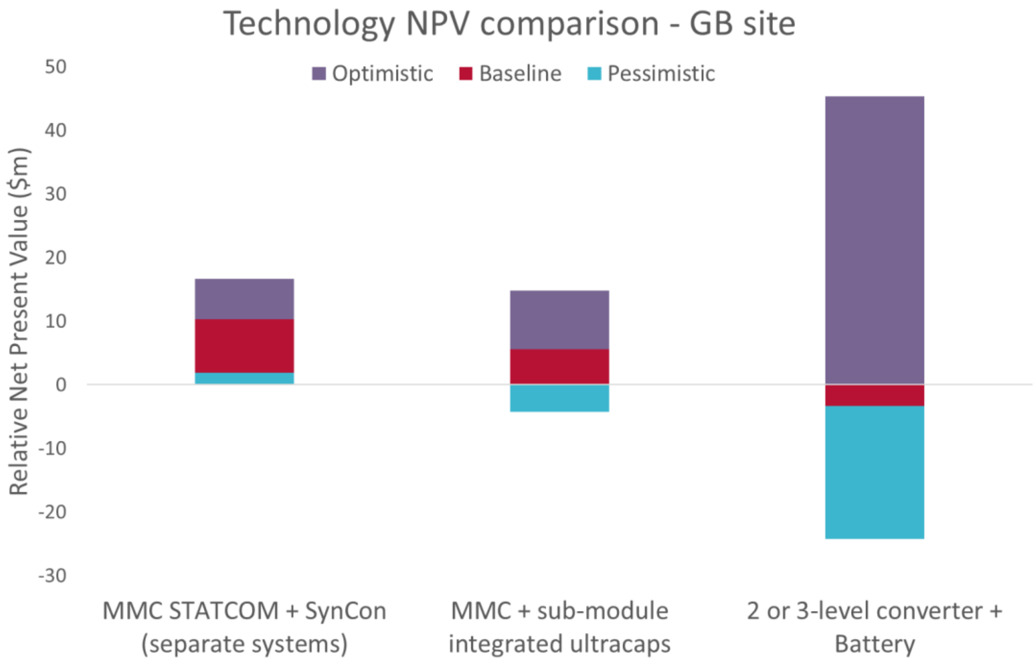

Figure 3: Net Present Value (NPV) in USD comparison relative to standard MMC STATCOM.

The key financial "tipping points" for viable investments in the two hardware technologies were found to be:

- **2- or 3- level converter with battery in the DC link:** NPV can be highly sensitive to market prices and service volumes secured. Considering existing revenue streams only (representative of markets in Denmark and Ireland), a positive NPV is achievable under an optimistic scenario however the investment case is stronger where markets for stability services are becoming available (i.e. current GB market).
- **MMC with embedded ultracapacitor energy storage:** The tipping point for positive NPV is when markets for stability services (inertial response and fault-current contribution) are accessible. Asset costs considered are based on a first-of-a-kind system – these costs are likely to come down with time and improve the NPV.

The non-financial benefits to investment in these systems were found to be:

- Development of grid forming capabilities to enable high penetrations of low-carbon inverter-based resource (IBRs) while enabling grid stability and resilience (and hence support the growth of the renewables sector).
- Support to creation of new markets for stability services and testing of Grid Code specifications.
- Complementary learnings to technology development for High-Voltage Direct Current (HVDC) with integrated storage.

4. Roadmap to implementation

Future work is required to implement an integrated energy storage and power converter for AC-connected offshore wind farms. The roadmap in Table 3 below describes the barriers that must be addressed to deliver commercial systems.

Connecting energy storage to the onshore substation of an offshore wind farm presents a unique combination of challenges, including adoption of new commercial arrangements, provision of emerging grid services and development of new technologies. To address these challenges, input will be required from a wide range of stakeholders including government policy departments, system operators, wind farm developers, technology manufacturers, and research institutions.

