

Submission Template for IET Research Journal Papers

Validating Grid-Forming Capabilities of Hybrid Power Park Technologies in future OFTO Networks

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Abstract: In recent years there has been considerable interest in convertor based generating solutions which to a greater or lesser extent mimic the behaviour of synchronous machines, thus overcoming many of the disadvantages of the existing technologies which are potentially destabilising at high penetration. Such solutions are frequently referred to as Grid Forming Convertors (GFC).

This paper focuses the application of GFC technologies in offshore windfarms, where installation, maintenance and/or modification of any offshore equipment is very expensive and carries greater commercial risks, requiring extensive testing and confidence building prior to deployment in real applications. This is time consuming and particularly significant for GB and where there are large quantities of offshore generation. Onshore solutions to stability are therefore desirable for Off-Shore Transmission Owners (OFTOs), especially, if they could be applied by retrofitting to existing conventional converter plant. Consequently, this paper proposes and investigates the performance of hybrid solutions for offshore networks where the conventional STATCOM onshore unit is replaced by alternative options such as synchronous compensator and VSM converter of similar (or appropriate) rating with the aim of achieving Grid-Forming capability. A laboratory scale implementation of the proposed control algorithm is also presented with selected validation test results.

1. Introduction

This paper reports on the outcomes of the National Grid’s “Hybrid Grid Forming Converter” NIA (Network Innovation Allowance) project, which utilised a Virtual Synchronous Machine (VSM) algorithm, also referred to as Grid Forming Converter (GFC) in this paper. The intention of the work was to improve the understanding of the implications of GFC proposals addressed through GC0100 Option 1 [1] and subsequently the VSM Expert Group [2]. The main objectives of the projects can be summarised as follows:

1. To design and test a VSM algorithm in line with general GFC/VSM principals such as GC0100 option 1 [1];
2. To establish which plant control principals, parameters and tests are particularly relevant to grid stability;
3. To understand how grid forming performance affects one of the possible convertor designs and strategies which might mitigate any negative effects;
4. To establish whether it is possible to provide grid forming performance from hybrid solutions (for example STATCOMs) where not all of the converters are grid forming.

Table 1 shows a matrix of future anticipated GB transmission system, convertor growth inhibitors in the columns and the potential counter measures in the rows. The cells which intersect the columns and rows, show which counter measures are capable of resolving the various inhibitors. It can be seen from Table 1 that only three counter

measures are believed to be holistic, potentially solving all or most of the anticipated inhibitors, either on their own or in combination. This does not mean that the other counter measures investigated are not useful but would need to be combined with other solutions which uniquely solve other areas.

Table 1 Future system inhibitors and counter measures

Solution	Estimated Cost	Ricof	Sync Torque/Power (Voltage Stability/ReI)	Prevent Voltage Collapse	Prevent Sub-Sync Osc. / SG Compatible	Hi Freq Stability	RMS Modelling	Fault Level	Post Fault Over Volts	Harmonic & Imbalance	System Level Maturity	Key
Constrain Asynchronous Generation	High	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	Doesn't No Resolve Issue P Potential I Improves Resolves Issue These technologies are or have the potential to be Grid Forming / Option 1
Synchronous Compensation or More Sync. Gens at lower load	High	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	
VSM	Medium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	P	Modelled	Has the potential to contribute but relies on the above Solutions
VSM/SH	Low	No	Yes	Yes	No	P	P	P	Yes	P	Modelled	
Synthetic Inertia	Medium	Yes	No	No	P	No	No	No	No	No	Modelled	
Other Projects	Low	Yes	P	Yes	No	No	No	P	P	No	Theoretical	

Preliminary results of the various contributions of this project (and a second associated NIA project) have been presented earlier in the form of five conference papers presented at the Wind Integration Workshop in October 2019 in Dublin [3]-[7]. Fig. 1 shows the overall block diagram of the controllers implemented within these two GFC focused projects. The implementation of the controllers and associated hardware differ slightly as each project focused on different aspects of the design but both are similar implementations and are discussed in the relevant papers as

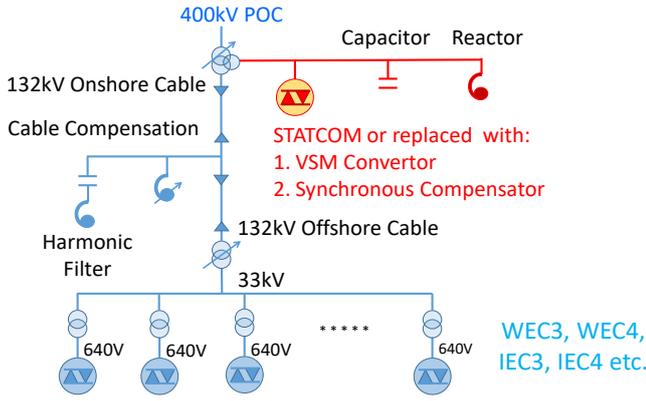


Fig. 2. Typical Topology of an OFTO's Network and Associated Offshore Wind Farm

The main components of the example Offshore Windfarm presented here are:

