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Generator response following as a primary frequency response control strategy for VSC-HVDC connected offshore wind farms

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Abstract

As penetration of renewable energy sources increases, the proportion of synchronous generators with rotating masses directly coupled to the grid decreases. In the case of wind generation, the kinetic energy stored in the machine rotor is not available to perform the natural task of frequency support for the AC power system. New active control methods must therefore be developed to synthetically recouple this inertia characteristic to the grid. European offshore windpower is growing and the average distance to shore is increasing. Voltage Source Converter based HVDC (VSC-HVDC) is a promising method for transporting this power to the onshore AC grid over long distances. The fast power transfer capability of VSC-HVDC offers the opportunity for new control strategies to provide frequency support to the AC grid. The authors propose a method for using a VSC-HVDC transmission link to follow and amplify the traditional primary frequency response behavior of a small synchronous generator connected at the point of common coupling (PCC). In terms of frequency support, the onshore grid will then see the HVDC connected offshore windfarm (OWF) and small synchronous generator together as one large synchronous generator with rotor inertia directly coupled to the grid (i.e. synthetic inertia). The method will therefore enable the OWF to provide frequency support services equivalent to that of a traditional power plant at the same rating. Electromagnetic transient simulation is used to investigate the proposed active control strategy. Fiber-optic technology is considered as a method of remote communication between the OWF and the small synchronous generator (SSG). A second communication-less method is also considered which utilizes a cascaded droop frequency to DC voltage control at the Grid Side VSC (GS-VSC) and then DC voltage to frequency at the Windfarm Side VSC (WF-VSC). Simulation results are used to justify the proposed method.

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Keywords:
VSC-HVDC, Synthetic Inertia, Offshore Windfarm, Frequency Support, Primary Frequency Response

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Nomenclature

GRF	Generator Response Following
PCC	Point of Common Coupling
OWF	Offshore Windfarm
LSG	Aggregated Large Synchronous Generator and Strong Frequency Grid
SSG	Small Synchronous Generator
WTG	Aggregated Wind Turbine Generator and Weak Frequency Grid
WF-VSC	Windfarm Side Voltage Source Converter
GS-VSC	Grid Side Voltage Source Converter

1. Introduction

In a traditional AC power system, frequency is an indicator of the global balance between generation and demand of active power [1]. Primary frequency control is a method for coordinating the load responses of a system of generators in an AC system. It stabilizes frequency excursions through adjustment of prime movers with a droop control [2]. When the active load of the system changes, the frequency adjusts inversely. This frequency deviation is the same across the entire AC system as frequency is a global variable. Each AC generator takes on a portion of the active load according to the global frequency deviation and a predefined Power-Frequency relationship specific to that generator. In turn, the Power-Frequency relationship of all the synchronous generators in the system defines the new steady state frequency of the system.

Inertial response is the rate of change of frequency as it approaches a new steady state according to a system active load change and the primary frequency control. This rate of change is a function of the stored kinetic energy of the total rotating mass directly coupled to the AC grid. In the moments leading up to a power system imbalance, the inherent inertial response of traditional synchronous machines limits the frequency rate of change [2]. It provides time for the primary frequency control to adjust prime movers and coordinate generation with demand.

Larger penetration of renewables with power electronic interfaces reduces the amount of inertia directly coupled to the grid in proportion to the active power being supplied. This leads to larger steady state frequency deviation and increased rate of change of frequency. Therefore, short term grid stability issues become more of a concern for grid operators [2]. This paper explores the concept of synthetic inertia through active power injection at the Grid Side VSC (GS-VSC) of VSC-HVDC connected Offshore Windfarms. Various control strategies are explored which exploit the fast power transfer capability of the VSC-HVDC transmission link but do not influence the grid frequency. Some methods are also given which coordinate between traditional directly coupled rotor inertia and converter synthetic inertia methods and therefore influence steady state frequency deviation. The Generator Response Following (GRF) method falls into this category.

The paper is organized as follows. Section 1.1 introduces the concept of synthetic inertia from individual wind turbine generators. Section 1.2 then introduces the VSC-HVDC link and the prospect of synthetic inertia from offshore windfarms. Section 2 presents some frequency control strategies that may be implemented at the GS-VSC of a VSC-HVDC connected offshore windfarm. It also describes some strategies that have been proposed integrating some of the previously mentioned concepts with traditional direct coupling. Section 3 introduces the Generator Response Following method and the use of communication channels. Some theoretical background is given for the windfarm controller and PSCAD/EMT^{TM} simulation results are presented. The paper concludes with section 4 summarizing the survey and suggesting where the Generator Response Following concept fits into the larger picture.