Table 3: Summary of the key barriers and associated stakeholders

Barrier		Requirement to Address
Category	**Description**	
1. Market	Markets for stability services (e.g., inertia, fault-level) do not exist (EU) or are immature (GB).	Stability markets with clear volume requirements.
2. Commercial	New arrangements for Grid Code responsibility sharing and land rights allocation with TSO/ Offshore transmission operator (OFTO). Business case is also complex.	Commercial arrangements for land rights and reactive power compensation responsibilities.
3. Technical	TSOs need to provide clarity on grid forming technical requirements and demonstration against these requirements is required to build TSO confidence. Technology must also be matured.	Technology development and demonstration program.

4.1. Market Barriers

4.1.1. Stability Services

Barrier: Limited markets have emerged for stability services over the last few years, as a means to operate the electricity system securely and reliably, with increasing proportions of inverter-based resources. These markets have come in the form of tendered stability contracts in GB for short-circuit level, inertia response and dynamic voltage control as part of National Grid ESO's Stability Pathfinder projects. Phase 2 of Stability Pathfinder will focus on new technologies to provide these services. Elsewhere in the world, government funding has been provided for pilot projects that demonstrate the ability of inverter-based resources to provide similar services.

Market development has been supported by the design of technical specifications for grid forming capabilities. In Germany, TSOs have produced the VDE-AR-4210 Guideline which contains a proposed set of test cases and verification criteria for grid forming HVDC which also applies to STATCOMs and other inverter-based systems. In GB, National Grid ESO has led Grid Code modification (GC0137) to include a non-mandatory specification for grid forming capabilities in the GB Grid Code[3]. However, these requirements must be combined with grid forming capability services, whether connected to the

[3] GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability) https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required

transmission or distribution networks. Including this specification in the Grid Code, rather than only in a contract, gives greater transparency of requirements to industry, and provides formal routes for review and comment during the Grid Code modification process.

Despite these developments, there is a lack of direction from TSOs on future, higher volume markets for grid forming capabilities. This market signal is particularly important for storage systems connected to the edges of the onshore network where offshore wind farms are located; there is a significant opportunity to provide voltage control and fault-level contribution support to the grid at these locations.

Requirement: TSOs must provide clarity on expected future market arrangements including: pricing models, auction/tendering approaches, eligibility criteria, tendered volumes and timelines for implementation. This clarity is required as soon as possible, and within the next two years, to build investor confidence. These new market arrangements must be supported by government policy as and when needed.

4.2. Commercial Barriers

4.2.1. Sharing of Grid Code Responsibilities

Barrier: Both TSOs and OFTOs are responsible for maintaining grid voltage within statutory limits, so new offshore wind farm connections are required to meet reactive power compensation requirements at the point of connection.

In GB, the requirements for OFTOs are imposed at the interface point with the onshore network through the System Operator and Transmission Operator Code (STC), while requirements for offshore wind farms are specified at the offshore grid entry point. Reactive power compensation equipment is usually installed by the wind farm developer (and divested to the OFTO) at the onshore connection point in order to satisfy STC reactive power compensation curves.

Therefore, if an onshore converter system was to be owned by the wind farm operator and meet the OFTO's reactive power compensation requirements, this arrangement would need to be contractually agreed with the OFTO and National Grid ESO.

This transfer of responsibilities would be achieved contractually through requirements specified by the OFTO in the Connection Site Specification, which National Grid ESO would then transfer to the technical appendix of the offshore wind farm's Bilateral Agreement. Payments will then be made to the Wind Farm Operator according to Appendix K of the STC.

Requirement: Offshore wind farm developers will need to agree appropriate detailed commercial arrangements with TSOs or OFTOs for taking on these additional responsibilities.

4.2.2. Land Rights

Barrier: Offshore wind developers must arrange for suitable land rights so the converter system is situated on land owned/leased by the wind farm operator, while the remaining onshore substation infrastructure is located on land owned/leased by the TSO/OFTO.

