Performance of Hybrid Power Park Technologies in future OFTO Networks with the aim to achieve Grid-Forming Capability

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***Abstract*— There has been considerable interest in convertor solutions which to a greater or lesser extent mimic the behaviour of synchronous machines, thus overcoming many of the disadvantages of the existing technology which are potentially destabilizing at high penetration. These solutions are frequently referred to as Grid Forming Convertors (GFC).**

For offshore installations, where some equipment is on shore, locating equipment offshore is more 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 significant quantities of offshore generation. Onshore solutions to stability are therefore desirable for Off-Shore Transmission Owners (OFTOs) and might also be applied by retrofitting to existing conventional converter plant.

Consequently, NG ESO and UoS embarked on a project to investigate hybrid solutions for offshore networks where the STATCOM onshore 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.

Keywords—Grid Forming Convertors (GFC), Virtual Synchronous Machine (VSM), RMS Modelling, Offshore Wind, OFTO, GC0100, Grid Codes (GC), Inertia

I. INTRODUCTION

This paper is the third of five papers describing National Grid's two VSM (Virtual Synchronous Machine) NIA (Network Innovation Allowance) projects. These two projects have been undertaken in partnership with University of Nottingham (UoN) and University of Strathclyde (UoS). They are intended to improve the understanding of the implications of GFC proposals addressed through GC0100 Option 1 [8] and subsequently the VSM Expert Group [11]. The purpose of the projects and/or papers are:

1. To design and test a VSM algorithm in line with general GFC/VSM principals such as GC0100 option 1 [8].
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.

It should be noted that whilst the authors have sought to explore a possible implementation of VSM. It is not National Grid's intention to mandate any specific design. NG ESO (National Grid Electricity System Operator) only seeks to examine some of the practical considerations surrounding the technical requirements detailed in GC0100 option 1 [8] [11]. This is not intended to prescribe a design of a physical convertor, it is intended to simply illustrate one potential approach for discussion though it is noted that other implementations could be used, some of which are also discussed in the papers.

It is suggested readers first read [1] to get a broader introduction conclusions on the topics and controller models presented in this paper and the other paper.

Table I below, shows a matrix of future anticipated GB transmission system, convertor growth inhibiters 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 inhibiters.

It can be seen from Table I that only three counter measures are believed to be holistic, potentially solving all/most of the anticipated inhibiters, 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, which are increasingly influencing the practical costs in the operation and planning of networks.

TABLE I. FUTURE SYSTEM INHIBITERS AND COUNTER MEASURES

Solution	Estimated Cost	RoCoF [1] [2]	Sync Torque/Power (Voltage Stability/Ref) [2] [*] [4]	Prevent Voltage Collapse [2]	Prevent Sub-Sync Osc. / SG Compitable [2] [*]	Hi Freq Stability [2]	RMS Modelling [1] [2] [*] [4]	Fault Level [1] [2]	Post Fault Over Volts [2]	Harmonic & Imbalance [5]	System Level Maturity	Notes
Constrain Asyncronous Generation	Hgh	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	These technologies are or have the potential to be Grid Forming / Option 1
Syncronous 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	
VSM0H	Low	No	Yes	Yes	No	P	P	P	Yes	P	Modelled	Has the potential to contribute but relies on the above Solutions
Synthetic Inertia	Medium	Yes	No	No	P	No	No	No	No	No	Modelled	
Other NG Projects	Low	Yes	P	Yes	No	No	No	P	P	No	Theoretical	

Key

No	Doesn't Resolve Issue
P I	Potential Improves
Yes	Resolves Issue

Fig. 1 below shows the overall block diagrams of the controllers implemented by NG ESOs partners UoN and UoS. The implementation of the controllers and associated hardware differ slightly as each partner focused on different aspects of the design but both are similar implementations and are discussed in the relevant papers. In addition to the physical implementation and realization of the convertors both partners and NG have built models in MATLAB, RTDS and RMS models in PF (PowerFactory).

The numbers [2] [4] etc. in Figure 1 indicate where specific topics are covered by specific papers and [*] refers to this paper.