1. Three winding transformer 400/132/13kV (211 MVA and 120 MVA tertiary)
2. STACOM and reactors (4 x 15 MVar) and capacitors (3 x 15 MVar) for voltage support at the POC
3. Compensation Reactor (60 MVar) for the Cable
4. Harmonic Filter (20 MVar)
5. Onshore (40 km) and Offshore (50 km) 132 kV Cables
6. Offshore Compensation (if fitted – not used here)
7. 2 Winding Transformer 132kV/33kV (211 MVA)
8. LV offshore collector grid (not modelled)
9. Wind Turbine Generators (WTG) including convertors and transformers (modelled as a four tap 211 MVA 33 kV to 690 V transformer and PowerFactory Static Generator rated at 210 MVA)

For the purpose of modelling, the offshore WTGs are often aggregated into one single device, and this approach is also adopted here.

Before considering whether a HGFC solution is workable, it was necessary to build a suitable Offshore Wind Farm model and benchmark it by performing dynamic studies, subjecting it to a variety of scenarios including:

1. Type A faults (140 ms 3-ph) and Type B faults (500 ms, and long voltage dips)
2. Voltage steps, 1%, 2% and 5%
3. Frequency Ramps 0.5 Hz/sec and 1 Hz/sec
4. Vector Shifts (4.5°, 9° and 18°)
5. Various other tests including, but not limited to, frequency sweeps, frequency perturbation, power limiter, islanding, and different combinations of equipment.

Windfarm models were taken from the WECC and IEC type 3 and 4 standard models available in PowerFactory. These were then adapted to include the components for an OFTO network. The components general topology and parameter values for the power system components were taken from averaging typical values available from public sources such as the ETYS data [11]. This included the initial values of the STATCOM rating capacitors and reactors, etc.

For the STATCOM dynamic model a voltage droop controller with PI stabilizing and PowerFactory Statgen power converter was used. This was configured to provide voltage control at the POC, as required by the GB Grid Code. In contrast, the WEC and IEC turbine and power park controllers were setup to operate in constant PF/MVar mode delivering approximately -20 MVar's into the LV side of the 132/33kV SGT, partially to offset the reactive power produced by the cable (the 132kV winding typically absorbs 43MVar from the cable).

The voltage at the 132 kV and 33 kV busbars were controlled through transformer tapping of the LV/MV side of the associated transformers.

3. Wind Farm simulation and testing

3.1. Load Flow Tests

To ensure OFTO network and windfarm had adequate tapping range on all transformers and sufficient reactive reserves, 16 combinations of active and reactive power, POC voltage and fault level were studied. This was done to ensure there were reserves both to maintain control and deliver the required reactive response for the entire operating range and for all operating conditions.

The 16 conditions were derived by creating all possible combinations of the following:

1. Max and Min ($400\text{kV} \pm 5\%$) volts at the POC (Point of Connection) between the OFTO and On Shore transmission system.
2. Max reactive power import and export at the POC (0.95 Lead and 0.95 Lag)
3. Max and Min fault level of approximately 4500MVA and 400MVA respectively (this is controlled by series reactors placed between the POC and controlled infinite bus)
4. Max and Min active power 200 MW (max), and 100MW (min at 0.95 Lead) and 40 MW (min at 0.95 Lag) – from CC.6.3.2 in the GB Grid Code [12].

3.2. Vector Relationship Between Voltages

Fig. 3 shows the relationship between the converter voltage (E), voltage at the point of connection (V_{poc}) and the impedance between them, which is typically dominated by the filter and transformer reactance, denoted here as X_f and X_t (all quantities are pu).

If we assume that the resistance and other impedances are not significant and can be ignored, the vectors E and V_{poc} form a triangle where the third voltage is the voltage across the impedance $X_f + X_t$ and the angle between them is the operating angle of the converter (where X_f is the convertors internal filter and X_t is the transformer reactance).

In the case of the algorithm developed here, E is the PWM voltage at the transistors as indicated in [13]. This vector diagram is superimposed onto the operating chart and we can see that the length of the vector V_{poc} is roughly $1/(X_f + X_t)$ if we ignore the other impedance effects. Although not drawn to scale (V_{poc} is normally longer) we see that changes in power are dominated by changes in delta and changes in reactive power by E and V_{poc} .

