Enhanced Virtual Synchronous Machine (VSM) Control Algorithm for Hybrid Grid Forming Converters

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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.

This paper presents and discusses findings of the second stage of the research focusing on the enhanced control algorithm for Hybrid Grid Forming Convertors for Offshore Wind Applications and its performance, while the previous paper [3] presents the initial findings comparing various hybrid solutions for offshore networks where the STATCOM onshore is replaced by synchronous compensator and GFC or Virtual Synchronous Machines (VSM) converter of similar rating with the aim to achieve levels of 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 fourth 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 some 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] [3] [*]	Prevent Voltage Collapse [2]	Prevent Sub-Sync Osc. / SG Compitable [2] [3]	Hi Freq Stability [2]	RMS Modelling [1] [2] [3] [*]	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 – Potential; I – 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 Fig. 1 indicate where specific topics are covered by specific papers and [*] refers to this paper.

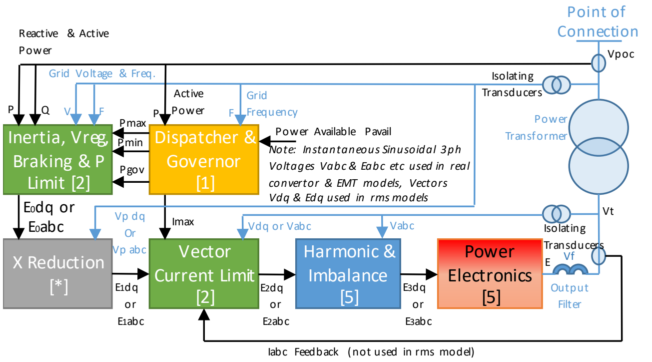

Fig. 1. Simplified Block Diagram of potential VSM Implementation

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

(i) Dispatcher and Governor

(ii) VSM (Inertia Simulation and Stabilizing, Dynamic Braking, Voltage Control and Power Limiter).

(iii) Impedance Reducer

(iv) Vector Current limiter

(v) Harmonic and Imbalance Management

(vi) Convertor Output Stage and Power Electronics

This paper focuses on (iii), the impedance reducer. This is an enhanced GFC control algorithm is based on the aforementioned GFC/VSM controller which employs modifications to further improve performance on voltage angle shift events without incurring significant increase in converter rating or reduction in the filter and transformer impedance.

The proposed enhanced VSM control algorithm is applied in the offshore windfarm model described in the associated paper [3], its performance is tested through case studies (network angle shift) and compared with other options such as models of the current technology, synchronous compensator (SC), original VSM presented in [4] and previous level of performance with algorithm disabled.

II. X Reduction Algorithm for OFTO Systems

A. Introduction

This paper discusses the second stage of a project considering a hybrid approach to Grid Forming Convertors, principally for offshore windfarm applications but the technique may also be useful for onshore and retrofit applications. The first part of the project was discussed in [3] but is summarized here.

Locating equipment offshore increases both the installation and running cost. Additionally, from the developers and manufacturers perspective, there are considerable financial and reputational risks when implementing new designs, because the financial risks are much greater in offshore applications. New designs are therefore frequently developed, tested and proven onshore first.

AC offshore windfarms and transmission networks differ in their design and operation as they typically operate the windfarm such that control is applied to minimize the MVAr flow in the cable, often offsetting some of the cable capacitance with the windfarm or reactors.

The GB Grid Code stipulates that reactive droop voltage control must be provided at the interface point between the onshore grid and OFTO network and this is typically achieved using a combination of onshore components including a STATCOM, reactors and / or capacitors.