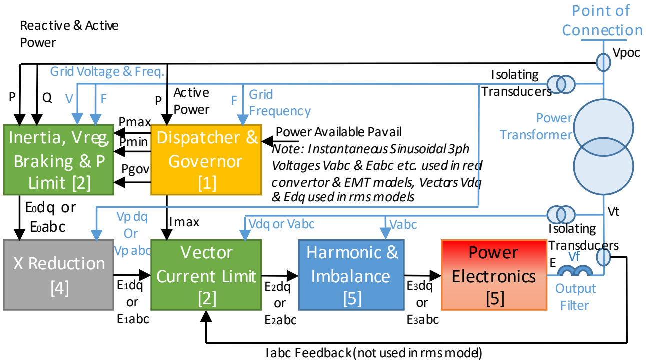

Fig. 1. Simplified Block Diagram of potential VSM Implementation

From Fig. 1 we can see the converter design largely consists of 6 major blocks:

- Dispatcher and Governor
- VSM (Inertia simulation and stabilizing, Dynamic braking, Voltage Control and Power Limiter).
- Impedance Reducer
- Vector Current Limiter
- Harmonic and Imbalance Management
- Convertor Output Stage and Power Electronics

The results in this paper use the models described above but the paper itself does not focus on the model. The paper uses the model in combination with various wind farm models and network elements (Transformers, Lines, STATCOMs, etc.) to build an OFTO network and test the combined solution against standalone VSM and Synchronous Machines (SM's).

Findings from the first stage of the research will be presented and discussed in this paper where a typical OFTO network is constructed and tested using WEC and IEC WTG (Wind Turbine Generator) and plant controller models. A variety of test conditions are applied to the network and WTG, and these are bench marked against a conventional synchronous generator and non-hybrid VSM solution. The onshore STATCOM is then replaced with a Grid Forming VSM convertor or Synchronous Compensator (SC), retested and the results presented. Finally, parameters and ratings are adjusted to improve and provide comparable performance with the Synchronous Generator (SG) / Synchronous Machine (SM) and standalone VSM solution.

II. BUILDING A TESTABLE OFTO AND WINDFARM MODEL

A. *Introduction*

In recent years, there has been considerable interest in GFC within Europe and elsewhere in the world. In Europe, with the ENTSO-E working group recently publishing ENTSO-E TG HP Report [7] and NG ESO the GC0100 option 1 proposals [8]. Additionally, a number of researchers and manufacturers have proposed a variety of solutions (e.g. see [9]). Furthermore, some of these solutions have achieved a maturity level that has seen them move from the laboratory to field trials (e.g. see [10]).

Whilst there has been considerable progress in recent years, uncertainties still remain with regard to specific convertor functionality requirements and testing, as well as manufacturer readiness to offer such solutions for offshore windfarms, as the financial risks are substantial. Considerably greater testing and confidence is therefore required.

Offshore windfarms with an AC connection back to the mainland typically contain convertor equipment in the turbines located offshore and normally a STATCOM located in the onshore substation (in a minority of cases an SVC might be used instead). The STATCOM provides the voltage control at the Point of Connection (POC), i.e. connection to the mainland Grid.

This paper considers whether it is possible to leave the offshore equipment and converter control unchanged and provide the GFC capability for the offshore windfarm, just using the onshore convertor, i.e. near the POC. The paper also considers the effect of replacing the STATCOM with a synchronous compensator of similar rating to the GFC (used to replace the STACOM).

In this paper, we refer to the mixed convertor solution as a Hybrid Grid Forming Convertors (HGFC), as the equipment offshore is not Grid Forming but the plant onshore is. Offshore installations are of particular importance to GB where currently approximatly 8GW proportion of its WTG population is located offshore and this figure is set to increase with most wind developments in England and Wales now occuring offshore.

In addition to reducing the time to market by reducing the risk and testing required, such a solution has further potential benefit, being cheaper to install and maintain and yet still further benefits as it is retrofittable and could potentially be used with a variety of technologies such as DFIG's.

Whilst the authors have tried to consider a variety of standard turbine models, HVDC connected systems are not considered within this work. The receiving end of a HVDC terminal would probably be one large VSM convertor and not the hybrid solution of the type presented here, and this arrangement is therefore not discussed.

B. *Typical Topology of an Offshore Windfarm*

Fig. 2 shows the typical topology of an AC connected offshore windfarm.