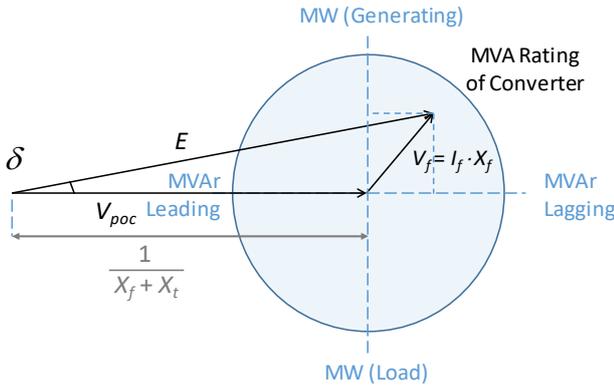


Fig. 3. Vector Relationship between Voltages

Converters typically have a lower coupling impedance to the network ($X_f + X_t$) than SM's and delta is therefore smaller, from the diagram we can see that this has two significant effects for GFC's. First, the GFC's are potentially considerably more responsive to vector shifts than SM's. Note however, SM's do have damper windings which provide some additional contribution to system events and there is no equivalent contribution in the algorithms presented in these papers. Second, a GFC or SM will lose synchronism when delta reaches 90 degrees (the UEL for the SM) but in the case of the converter this is outside the MVA limit operating circle provided the impedance is less than 1 pu.

Whilst GFC's close to a fault or loss of power infeed and subsequent vector shift, may perform less favourably to SM's (i.e. if the current or active power limit is activated), those at intermediate distance where the overall impedance is lower could be more responsive potentially providing increased support.

3.3. System Studies

Fig. 4 shows the model used to study the OFTO network and associated offshore wind farm which consists of an 'almost' infinite bus bar controlled by a test converter whose output voltage and frequency can be modified to perform a variety of tests. Attached to this are a variety of models including a GFC and SM connected to the bus via a 12% impedance transformer for bench marking performance and 7 OFTO networks configured as WECC 3 and 4 and IEC 3 and 4 all with STATCOM's, WECC 4 with GFC (this is the HGFC solution), WECC 4 with SC, WECC 4 with 50% SC and 50% STATCOM.

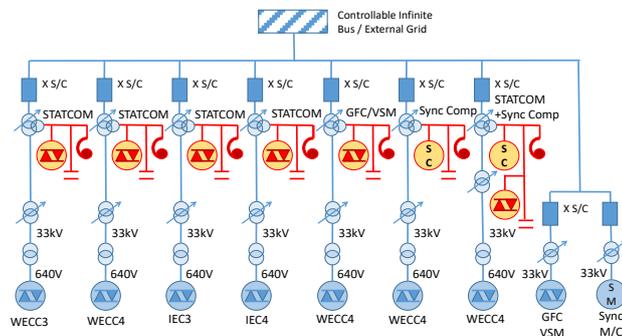


Fig. 4. Infinite Bus Model with all OFTO / WTG models tested

In all cases the dynamics voltage support elements (i.e. the STATCOM, GFC or SC) of OFTO network were sized to 67 MVA with 3x15 MVA of capacitors and 4x15 MVA of reactors (in the case of the 50:50 STATCOM/SC system both were sized at 33.5 MVA). Whilst in practice it is accepted different proportions might be used for economic reasons or to avoid operational limits, they have been scaled to 67 MVA here to allow comparison of performance against rating and in the case of GFC, to allow 33% headroom at 0.95 power factor.

From the studies performed it became apparent, that whilst all the studies were useful in demonstrating different performance characteristics and in many cases compliance with existing grid codes, two or three studies / tests, in particular provide indication of grid forming capability, namely:

1. Vector shift
2. Frequency ramp
3. Frequency perturbation

In the case of the vector shift study, the angle change is applied to the bus bar (although on site for compliance testing it might equally be applied to the GFC). From the graph in Fig. 5 we can see that the type 3 and 4 WECC and IEC wind farms show typical "Grid Following" behaviour and provide no significant power injection (the four blue and green flat lines in the left hand graph) to resist the vector shift but the GFC (black left graph), HGFC (black right graph), SC (blue 100%, cyan 50% right graph) and SG (red left and right graph) provide varying degrees of response.

The quantity of response is proportional to the increase in power for the applied angle change (which was the same for each generator). The level of response to the change in vector is largely dictated by the connecting impedance between the GFC/SC voltage source and the POC voltage.

The difference in frequency of the power swing, between the SC and the directly connected VSM and SG is due to the inertia which is set to 1.8 s in the SC and 6.25 s for the VSM and SG. If the SC inertia is increased to 6.25 s frequency of oscillation aligns with the VSM and SG. The inertia of the VSM in the HGFC is set considerably higher and is of the order of 10 s with damping parameter also altered although the algorithm is the same. Consequently, defining the response in terms of the inertia is not as straightforward as defining the overall response in terms of power produced for a given RoCoF (Rate of Change of Frequency).