1.1. Synthetic Inertia from Wind Turbine Generators (WTG)

In general, in order for windfarms to provide synthetic inertia services to the AC grid, the idea of using wind turbine generators has previously been proposed in literature. One method of doing this is to operate the individual wind turbines below the maximum power operating point. This way, instantaneous increases in power output are made available to the wind turbine level control algorithm. This may be referred to as spinning reserve margin, wind generator de-load, power margin, power reserve, etc. Likewise, instantaneous decreases in power are available as the generator is producing more than minimum capability when tracking the maximum power point [2,3]. Instantaneous surges of power may also be extracted from the kinetic energy of the rotor by rapid braking action or dynamic deloading of the turbine [4].

Supplementing the chosen mode of operation is a control loop at the wind turbine level, ready to increase or decrease the power output based on the measured frequency error input. The authors of [5] mention that since the windfarm AC collection grid likely has no loads connected to it, changes in frequency may be accomplished fairly easily. This suggests that variable frequency operation of the AC collection grid of VSC-HVDC connected OWF's is a plausible idea.

1.2. Problems and Opportunities with VSC-HVDC Connected Offshore Windfarms (OWF)

Due to it's fast power transfer capability and flexibility in terms of control, VSC-HVDC is becoming a popular electrical transmission technology. Other advantages over traditional thyristor based LCC technology include independent control of active and reactive power, small footprint and reduced harmonic filtering requirements [6]. Control methods for VSC-HVDC links are also customizable to the existing infrastructure. Application engineering is therefore reduced and control methods may be tailored for strong versus weak systems at the sending end versus the receiving end [7]. Despite all advantages mentioned above, interfacing more power electronics with the grid brings disadvantages as well. VSC's contribute limited short circuit current, therefore reducing overall system strength [8]. Also, VSC's contribute no inertia, again reducing overall system stability. Therefore there is an increasing interest by operators to request inertial and primary frequency response services from non-synchronous energy sources such as OWF's [2].

In Great Britain for example, installation of VSC connected OWF's is limited due to stability concerns. According to simulation, non-synchronous generator penetration is limited to 65% because of the estimated system stability limits. The authors of [8] suggest that VSC-HVDC control methods designed to mimic the inertial response of traditional synchronous generators may be a solution to this problem.

2. Frequency Control with VSC-HVDC

Typically, VSC-HVDC links are designed for active power control at the sending end converter and DC voltage control at the receiving end converter. Reactive power is then controlled at both ends in order to maintain the AC voltage and the reactive power at the required level. The VSC-HVDC link may be viewed as a fast, controllable, synchronous machine when connected to the AC grid through an AC filter. Frequency control may then be included in the active power or DC voltage loop of the GS-VSC. Four methods are summarized in this section; Fixed Frequency, Power-Frequency, DC Voltage-Frequency and Inertia Emulation Control. Two coordinated control strategies are also summarized which integrate one of the GS-VSC outer control loop strategies with WTG synthetic inertia (section 1.1) and with traditional direct coupled synchronous generation.

Fixed frequency is the simplest GS-VSC outer control loop frequency control strategy and may be used for isolated systems without any other means of frequency control. In this method, a fixed frequency reference is supplied to the outer control loop of the converter. Frequency errors will then result from changes in the power flow. The control loop will work to bring the frequency back to nominal [9]. In Power-Frequency Control, the frequency control loop is added to the outer active power loop. The method may employ proportional (droop) control of the steady state frequency or PI control for correction of the steady state frequency deviation as well [9]. In V_{DC}-Frequency Control, the frequency control loop is added to the outer DC voltage loop. When system frequency changes, instantaneous power is taken from the DC link capacitor. This in-turn influences the DC voltage across the capacitor. V_{DC}-Frequency Control uses this DC voltage change and the capacitor energy storage capacity to design a droop controller which governs the dynamics of this interaction. The authors of [9] suggest that frequency performance is significantly improved by these methods, especially in isolated power systems.