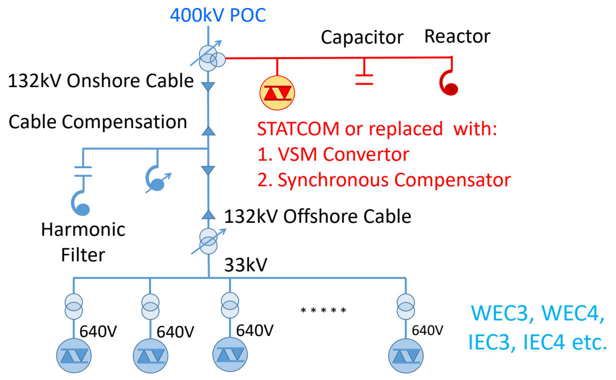

Fig. 2. Typical Topology of an OFTO's Network and Associated Offshore Wind Farm

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

1. Three winding transformer 400/132/13kV (211MVA and 120MVA tertiary)
2. STACOM and reactors (4 x 15MVAr) and capacitors (3 x 15MVAr) for voltage support at the POC
3. Compensation Reactor (60MVAr) for the Cable
4. Harmonic Filter (20MVAr)
5. Onshore (40km) and Offshore (50km) 132kV Cables
6. Offshore Compensation (if fitted – not used here)
7. 2 Winding Transformer 132kV/33kV (211MVA)
8. LV offshore collector grid (not modelled)
9. Wind Turbine Generators (WTG) including convertors and transformers (modelled as a four tap 211MVA 33kV to 690V transformer and PowerFactory Static Generator rated at 21MVA)

NB for the purpose of modelling, the Offshore WTGs are often aggregated into one single device and is adopted here.

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

1. Type A faults (140ms 3-ph) and Type B faults (500ms and long voltage dips)
2. Voltage Steps, 1%, 2% and 5%
3. Frequency Ramps 0.5 Hz/sec 1 Hz/sec
4. Vector Shifts (4.5, 9 and 18 Degrees)
5. Various other tests… (Frequency Sweeps / Frequency Perturbation, Power Limiter, Islanding, and different combination of equipment etc.)

The initial windfarm models were taken from the WECC and IEC type 3 and 4 standard models. 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 [6]. 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 convertor 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 the 132/33kV SGT, partially to offset the MVArs produced by the cable (the 132kV winding typically absorbs 43MVAr from the cable).

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

III. WIND FARM SIMULTAION AND TESTING

A. *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 (400kV ±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 [13].

B. *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).

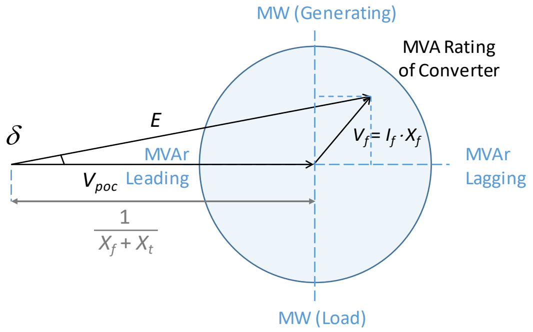

Fig. 3. Vector Relationship between Voltages

In the case of the algorithm developed here, E is the PWM voltage at the transistors but as indicated in [2]. 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}.

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 convertor 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.

C. System Studies

Fig. 4 shows the basic WECC and IEC model configurations with and without the OFTO network used to study the various solutions. The PowerFactory station controllers and dynamic controllers are configured in different modes for OFTO and non OFTO operation.

Without the OFTO the controllers are set to provide voltage droop response at the POC for the WEC controllers and the WTG is in local mode for the IEC controllers. When combined with the OFTO network the Controllers of the WECC and IEC models are set to provide constant reactive power at the connection point of the subsea cable to the shore (initially using the PowerFactory station controllers). The STATCOM, its associated station controller and additional reactive resources (capacitors and reactors) provide voltage droop control at the POC, both for dynamic and load flow simulations. Optionally the STATCOM can be replaced by a GFC or a SC or combination of SC and STATCOM, to test these configurations too. Feedback measurement points are taken from the POC of the onshore transmission system for both the STATCOM and VSM convertor used in place of the STATCOM.