The frequency ramp studies show how much equivalent inertial response is provided by each configuration of wind farm and OFTO. It is necessary to take some care when interpreting this result as the response curve shape is affected by contributions from the inertia, damping and droop governor, if active. Again, as can be seen in Fig. 6 there is no significant response from the standard WECC and IEC models (colours and graph format are as Fig. 5).

The frequency perturbation test is detailed in [14] and not displayed here but we make readers aware of it because it is particularly useful for determining phase shifts and bandwidths of the various control system elements, e.g. where the governor response ends and the inertial response starts.

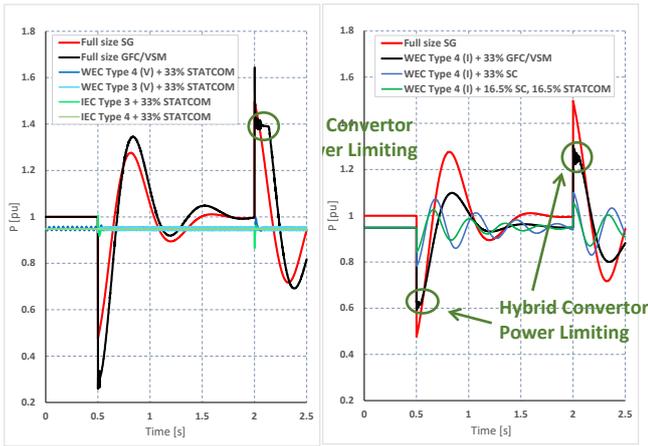


Fig. 5. Responses of differing control solutions to a 9° vector shift

It is particularly interesting to note that in both the vector shift and frequency ramp the HGFC solution outperforms the SC. Furthermore, fitting a solution where 50% of the rating is provided by a SC and the other by traditional STATCOM worsens the response to vector shifts although it may be more beneficial for traditional problems such as voltage support.

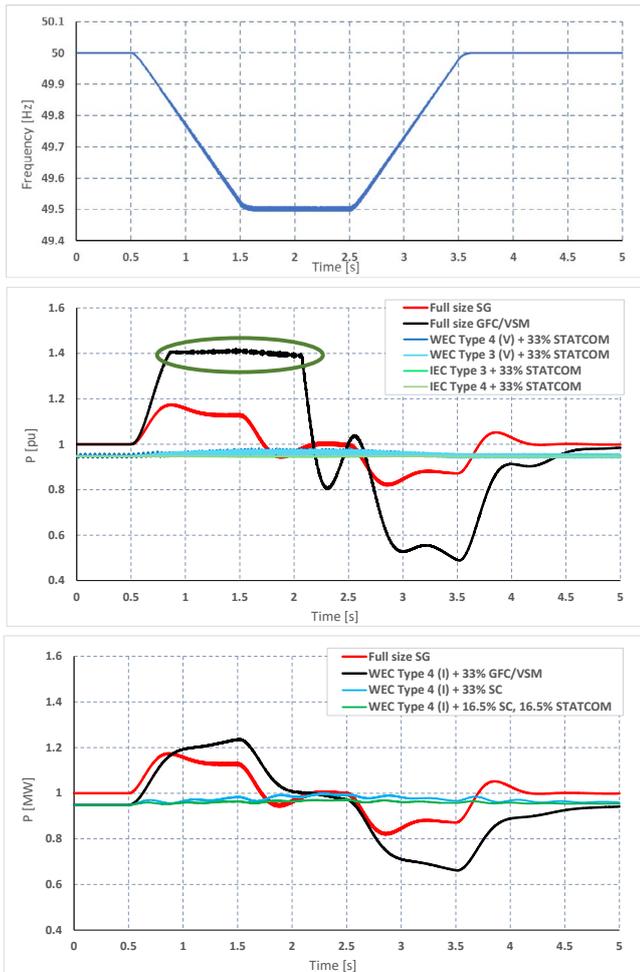


Fig. 6. Responses of differing control solutions to a frequency ramp

3.4. Critical Impedances

It is clear from the vector diagram, displayed in the previous section (Fig. 3), the impedances between the major voltage and power sources dominate the response to the vector shift studies. The lower the impedance the greater the response. The simplified diagram in Fig. 7 shows the equivalent circuit diagram with most significant impedances between the key components responsible for a HGFC.

The performance level is determined by the amplitude of the response and whilst the HGFC model initially used, did not perform quite as well as reference SM or GFC, changing its filter or connecting transformer impedance, either in practice or artificially (by modifying the control system / software) improves performance.

The following paragraphs discuss the effect of reducing the physical impedance but the paper [6] describes an algorithm which was applied to an RMS model and has the same effect as reducing the impedance.

After publication of [5] which included the results shown in Fig. 6, it was noted that the VSM converter's response to a frequency ramp was significantly higher than equivalent synchronous machine. Subsequent further investigation has revealed marked differences in the performance of the differing stabilising algorithms discussed in [4] and [13] which provide damping to the $\frac{1}{2Hs}$ term. Whilst these algorithms can be tuned to give a similar response levels to a vector shift, their response to a frequency ramp varies significantly.