Inertia Emulation Control (INEC) takes the V_{DC}-Frequency Control strategy one step further by allowing a desired emulation inertia constant to be specified. The derivation is similar to that of V_{DC}-Frequency Control but modified so that stored energy can be quantified with the variable H_{VSC}. The derivation can be found in [1]. This strategy requires that the designer make informed decisions about capacitor size, VSC power rating, VSC voltage and allowable VSC voltage variation and balance this with the desired inertia emulation. A rule of thumb for VSC-HVDC voltage deviation limit is ±15% to preserve stability [10]. Also, [1] explores the prospect of emulation inertia constants in the range of zero to four seconds for capacitors of size 2mF and 5mF. Then for a larger emulation inertia constant a larger capacitor is needed but this relationship is not linear and required capacitor size quickly becomes quite large. The authors of [1] conclude that this method enhances AC system stability during frequency deviations as well as busbar load angle deviations. They also conclude the method does not hinder an important feature that HVDC transmission links already provide, which is to decouple the strong onshore AC grid from the weak OWF AC collection system.

VSC-HVDC Coordinated Control Strategy combines the WTG Synthetic Inertia method described in Section 1.1 with the INEC method. The purpose of this is to increase the size of the inertia emulation time constant while maintaining a reasonable size DC link capacitor. This can be achieved by supplying the energy requirement of the INEC controller from two sources; WTG rotor kinetic energy and DC link capacitor [10]. The INEC Controller energy requirement is communicated to the WTG installations by a cascaded droop from DC link voltage to collection grid frequency. The voltage deviation of the DC link is initiated by the action of the INEC Controller draining energy (and therefore voltage) from the DC link capacitor at the GS-VSC.

Wind-Thermal-Bundled DC Modulation explores a coordination between the Power-Frequency Control method of a VSC-HVDC described earlier with the traditional primary frequency regulation (PFR) of a thermal power plant. The HVDC link and the thermal power plant are coupled together at one common bus to provide the necessary frequency support services for a wind farm. Note that this study takes place at the WF-VSC but is nevertheless relevant to the present discussion and could be adapted to the GS-VSC. It assumes a strong grid at the far end of the HVDC link and a weak grid at the point where the system is being analysed. Traditional Primary Frequency Regulation has a feature called governor dead-band. This feature allows the governor to be programmed to ignore small frequency deviations. However, this dead-band must not be so large that it ignores significant disturbances. The frequency regulation range of traditional turbine governors is also small in comparison to the range required to regulate a wind farm on a weak grid. This is due to the significant variability of wind speeds [7]. Two operational modes are proposed: 1) Generator-Master, DC System-Slave and 2) DC System-Master, Generator-Slave. Mode 1 is realized with a small governor dead-band and a shallow slope for DC system droop. Mode 2 is realized with a large governor dead-band and a steep slope for DC system droop. The study compares mode 1, mode 2 and ”PFR only” against collection grid frequency variability due to wind speed fluctuations. Results indicate that mode 1 yields the best operational performance of the three. Mode 1 results have the smallest maximum frequency deviation, the smallest steady state frequency deviation and a consistently stable post-disturbance steady state. This was verified for both islanded and interconnected operation. In contrast, mode 2 is found to yield the best results under fault conditions [7].

3. Generator Response Following

This section presents the Generator Response Following (GRF) concept. In this method a SSG, located at a PCC with the OWF, responds in a typical way to changes in load in an onshore AC system employing load frequency control. This response can be measured and the information sent offshore allowing the OWF to mimic the load-sharing behavior of the SSG. For the purpose of demonstration, this study uses a SSG with a power rating of 25% × OWF power capacity. However, prior experience suggests the SSG can be as small as 5% × OWF power capacity. Simulation has been conducted in PSCAD/EMT$^{\text{TM}}$.