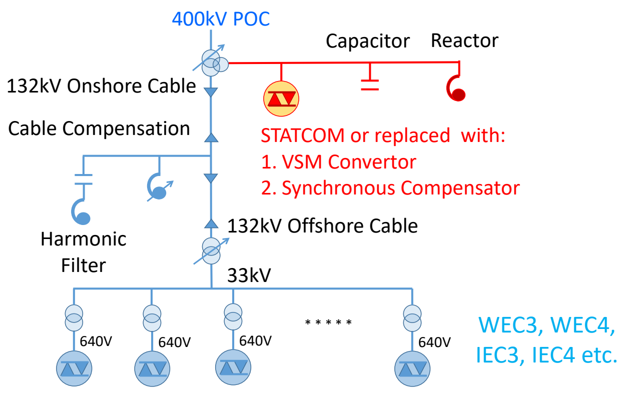

Fig. 2. Single Line Diagram (SLD) of a model for a typical OFTO

Fig. 2 above, shows a SLD of a model for typical OFTO and windfarm. For more information on how this model was developed please refer to [3].

In the first part of this project also described in [3], we considered whether it was possible to change the STATCOM for a GFC and leave the offshore windfarm unaltered in order to reduce the cost of the solution and risk to manufacturers, developers and ultimately, the owners / generators. Such a solution where the generator is left unaltered and a supplementary system provides the grid forming capability, is referred to here as a Hybrid Grid Forming Convertor (HGFC).

Many studies were performed but three in particular were useful for demonstrating "Grid Forming" capability, namely:

1. Vector Shift / POC Voltage Angle Change
2. Frequency Ramp
3. Frequency Perturbation

Studies demonstrated that a HGFC provides a significant response to a vector shift when typical grid coupling impedances are used i.e. a typical three winding transformer in Fig. 2 and a convertor with a 10% filter. However the response was not as big as the response obtained from a SM or directly connected GFC.

Reducing the filter impedance of the hybrid solution from 10% to 1% and increasing the rating of the tertiary winding from 120MVA to 150MVA improved the response and this is one of the methods of achieving a similar level of response to a SM or directly connected GFC.

The second part of this project however, considers a different approach where the filter impedance and transformer MVA is left unaltered and instead a control algorithm is implemented which counters the impedance, so as to artificially lower it.

At the time of writing this idea has been tested using models and the project is due test this solution using real convertors in the configuration shown later in section IV.

B. *Principle of Operation*

Fig. 3 shows a vector diagram initially presented in paper 3 [3]. The discussion in paper 3 [3] surrounding the vector diagram, explained that the change in δ, largely affects the real power produced by the convertor, and changes in E (the convertor output voltage) or V_{poc}, the supply voltage at the Point of Connection (POC), see Fig.1 i.e. the connection point between the OFTO and on land Transmission System, largely affect the reactive power output of the convertor.

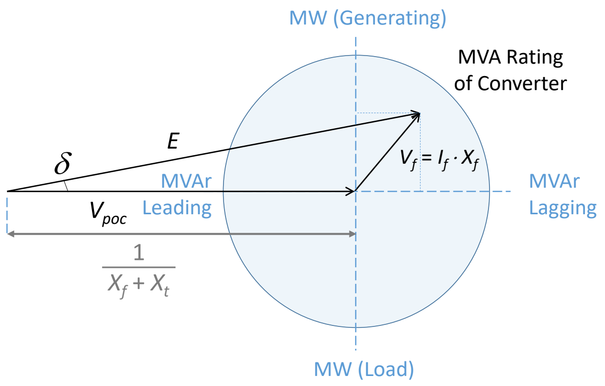

Fig. 3. Vector Relationship between Voltages

NB, the p.u. on MVA continuous convertor rating system is used for all quantities.

Assuming the reactance in between V_{poc} and E was dominant and other impedances and resistances can be ignored, it was also stated that the length of V_{poc} was $1/X$ where X is the sum of all impedances, e.g. X_f (filter impedance), X_t (transformer impedance), X_l (line impedances), etc. The length of the vector is the short circuit ratio or the voltage required to achieve full load current. For example a 10% impedance only require 10% volts across the impedance, to achieve rated current and the operating point reach the circumference of the MVA rating circle, the length of V_{poc} would therefore be ten times the circle radius.

Smaller values of X, result in longer V_{poc} and E vectors in relation to the unit MVA rating circle of the convertor (if $X =$ 1pu, V_c would be the length of the radius).

Consequently, smaller values of X result in larger changes in real power for the same change in δ (the operating angle, i.e. angular difference between V_{poc} and E).