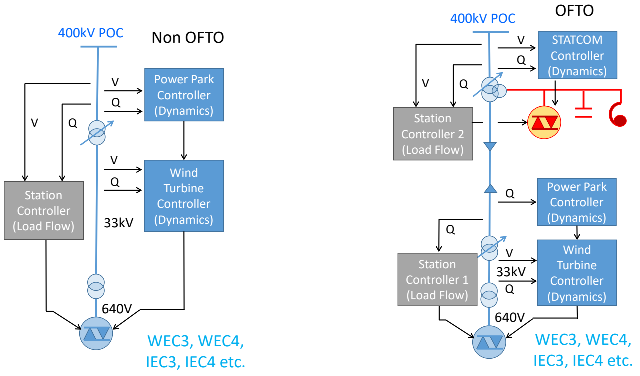

Fig. 4. Basic WECC and IEC model configuration with and without OFTO

Fig. 5 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 and finally a hybrid solution where the WTG are GFC's and the voltage support is provided by a STATCOM.

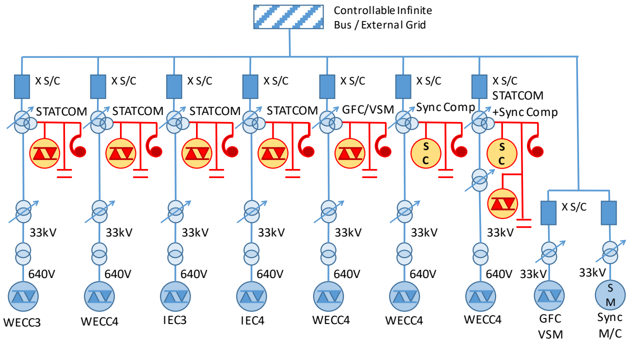

Fig. 5. Infinite Bus Model with all OFTO / WTG models tested

In all cases the dynamics voltage support elements (i.e. the STATCOM, GFC or SC) of OFTO network were sized to 67MVA with 3x15MVA of capacitors and 4x15MVA of reactors (in the case of the 50:50 STATCOM/SC system both were sized at 33.5MVA). 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. 6 we can see that the type 3 and 4 WECC and IEC wind farms provide "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 vector is largely dictated by the connecting impedance between the GFC 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 1.8s in the SC and 6.25s for the VSM and SG. If the SC inertia is increased to 6.25s it 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 10s with damping parameter also altered although the algorithm is the same. Consequently defining the response in terms of the inertia is not as straight forward as defining the overall response in terms of power produced for a given RoCoF (Rate of Change of Frequency).

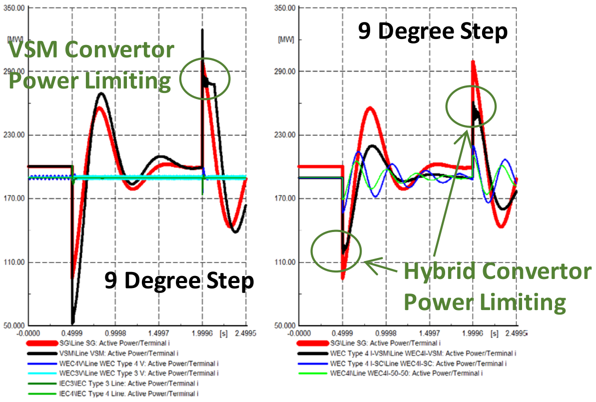

Fig. 6. Responses of differing control solutions to a vector shift

The frequency ramp study's 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. 7 there is no significant response from the standard WECC and IEC models (colours and graph format is as Fig. 6).

The frequency perturbation test is detailed in [12] 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.

It is particularly interesting to note that in both the vector shift and frequency ramp the HGFC solution out performs 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.

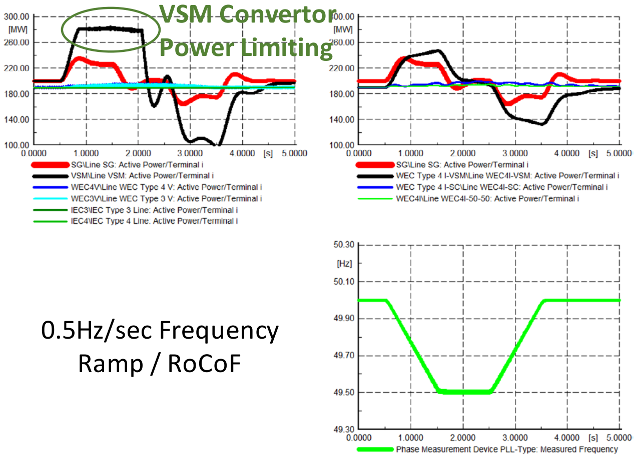

Fig. 7. Responses of differing control solutions to a frequency ramp

D. *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. 8 shows the equivalent circuit diagram with most significant impedances between the key components responsible for a HGFC.