3.1. Reference Circuit

The reference system consists of a 400MW OWF connected to an onshore AC system by a point-to-point VSC-HVDC connection (see Figures 1 & 2). The onshore AC system is made up of an aggregated large synchronous generator (LSG) connected to the PCC by a 245kV transmission network represented by a equivalent π model with lumped parameters. This AC network has an effective short circuit ratio greater than ten according to section 5.1 of [11] and an effective inertia constant greater than three according to section 10.6.5 of [12] to accommodate the connection of an HVDC link. The network has an X/R ratio of approximately ten which is typical for traditional 245kV AC transmission and a stiffness of about 20 which is typical for steam turbine generation (section 6.1.5 and

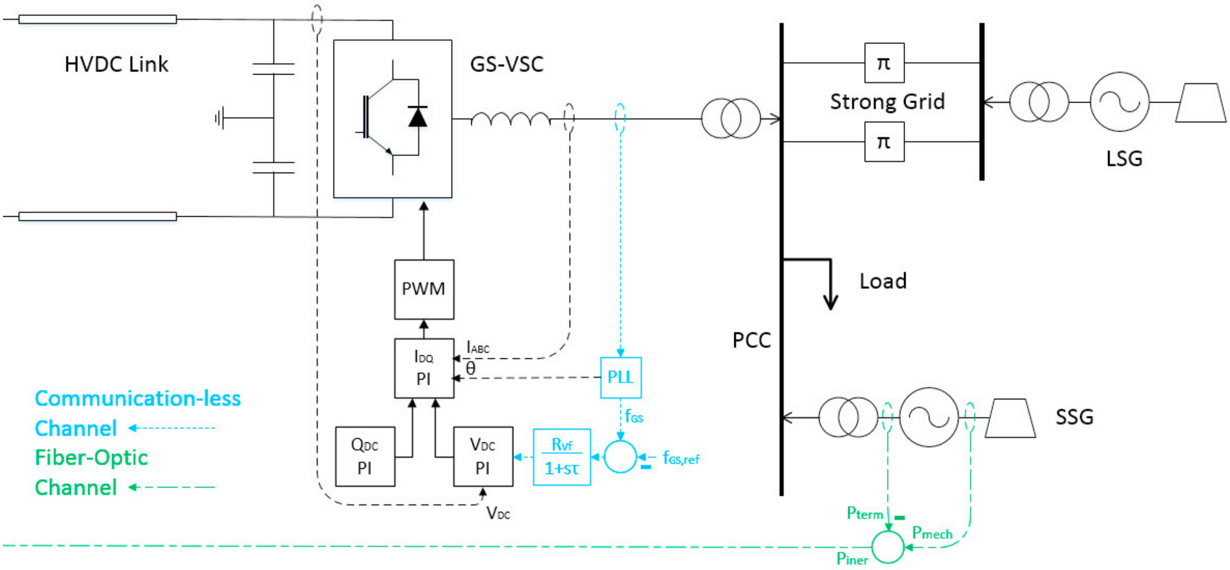

Fig. 1. Onshore Reference Circuit

11.1.4 of [12]). A SSG is also connected at the PCC for interaction with the OWF. For simplified AC system stability design, this study assumes manual excitation from all contributing synchronous machines (see section 12.3.2 of [12]).

The OWF is represented by an aggregated wind turbine generator (WTG). This WTG is assumed to be a variable speed synchronous generator connected to the AC collection grid by a full scale back-to-back power converter and transformer which decouples generator speed from grid frequency. The offshore submarine cable network is modelled as an equivalent π network with lumped parameters. The network is assumed to be low voltage and therefore exhibits an X/R << 1.0 but with a high capacitance due to the cables. In order to exploit the resistive properties of this low voltage network the WTG is modelled as an ideal voltage source. This is acceptable because the WTG back-to-back converter can act as a fully controllable voltage source at the interface with the network (section 3.5.1 of [13]). The ideal voltage source is then fitted with controls that allow it to accept frequency information from the WF-VSC and vary the voltage magnitude relative to the WF-VSC voltage in order to deliver the requested power.

The VSC-HVDC converters are represented with an average switching model rather than a standard switching model. This project is concerned with the time-scales associated with power flow dynamics not switching operations or voltage transients. Since frequency is decoupled from power on the collection grid, the grid follows the frequency dictated by the WF-VSC (see also section 2.3 of [14]). The WF-VSC also provides a constant AC voltage magnitude at the terminals of the cable network and accepts the power flow sent from the WTG. The HVDC submarine line is made up of two cables in a bipolar configuration and is assumed to be 400km in length with a 500kV/500MW rating, operated at 400MW. This results in approximately 94% efficiency at rated power flow according to simulation. Power flow is considered to be uni-directional from OWF to onshore network and the converters at either end of the link are assumed to be loss-less ($P_{AC} = P_{DC}$). The GS-VSC regulates the DC voltage of the line and operates independently of power flow.