In the case where the filter impedance was 10% and a typical OFTO transformer was used, the HGFC solution could not achieve the same response as the SG or directly connected GFC, because the impedance was too high so the change in power for the same vector shift was not as big.

The equation which governs this behaviour is:

$$P = \frac{V_{poc} \cdot E \cdot \sin(\delta)}{X}$$

Where P is the real power out of the convertor.

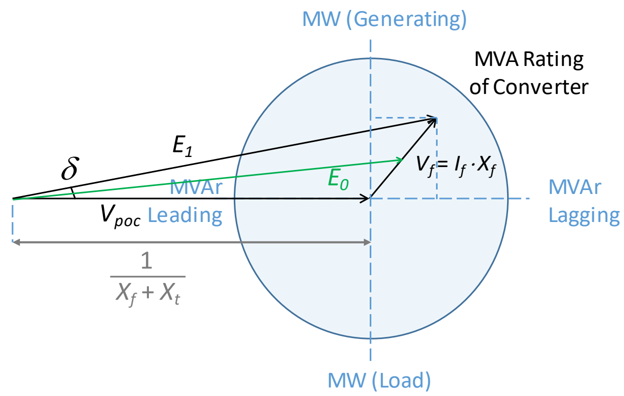

Fig. 4. Vector Diagram for modified relationship between Voltages

From this equation we can see that in order to get a greater response in terms of P, without changing V_{poc}, E and X, we must increase/amplify the change in δ and this is the principle that is applied in this algorithm. The vector diagram in Fig. 4 shows how this is achieved.

In Fig. 4 we see that we now have two values of E, E_0 and E_1 which are the input and output signals respectively to the impedance reduction algorithm (see Fig. 1). E_0 is the original voltage developed by the output oscillator discussed in paper 2 [2]. It should be noted that in the actual convertor E_0 is actually three signals ($E_{0,abc}$) representing the three AC voltage phase quantities. In the RMS model E_0 is two quantities representing D and Q (real and imaginary axis) of the AC voltage vector.

Ordinarily, if the impedance reduction algorithm were inactive E_1 would equal E_0 and this is the signal that would be fed to the output stage of the convertor.

Like E_0, E, and E_1 and V_{poc} are actually two quantities representing the voltage vector in the RMS model and three quantities representing the AC voltage waves in the real convertor and EMT simulations.

The vector V_{poc} is subtracted from E_0 to give the voltage across the impedance, V_x. A proportion of this voltage, controlled by the gain G, is then added back onto E_0 to produce E_1. E_1 is the signal that is then amplified into the real output voltage of the convertor by the output stage, assuming of course this control signal does not exceed the convertor current rating. This control signal passes through the current limiter and harmonic and imbalance control, before reaching the output stage. The current limiter and harmonic and imbalance control are normally largely passive and allows the signal to pass unchanged, unless the convertor ratings are exceeded. The operation of these and the other elements in the diagram are presented in [1] [2] and [5].

III. ALGORYTHM IMPLEMENTATION

A. Impelmentation in RMS model (PowerFactory)

Fig. 5 shows the block diagram for the RMS model in PowerFactory. Here V_{pd} and V_{pq} and E_{0d} and E_{0q} are represented by two quantities which represent the real and imaginary components of the two positive phase sequence vectors. Subtracting each from the other produces the real and imaginary parts of the phasor V_f (V_{fd} and V_{fq}), which are simply multiplied by G and added back onto E_{0d} and E_{0q} to produce E_{1d} and E_{1q}.