The algorithm used in this paper, is used and described in [13]. Unlike other algorithms it uses the rate of change of the internal frequency state variable rather than the actual measured system frequency. In [13] it was indicated that this could be a preferential because it is not susceptible to noise in the measured frequency signal. However, here we see a disadvantage as this stabilising signal requires the internal frequency to change before damping occurs and this delay results in greater difference in response, whereas other algorithms respond more promptly to external frequency changes.

The response in Fig. 6 has demonstrated the importance of extensive testing with a wide variety of scenarios and the need for further work to optimise this particular aspect of the design, the stabilising algorithm, for all scenarios.

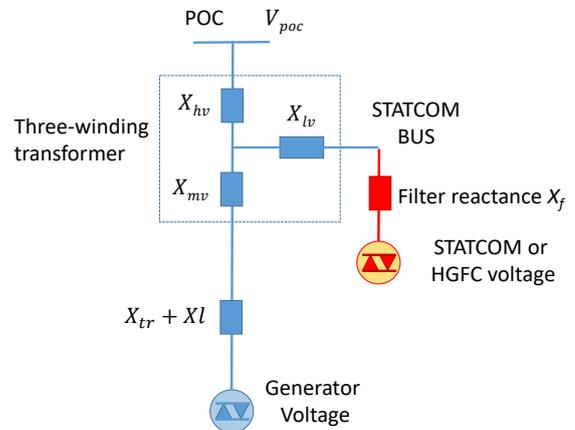


Fig. 7. Simplified Impedances for an Offshore Wind Farm

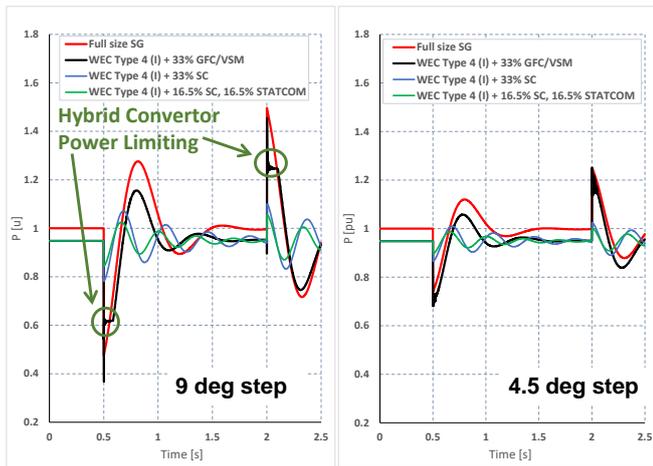


Fig. 8. Vector shift response with filter impedance reduced from 10% to 1%

The graph in Fig. 8 shows the HGFC response to the same test but here it is assumed that a converter solution is provided which utilizes only 1% impedance in its output filter and the tertiary winding of the transformer is uprated from 120MVA to 150MVA which effectively reduces its impedance by the same proportion. This design would rely heavily on the 3-winding transformer to provide additional decoupling from the network and the current limiter and converter protection would need careful consideration with such a low filter impedance. However, practicalities aside it can be seen, the response is improved outperforming the SG for 4.5° vector shift.

Likewise, because the HGFC inertia is typically programmed in software and the SC inertia, unless a flywheel is fitted, has a lower value ($H = 1.8$ s was used) than a Synchronous Generator, HGFC outperforms the SC in terms of inertia. It is evident in the results both in terms of the magnitude of power injected for the vector shift and rate of change of frequency study results the HGFC performance is better. The 50:50 SC/STATCOM solution as might be expected, provides less performance but it is not proportional as the tertiary winding impedance is still set to 120 MVA and not reduced.

In addition to the potential performance benefits of HGFC, if fitted with batteries for energy storage, such systems can store or provide energy when not being used for grid forming control.

3.5. Equivalent Synchronous Compensator Performance

The parameters used for the synchronous compensators were the same as the base case synchronous generator with the inertia and MVA being the only exceptions. The inertia and MVA of the synchronous compensator were set to 6.25s and 211MVA to match the synchronous generator and the system was retested. There was a considerable reduction in the frequency of the power oscillation and significant increase in the power produced for vector shifts. However even with 211MVA rating for the synchronous compensators, the power swing for a 4.5degree angle change was only about 50% of the HGFC or synchronous machine responses.

The difference can be explained by increasing the rating of the 3 winding transformer or reducing its impedance which significantly improves performance. Both increasing rating or reducing the impedance effectively reduces the overall impedance.

The 211MVA synchronous compensator is still outperformed by the HGFC for a 9-degree change, even though the HGFC limits its output power. To achieve a significant performance improvement, both synchronous compensator and transformer impedance have to be reduced.