3.2. Communication Schemes

In order to demonstrate the various design options available in this method, both a communication-less and a fiber-optic communication channel are employed. Figures 1 & 2 are the onshore and the offshore network respectively. The communication-less channel carries primary response information taken from the strong global frequency of the onshore AC grid. It is shown in the figures as a dotted line. The fiber-optic channel carries inertial response information taken from the shaft of the SSG. This channel is shown in the figures as a dot-dash line.

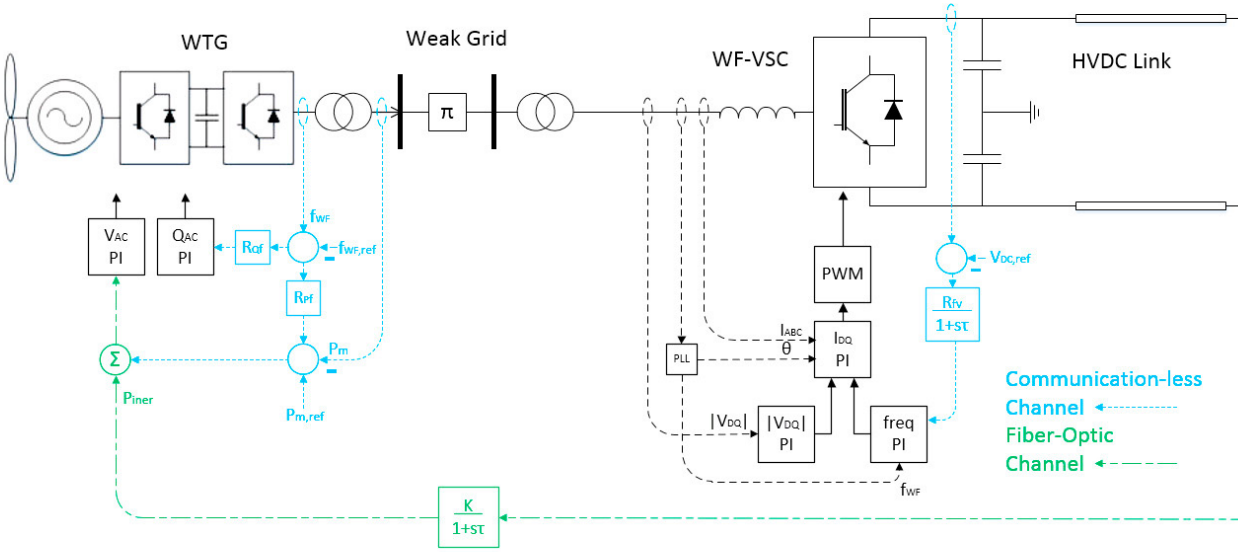

Fig. 2. Offshore Reference Circuit

The communication-less channel is used to bring onshore frequency information to the offshore WTG for primary frequency regulation at the PCC. This is accomplished by exploiting the fact that V_{DC} is independent of power flow at GS-VSC. Frequency is measured at the converter and translated to voltage magnitude which is then applied to the DC transmission link (Figure 1). DC current then compensates so that DC power can remain constant. At WF-VSC, a feed-forward voltage associated with series line resistance ($V = I \times R_{line}$) is subtracted from the measured voltage. This allows the WF-VSC to read a voltage closer to that applied at GS-VSC before translating to frequency at the offshore network (see section 2.8 of [14]). The AC voltage controls at WF-VSC provide a constant voltage magnitude and variable frequency source. This frequency is then received by the WTG which in-turn provides a power flow (Figure 2).

The fiber-optic channel is used to communicate inertial response information from the SSG to the WTG. A mechanical torque measurement is taken at the shaft and an electrical power measurement is taken at the machine terminals. These can then be combined in the per unit system according to the swing equation. Note that for load frequency studies, torque and power are interchangeable in the per unit system (section 11.1.1 of [12]). Once the inertial response of the SSG has been measured, it is sent to the WTG through a fiber-optic cable embedded in the submarine transmission line. Inertial response information is combined with primary response information at the WTG which uses it to guide power flow output. The WTG is essentially using this information to increase the Effective Inertia Constant of the onshore AC system. Effective Inertia Constant is defined in section 10.6.5 of [12] as

$$H_{DC} = \frac{\textit{total rotational inertia of AC system, MWs}}{\textit{MW rating of dc link, MW}} \tag{1}$$

and is a measure of the ability of the AC system to maintain voltage and frequency relative to the size of an HVDC link injecting power into it. The text recommends H_{DC} greater than 2 or 3 for satisfactory operation of line commutated converters. Although this study uses voltage source converter technology, the effective inertia constant continues to be a good measure of the relative frequency strength of the AC system. In this study, it quantifies the ability of the GRF method to improve the performance of the connected AC system.