Requirement: In GB and in EU jurisdictions where the wind farm developer also develops the transmission infrastructure, this approach will require management of suitable transfer of land rights, as part of the asset divestment process to the TSO/OFTO. In EU jurisdictions where TSOs develop and operate all offshore transmission infrastructure, developers will need to negotiate with the TSOs to secure suitable land rights.

4.2.3. Business Case Development

Barrier: Business cases for energy storage units are complex with multiple potential revenue streams. For these novel converter systems, the business case is made additionally complex by the provision of the Grid Code reactive power compensation requirements, as well as, stability services.

Requirement: When developing business cases for these systems, developers should consider:

- For battery systems, the expected cost of repowering events mid-life to replace battery cells/packs.
- If black start services will be provided, the storage capacity that must be reserved that is not available to provide other services. If significant additional fault-level contribution is to be provided, the additional cost of oversizing the converter hardware may need to be considered.
- An assessment of any limitation to provision of active power services due to the concurrent provision of reactive power services.

4.3. Technical Barriers

4.3.1. Grid Forming Technical Specifications

Barrier: To date, markets for providing grid forming capabilities have been hindered by the lack of technical specifications for these capabilities. The situation has recently improved with the publication of the VDE-ARN 4131 technical connection guideline in Germany and the development of the non-mandatory grid forming specification, GC0137, for Grid Code in GB.

Requirement: Significant work remains to specify requirements for delivery of these services globally, which are both specific enough to ensure the requirements are met whilst remaining technology neutral. TSOs must build on recent initiatives to develop technical specifications for grid forming capabilities and appropriately reference these specifications when procuring stability services. Based on learning from the NGESO Stability Pathfinders and similar trials, these specifications should be iterated to encourage cost-effective provision of these services.

4.3.2. TSO Confidence in System Capabilities

Barrier: Further investigations into the performance of converter-interfaced systems using grid forming control under a range of conditions in realistic (or actual) network environments are required to increase TSO confidence.

Requirement: Research institutes and developers should prove that performance of novel converter technologies is acceptable through a suitable demonstration programme. This demonstration programme should consider all necessary test cases in simulated and field environments. This demonstration also has the advantage of improving investor and developer confidence in system performance.

4.3.3. Technological Maturity

Barrier: Whilst the majority of the elements of the novel converter-interfaced energy storage designs are existing, well-proven technologies, some elements require further development. In particular, the grid forming control for both system designs is not yet a standard offering from manufacturers despite limited trials on grid-connected systems[4]. The integration of energy storage into the modular multilevel converter (MMC) is also at a lower level of technological maturity, with only small-scale prototype system reported.

Requirement: Original equipment manufacturers should further mature these technologies while working with research institutes to demonstrate their performance. The control must be shown to continuously operate while providing a range of grid services without damaging the converter hardware. Through the design process, the hardware must be shown to meet desired technical specifications while addressing any reliability risks.

[4] For previous trials on grid-connected systems see (https://arena.gov.au/assets/2019/11/large-scale-battery-storage-knowledge-sharing-report.pdf) and (https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf?la=en&hash=B4E20D68B23F66090ADA5FD47A50D904)

5. Glossary

Active harmonic filtering	Cancellation of harmonics in the power network.
Fault level contribution	Ability to supply fault current in the event of a short circuit fault, increasing the ability to detect and respond to faults, thus improving system stability. Also referred to as *Short Circuit Level*.
Frequency regulation/ primary control	Restores system operating frequency to the nominal value after an event.
Inertia response	Responds to changes in frequency on the network, reducing the rate of change of frequency.
Oscillation damping	Detects oscillations in the network and produces a response to cancel the oscillations.
Part of the Black Start capability solution	Restarting the electricity network after a full or partial shutdown.
Reactive power compensation	Manages system voltage limits within safe and efficient levels.
Scheduling and dispatch of active power	Meet the gap between supply and demand after a discrepancy between planned demand and real time demand.

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