4. Hardware implementation and laboratory testing

The final stage of the GFC project undertaken by the University of Strathclyde involved Power Hardware-In-the-Loop (PHIL) implementation of the selected models and scenarios. To this end, an experimental testbed at the Power Networks Demonstration Centre (PNDC) was setup. The main elements / tasks of this development included:

1. A real time RTDS model of a DFIG based off-shore wind farm in the RSCAD environment, with a real-time controllable voltage source to represent 13kV STATCOM bus allowing the connection of real VSM converter. This was achieved using Triphase power converter platform configured as a controllable voltage source.
2. A second Triphase converter was programmed with VSM with Zero Inertia (VSM0H) and a conventional Direct-Quadrature Current Injection (DQCI) control logic to represent the STATCOM.
3. The VSM0H control was extended to include an inertial element, to achieve a grid forming behaviour, turning it into a VSM converter.
4. Each element was first tested on its own, then the two Triphase converters were connected to the RTDS windfarm model and the complete system was tested with a specific sub set of test scenarios.

High level arrangement, utilised in these tests, is presented in Fig. 9. More detailed description of the testbed is included in section 4.4.

4.1. Converter model implementation on Triphase

The Triphase platform (custom built for PNDC by the manufacturer) is a configurable AC and DC controllable power supply that implements six 90 kVA power converters (summing to a total of 540 kVA). The Triphase system can be configured to operate both in AC and DC modes of operation. For the purposes of this work, the Triphase was operating in 3-wire configuration with 3 units operating in AC Voltage Source (VS), and 3 units operating in Current Source (CS) mode. In the 3 CS operating converters the native control is subsequently replaced by the GFC/VSM and DQCI algorithms. The other 3 converters operate as a strong voltage source which acts as an interface between the converter prototype (VSM0H, VSM or DQCI) and the RTDS model. In this mode the tests can be performed at 480V, with 390A, and deliver up to 270kW of power.

4.4. Laboratory setup and results

The laboratory testbed was realised through the connection of the Triphase unit (running the GFC type control) with the RTDS rack running the windfarm and grid simulation (refer to Fig. 9). The power hardware interface was arranged as follows. The measurements of 3-phase voltage from the windfarm PCC to the grid are gathered and sent from the RTDS to the DQCI/GFC control in Triphase that in turn (after calculating the appropriate currents) injects them back into the grid in RTDS thus closing the loop of the Power Hardware in the Loop (PHIL) simulation. This is necessary because the STATCOM or VSM must inject reactive power to control the voltage at the PCC embedded within the RTDS model and not the local STATCOM bus.

In Fig. 12 response of the hybrid windfarm solution (with GFC replacing conventional STATCOM) to the 0.5 Hz/s frequency ramp is presented. It can be observed that the time and shape of response, and return to steady state after 4.5 s bear similarities to the results from the offline PowerFactory simulation (included in Fig. 6), in particular, it resembles actual SG response. The more pronounced PowerFactory VSM response is due to the stabilising algorithm used to damp the swing equation. Additionally, to illustrate the impact of the VSM based STATCOM solution, the power response from the conventional DFIG based wind park (i.e. without VSM capability) is also included in Fig. 12.

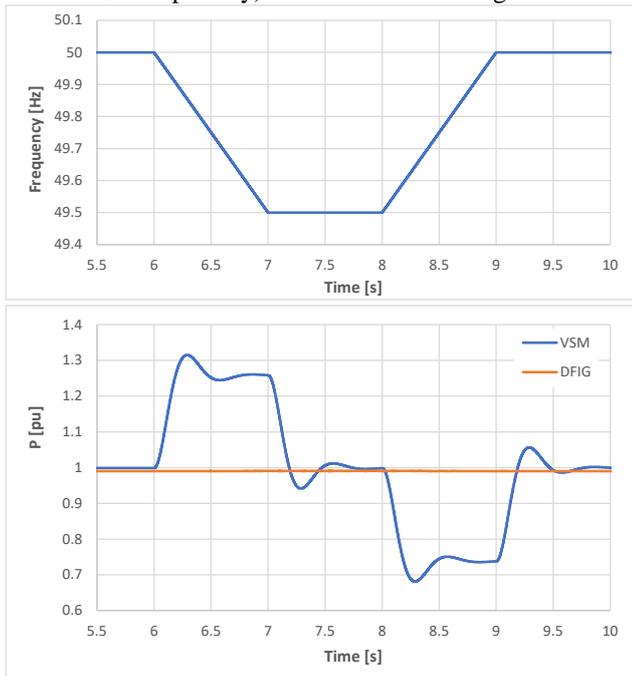


Fig. 12. Laboratory PHIL based hybrid OFTO response to a 0.5 Hz/s frequency ramp

In Fig. 13 and Fig. 14 the HIL test results for 9° and 4.5° voltage phase jumps are presented respectively. The three traces are included in each figure to illustrate the difference in response between conventional current control (negligible response similar to DFIG based windfarm with STATCOM), and grid forming type responses from the VSM0H and VSM control models. The initial power step is determined by the total series impedance in the system (which is the same in both cases) and the following dynamic transient depends on the specifics of the control algorithm. In the VSM