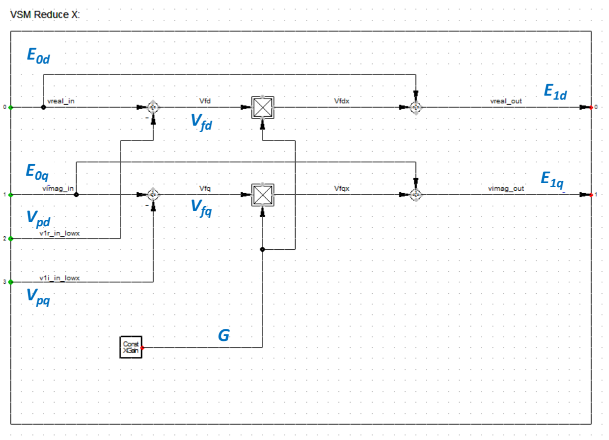

Fig. 5. RMS Impedance Reduction Algorithm

B. Effect on the Existing Elements of the Control System

To understand the effect of the X reduction algorithm on the other elements in the control system, consider a situation where G is initially set to 0 but then whilst the convertor is operational and set at 50% power output we gradually increase G from zero to 1, the vector V_f will be increased and added to the oscillator signal, increasing the angle and power output, at which point the governor and inertia simulation will reduce the power output back to its set value by reducing the angle between E_0 and V_{poc}

This process will continue until G is set 1, at which point the difference between the oscillator angle and the voltage at the terminals V_{poc} will be half that of the voltage angle across the output impedance.

The critical point here is that the output angle is calculated very quickly at a rate above the 1 kHz band width requirement in GC0100 option 1 [6]. Consequently, if the terminal voltage angle changes due to a network switching action e.g. generator disconnection elsewhere, the algorithm sees this difference and exaggerates it so as to further increase the angle and in doing so increase the response, this provides negative feedback resisting the angle change.

C. EMT and Real-time Convertor Implimentation of the X Reduction Algorythm

Fig. 6 below shows the block diagram for implementation in the real convertor. Here, AC 3-ph 50 Hz (nominal) sinusoidal voltages E_{0a}, E_{0b} and E_{0c} are subtracted from sinusoidal AC voltages V_{pa}, V_{pb} and V_{pc} to produce the AC filter voltages V_{fa}, V_{fb} and V_{fc}. These are multiplied by the gain G and then added back onto the AC voltage E_{0a}, E_{0b} and E_{0c} to produce AC sinusoidal voltages E_{1a}, E_{1b} and E_{1c}.

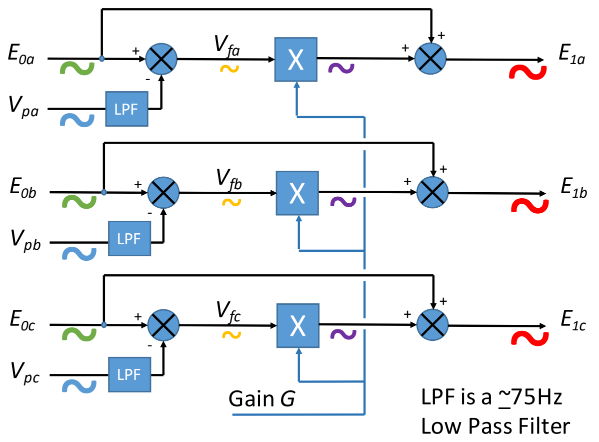

Fig. 6. Convertor and EMT Implementation of Impedance Reduction Algorithm

D. Results in the RMS simulation Algorythm

Fig. 7 and 8 show the results of increasing G from 0 (no impedance reduction) to 1 (effectively halving the impedance) for a vector shift of 4.5 and 9 Degrees where the convertor was connected to a low impedance bus bar by a transformer of 24% impedance (LV to HV) on 120MVA and a filter of 10% impedance on 67MVA.

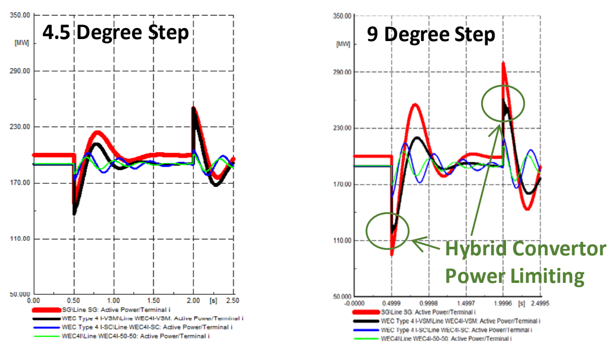

Fig. 7. Vector Shift Results with X Reduction Algorithm gain set to 0 (X Reduction switched off)

Fig.7.is the result with no impedance reduction, Fig. 8. is the same convertor with the algorithm gain set to 1. The red line shows the response of a directly connected synchronous

generator (SG) i.e. desired performance, the black line is HGFC, the blue line is the OFTO with synchronous compensator and the green line is OFTO with 50% synchronous compensator and 50% standard STATCOM. These combinations are explained in greater detail in paper 3 [3] and shown in Fig. 9.