3.3. Windfarm Controller

The windfarm controller design is based on the assumption of a low X/R ratio which means the inductance of the network is negligible compared to the resistance. Power flow in this type of network can be calculated as

$$S_{WTG} = P_{WTG} + j\,Q_{WTG} = \left[\frac{E_{WTG}\,(E_{WTG} - E_{WF-VSC}\,\cos\delta)}{R_{line}}\right] + j\left[\frac{E_{WTG}\,E_{WF-VSC}\,\sin\delta}{R_{line}}\right]. \tag{2}$$

δ can be assumed small and the equation expressed in per unit with E_{WF-VSC} regulated at rated voltage. The expression in (2) can then be reduced to

$$S_{WTG} = P_{WTG} + j\,Q_{WTG} = \left[\frac{E_{WTG}\,(E_{WTG} - 1)}{R_{line}}\right] + j\left[\frac{E_{WTG}\,\delta}{R_{line}}\right]. \tag{3}$$

Since power and frequency are considered independent in this offshore network, a simple mathematical operation can be used by the active power controller to assemble primary and inertial response information into a single power output reference (see Figure 2). Power flow is then initiated with a PI controller by creating a voltage difference between the terminals of the WTG and the regulated voltage at the WF-VSC.

Due to the residual inductance in any AC network, the assumption of power-frequency decoupling can never be entirely true. In this circuit, the variations in frequency at the WF-VSC from the communication-less method are in-fact creating some reactive power flow. This is represented by load angle δ in (3) and interferes with the power-frequency relationship. A reactive power controller can therefore be used at the WTG to match the reactive power flow initiated by the WF-VSC. A properly tuned reactive power controller then enforces the power-frequency decoupling assumption required by the active power controller. According to section 3.4.3 of [13], frequency can be coupled to reactive power by relating δ to Q_{WTG} in (3). This coupling equation is

$$\delta = \int \left[f_{WTG} - f_{WF-VSC}\right] dt = \int \Delta f\ dt \tag{4}$$

where frequency is related to reactive power by $f = R_{Qf}\,Q$, resulting in (expressed in derivative form)

$$\frac{d\delta}{dt} = R_{Qf}\,Q_{WTG} - R_{Qf}\,Q_{WF-VSC}\ . \tag{5}$$

This δ is incorporated into the implementation of the windfarm controller by realizing the right side of (5). "$R_{Qf}\,Q_{WTG}$" is present as a droop controller at WTG and "$R_{Qf}\,Q_{WF-VSC}$" represents the dynamics of the voltage source at WF-VSC freely regulating the frequency. The value of R_{Qf} at WTG is tuned to match the WF-VSC dynamics.

3.4. Simulation Results

Figures 3 & 4 represent a primary response from the OWF for a strong frequency onshore grid scenario defined by

$$H_{DC} = \frac{KE_{LSG} + KE_{SSG}}{P_{HVDC}} = \frac{H_{LSG}\,S_{LSG} + H_{SSG}\,S_{SSG}}{P_{HVDC}} = \frac{3.525 \times 1389 + 3.525 \times 100}{400} = 13.1\frac{MWs}{MW} \tag{6}$$

where KE is kinetic energy of the rotating mass in MWs, H is inertia constant in MWs/MVA, S is apparent power rating in MVA and P is DC power rating in MW. This example is intended as an ideal scenario to provide a frame of reference for demonstration of the GRF method. Inertial response is not needed from the OWF and the associated information was therefore not sent to the windfarm for this scenario. A theoretical calculation (based on section 11.1.3 of [12]) that assumes a 400MW synchronous machine at the end of an AC transmission line is given for comparison in Table 1. As can be seen in the table, the PSCAD/EMT^{TM} simulation follows reasonably close to theory.