response, where the swing equation is implemented, a damped power swing can be observed, similar to the response of a physical SG, whereas the VSM0H return to steady state much quicker. The responses of the DQCI and VSM models can also be compared with the PowerFactory simulations shown in Fig. 5. Although the relative magnitude of the response differs due to some differences in physical parameters of the laboratory setup (e.g. converter filter reactance), as well as, somewhat different implementation of the VSM algorithm, the overall shape and the direction of the response agrees quite closely. In particular, the DQCI weak power response matches closely that of a conventional Type 3 or Type 4 windfarm (LHS of Fig. 5), whereas, the VSM response, in its shape, corresponds to the hybrid converter solution (refer to the black trace on the RHS in Fig. 5).

Moreover, as expected from the physical testing, the HIL-based results are characterised by a relatively high frequency power oscillation. This is attributed to an interaction between the windfarm and the VSM which may not be adequately represented in the PowerFactory RMS based simulation model or appropriately damped out in the physical implementation. Consequently, this requires further investigation.

Nevertheless, even with those apparent differences, the behaviour observed in software was proved to be reproducible on a generic programmable converter platform, which was the main objective of the hardware prototype test at this stage.

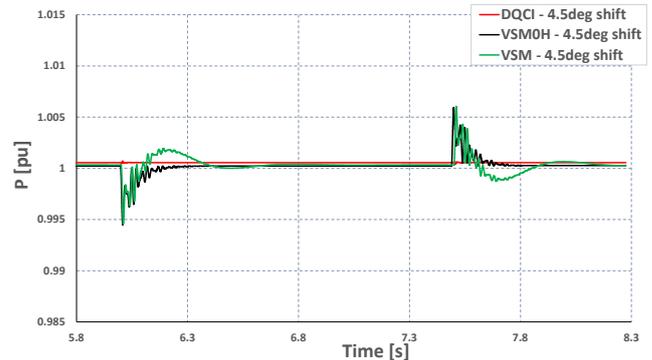


Fig. 13. Active power windfarm response to 9° phase jump (PHIL results)

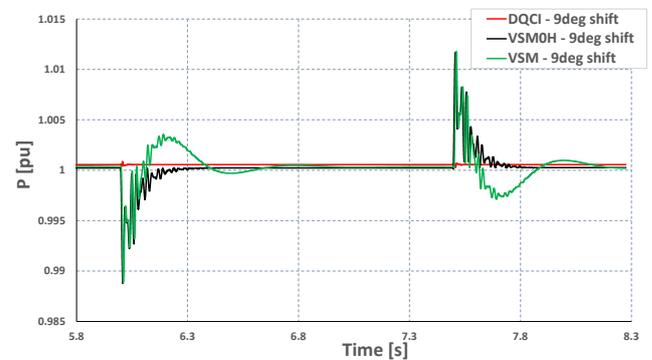


Fig. 14. Active power windfarm response to 4.5° phase jump (PHIL results)

5. Discussion

5.1. Key conclusions

This project has identified fundamental tests for evaluating and quantifying the properties of grid forming generation, in particular, resistance to vector shifts and RoCoF. During these tests grid forming convertors almost instantaneously and without measurement inject active power resisting the change in frequency or angle. These tests therefore provide a means of specifying and evaluating the performance of Grid Forming Convertors equivalent inertia or stiffness / impedance in terms of MW for given Hz/s and MW for a given angle change. This is particularly important when specifying the performance of hybrid systems as they are not a single voltage source behind an impedance, the rating of the convertor is typically smaller than the generator requiring parameters such as H to be scaled and because the response may come from more than one source.

In respect of these tests the PowerFactory simulations demonstrated that a 200 MW conventional offshore windfarm can perform to the same level or better than conventional synchronous generation, at least until the MVA rating of the onshore grid forming convertor is reached. In addition to testing of a 67 MVA onshore hybrid convertor solution, tests have also been performed with a 67 MVA synchronous compensator and a 50:50 combination of 33.5 MVA synchronous compensator and 33.5 MVA STATCOM, all of which were outperformed by the 67 MVA hybrid convertor in the two previously mentioned tests.

However, it should be pointed out that whilst it is impressive that a 67 MVA convertor was all that was necessary, it is possible its rating is too small for the onshore convertor or synchronous compensator as (depending on how fast and frequently other reactive components can switch in and out) it may need to supply up to 62 MVar and 66 MW simultaneously i.e. a rating of 92 MVA may be more appropriate.