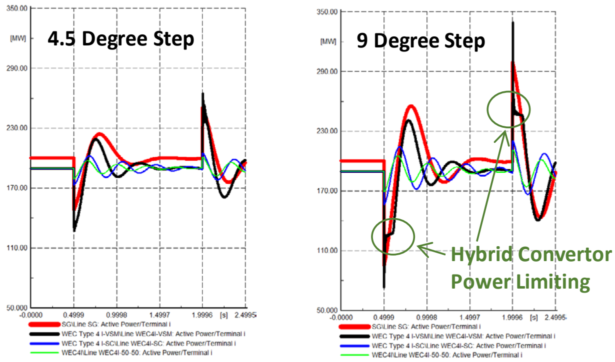

Fig. 8. Vector Shift Results with X Reduction Algorithm gain set to 1 (X reduction on and impedance halved)

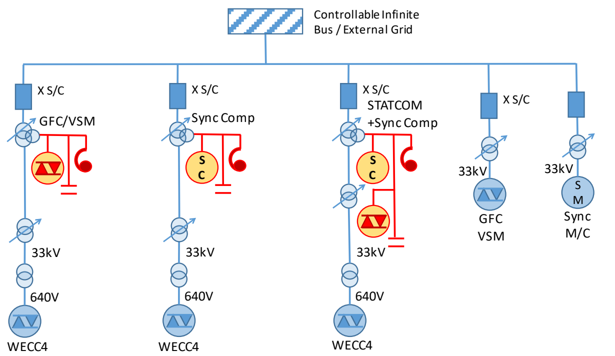

Fig. 9. Infinite Bus Model with all OFTO / WTG models tested

IV. Hardware Implementation and Lab Testing

Fig. 10 shows the lab configuration for the convertor test.

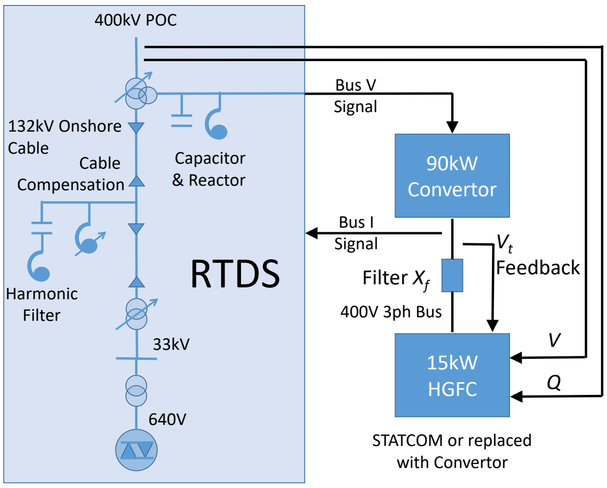

Fig. 10. Lab configuration for Convertor Test

The system comprises of a model built in an RTDS, which represents the entire wind farm, OFTO network and power system. This model outputs signals which represent the reactive current and voltage at the POC and signals to control a 90 kW convertor which produces scaled voltages and currents as seen between the GFC and the 3 winding power transformer.

At the time of writing the lab tests are incomplete and work on this part of the project is progressing.

V. HGFC Grid Code

In order to allow HGFC on to the system Grid Codes and/or Bilateral Agreements would need the appropriate wording adding to ensure system requirements surrounding it are captured.

In considering this the authors concluded that ideally no Grid Code specific to HGFC would be necessary and that these devices would be covered by a future Grid Code relating GFC in general. However, some of the wording in GC0100 option 1, would need to be changed.