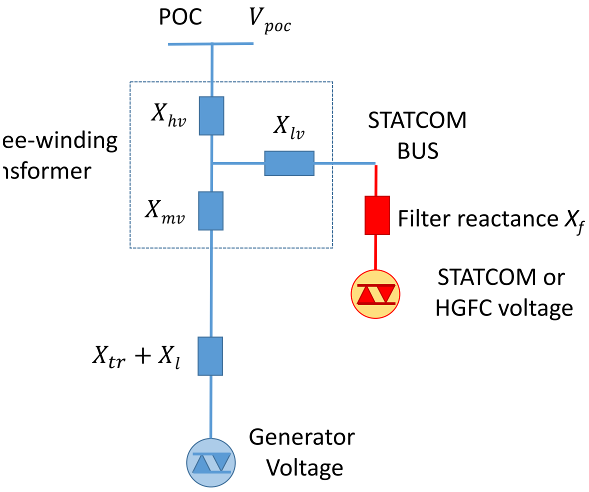

Fig. 8. Simplified Impedances for an Offshore Wind Farm

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 discusses the effect of reducing the physical impedance but the fourth paper [4] describes an algorithm which was applied to an RMS model and has the same effect as reducing the impedance.

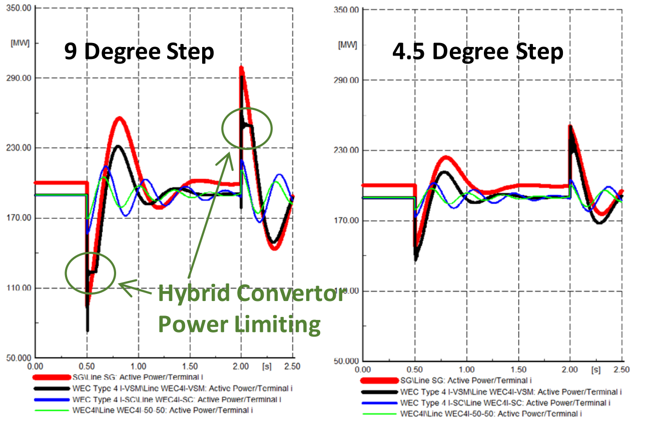

Fig. 9. Vector shift response with filter impedance reduced from 10% to 1%

The graph in Fig. 9 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 uprated from 120MVA to 150MVA which effectively reduces it 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 convertor 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 degrees.

Likewise, because the HGFC inertia is typically programmed in software and the SC inertia, unless a flywheel is fitted, has a lower value (H of 1.8 seconds 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's not proportional as the tertiary winding impedance is still set 120MVA and not reduced.

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

E. *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 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 extended 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 relatively 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 at least, perform better than others.

However, GFC's offer some significant 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.
- Provided sufficient energy reserves are provided (see paper 1 [1]), the quantity of inertia within GFC's is typically dependent on software parameters / variables 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 (pre-Stability Path Finder [14] [15] conclusions), 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 indeed. 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.

F. *Equivelent 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 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 reduce the impedance.

The performance of the 211MVA synchronous compensators performance 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.

IV. 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/Sec 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 project has demonstrated that a 200MW 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 67MVA onshore hybrid convertor solution, tests have also been performed with a 67MVA synchronous compensator and a 50:50 combination of 33.5MVA synchronous compensator and 33.5MVA STATCOM, all of which were outperformed by the 67MVA hybrid convertor in the two previously mentioned tests.

However, it should be pointed out that whilst it is impressive that a 67MVA 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 62MVAr and 66MW simultaneously i.e. a rating of 92MVA may be more appropriate.

If the rating of the synchronous compensator was increased to 92MVA, 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 1.5pu 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, unless the equipment off shore also complies, by fully compliant with GC0100 option 1. If the equipment offshore utilises a phase lock loop 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.

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.

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