If the rating of the synchronous compensator was increased to 92 MVA, its performance would increase significantly but not by enough to provide the same level of performance as the Hybrid Convertor System or equivalent synchronous generator.

GC0100 option 1, specifies a number of requirements, for example:

- The convertor must look like a voltage source behind an impedance over the 5Hz to 1 kHz band.
- The convertor must inject 1.5 pu fault current in the correct phase, which attempts to restore the voltage phase.

Whilst the results have demonstrated that the system provides a similar response to a standalone VSM in respect of vector shift and RoCoF, the Hybrid system cannot be fully compliant with GC0100 option 1, unless the equipment offshore also meets the compliance criteria. If the equipment offshore utilises a PLL current source convertor, it will to some degree, follow the vector shift. However, it is highly likely that such a system could be made to contribute 1.5pu fault current, although some questions may remain regarding the phase of the contribution from the generator.

Further consideration and consultation is therefore required to determine if such systems should be permitted, and if so, whether they are permitted on a time limited basis to allow deployment while offshore components are developed and tested, from which point full compliance would be required.

It may be possible, to measure the voltage and current at the medium voltage terminal of the three winding transformer with the aim of injecting a counter phase signal from the onshore hybrid convertor to deliver a compliant solution (e.g. voltage source behind an impedance). This may offer an alternative route to making the offshore equipment compliant were it necessary. Alternatively placing the offshore equipment in some limited voltage source mode where most of the response is delivered onshore might also be worth exploring.

Hybrid Grid Forming Convertor systems have a significant advantage when connected to batteries as they can be used to store energy as well as providing grid forming and reactive services. However, under the current regulatory regime, network operators and owners not permitted to own bulk storage technologies.

Grid forming convertors require storage unless otherwise curtailed (for example spilling wind). Generators and others are allowed to own storage, which raises the interesting question of whether the generator would be allowed to own the onshore convertor or whether the OFTO can sell a DC connection to a generator or battery owner. The rules relating to network owners (including OFTO's) regarding owning storage for grid forming purposes, need further clarification.

The laboratory based HIL tests demonstrated that the physical implementation of the VSM type algorithms is achievable using a standard power electronic platform, and the performance is similar to the PowerFactory simulation, with added higher frequency power fluctuations which may or may not be detrimental in a wider scale implementation in the power grid.

5.2. Additional observations

There are a number of characteristics and advantages and disadvantages of GFC's and SM's but perhaps six key characteristics are of particular significance or have been highlighted during this work.

Two relate to physical attributes, two to the current and power limit and two to readiness and additional services. In summary three are largely potential advantages of SM's and SC's and three advantages of GFC's.

For SM's and SC's the advantages are:

- The fault current is limited by the impedance only and the machines essentially maintain voltage behind an impedance behaviour although that impedance changes transiently. Conversely converter currents are limited by the rating of the semiconductors and there comes a point for close-up faults where the device must go into current limit to prevent damage.
- Likewise, the convertor AC and DC rail current limit results in an active power limit which once exceeded requires the device to rapidly reduce operating angle. The output power and current then become regulated to the rating of the convertor.

- SM's and SC's are established technology which are well understood, both in practice and from a modelling perspective. GFC's by contrast are a new technology and many manufacturers are implementing new and differing algorithms. Past experience has shown it is wise to assume that some implementations may initially, perform better than others.

GFC's offer the following advantages:

- The lower impedance coupling the voltage source to the network, results in greater response to vector shifts and provides stronger grid forming capability. This is of greater significance at increased distance to any disturbance, i.e. where the majority of plant are likely to be located. This is also an advantage in the OFTO and HGFC applications discussed in this paper.
- Assuming sufficient energy reserves are provided (see paper 1 [1]), the quantity of inertia within GFC's is typically dependent on software parameters rather than the physical attributes of the system. By contrast, SC's, unless fitted with fly wheels, have less inertia than SG's and therefore provide reduced support during frequency / RoCoF events. Their performance is considerably reduced when compared with Synchronous Generator's, GFC's and HGFC's.
- SG's fitted with clutch or able to spin at no load, and GFC's and HGFC's fitted with batteries, have the advantage that they can be used to generate or store energy whereas SC's only provide a sub set of the services which are limited to grid and voltage stability. Whilst it is difficult to determine the economics at the time of writing, it is feasible that in this respect GFC's and HGFC's could be more economic to operate, particularly as they contain no moving parts.

GB wide system studies were not performed as part of this work and it is therefore only possible to speculate what the effects this might have on the wider transmission system. However, with fault current and power infeed only limited by their impedance it would be logical to assume that SM's would perform better in this respect, when very close to a fault or loss of infeed. However, if SC's MVA is not increased nor the impedance reduced, HGFC's have the potential to outperform them at increased electrical distance, in retrofit applications and OFTO networks.

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