For example, GC0100 specifies a 10% impedance, which was added to a large extent as discussion point as it was felt that the impedance between the voltage source and POC should be specified. This work has demonstrated that high impedance is detrimental to the generator vector shift (voltage angle change) response at the connecting bus bar and some control / specification is needed. However, in this application the impedance is difficult to define as there are three interconnecting points which can only be reduced to three impedances. It therefore makes more sense to define the percentage active power response to a given angle change at the POC.

These principles, can equally be applied in other areas of the Grid Code and this is discussed in greater detail in [1].

The above has not been subject to the full scrutiny and review and caution is therefore required. However, it would seem that one specification for both GFC and HGFC might be accommodated, with the exception that the performance is specified at the point of connection between the OFTO and on shore transmission system in the case of HFGC. This would simplify any future code with the prospect of increasing understanding, ensuring a greater likelihood of compliance, with less issues post commissioning.

VI. Conclusions

This project has highlighted some interesting aspects of GFC within OFTO and offshore systems and GFC more generally. Whilst the RMS results look very promising, lab tests will provide further confidence, or otherwise, as the effects of noise and other issues are more likely to be observed under these circumstances. At this time however we are not aware of any potential issues.

System Operators are ultimately only interested in the response and not how it is achieved. However, in keeping with the GC0100 option 1 [6] requirement, that the convertor behaves as a voltage source over the 5 Hz to 1 kHz bandwidth, it is critical for designers to consider where any algorithm to produce this affect sits within the overall control system. In the example presented here the AC voltages are to be sampled at a frame rate of $\leq$500 us and the output signals to the PWM generator updated $\geq$2 kHz rate with both edges being controlled, ensuring this part of the control system operated above 1 kHz.

Placing an alternative control strategy further back (for example in the governor) or running it at a slower frame rate or using delayed (or heavily filtered) feedback signals with the cut off frequency is under 1 kHz [6] would not meet the GC0100 requirements relating to bandwidth.

System Operators would not advocate or rule out the use of this or similar algorithms or other techniques. For example, some of the response from within SM's results from the damper winding and it may be possible to use an approach which simulates this transient response. Alternatively, suitably sized SC or some new design of rotating machine or transformer interconnection may achieve the same effect. The speed and nature of the response is critical however and other approaches would therefore need to comply with any future Grid Code and associated Bilateral Contracts.

REFERENCES

[1] R.Ierna, A.Johnson, B.Marshall, H.Urdal, C.Li, M.Sumner, A.Egea-Àlvarez, "Dispatching Parameters, Strategies and Associated Algorithm for VSM (Virtual Synchronous Machines) and Hybrid Grid Forming Convertors", 18th Wind Integration Workshop, Dublin, 2019

[2] R.Ierna, S.Pholboon, M.Sumner, C.Li, "VSM (Virtual Synchronous Machine) Control System Design, Implementation, Performance, Models and Possible Implications for Grid Codes", 18th Wind Integration Workshop, Dublin, 2019

[3] M.Yu, R.Ierna, A.Dyśko, A.Egea-Àlvarez, A.Avras, Can Li, M. Horley, C. Booth, H. Urdal "Performance of Hybrid Power Park Technologies in future OFTO Networks with the aim to achieve Grid-Forming Capability", 18th Wind Integration Workshop, Dublin, 2019

[4] A.J.Roscoe, M.Yu, R.Ierna, H.Urdal, A. Dyśko, C.Booth, J.Zhu, et al., "VSM (Virtual Synchronous Machine) Convertor Control Model Suitable for RMS Studies for Resolving System Operator/Owner Challenges", in 15th Wind Integration Workshop, Viena, Austria, 2016

[5] M.Sumner, S.Pholboon, R.Ierna, C.Li, "VSM (Virtual Synchronous Machine) Power Quality, Harmonic and Imbalance Performance, Design and Service Prioritisation", 18th Wind Integration Workshop, Dublin, 2019

[6] GC0100 Consultation - https://www.nationalgrideso.com/codes/grid-code/modifications/gc0100-eu-connection-codes-gb-implementation-mod-1