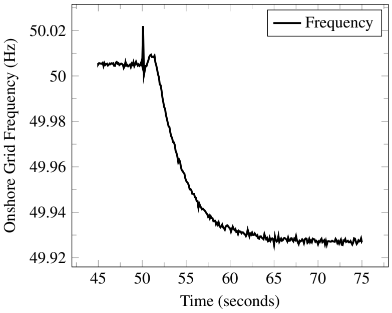

Fig. 3. OWF Contributes to Primary Response (H_{DC} = 13.1)

	Δf_{ss} (Hz)	ΔP_{LSG} (MW)	ΔP_{SSG} (MW)	ΔP_{WTG} (MW)	Total (MW)
Theory	-0.076	46.0	6.3	12.2	64.5
Fig. 3, 4	-0.077	44.1	6.3	12.5	62.9
Fig. 5, 7	-0.056	31.9	4.7	27.2	65.5

Table 1. Steady State Summary

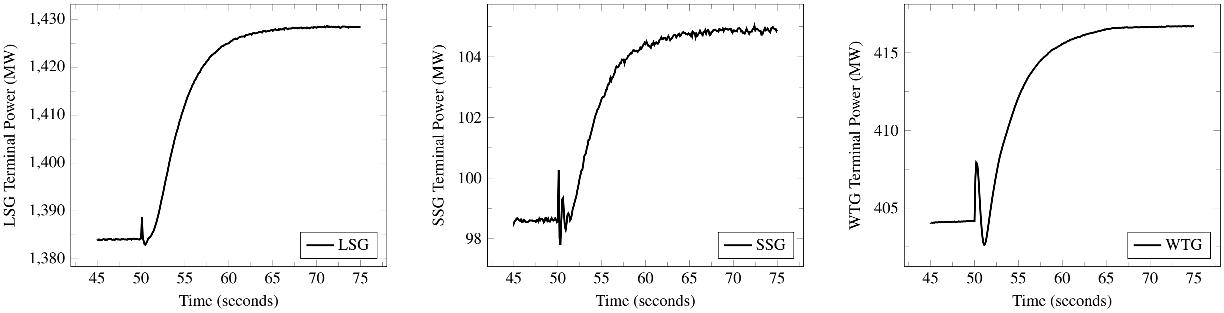

Fig. 4. OWF Contributes to Primary Response (H_{DC} = 13.1)

Figures 5, 6 & 7 represent a primary response combined with an inertial response from the OWF for a weak frequency onshore grid scenario defined by

$$H_{DC} = \frac{KE_{LSG} + KE_{SSG}}{P_{HVDC}} = \frac{H_{LSG}\,S_{LSG} + H_{SSG}\,S_{SSG}}{P_{HVDC}} = \frac{0.01 \times 1389 + 3.525 \times 100}{400} = 0.92\frac{MWs}{MW}\,. \tag{7}$$

These plots demonstrate the effect of the GRF method and the associated synthetic inertia response. The background plots in Figures 5 & 7 are provided for direct comparison with and without the tuned GRF contribution. Notice the instantaneous oscillations in the global frequency waveform at the moment of load change. This high rate of change of frequency is evidence of low inertia in the system and is a stability concern. The same instantaneous oscillations can be observed in the SSG power waveform (Figure 7, center) because of the small power rating of the machine relative to the system as a whole. This feature is significant for implementation of the GRF method as it allows power associated with inertial response to be extracted from the total power waveform at the SSG. This inertial response waveform can then be tuned for an optimal closed loop instantaneous power flow response from the terminals of the WTG.

The foreground plots in Figures 5 & 7 are the modified waveforms with the GRF contribution. The instantaneous oscillations have been removed from the frequency and SSG power waveforms. PSCAD/EMT^{TM} simulation therefore suggests the addition of an inertial response from the OWF can be used to improve the stability of the onshore AC system. As will be outlined in Section 3.5, gain and time delay of the inertial response must be tuned to achieve this. The optimal choice for the present scenario is a gain multiplier of two and a time delay of 0.01 seconds (see Figures 8 & 9).

Figure 5 also exhibits a reduced steady state frequency deviation which suggests application of the GRF method has increased the stiffness of the onshore AC grid. As a result, power output from the synchronous generation sources participating in power-frequency regulation is reduced. The OWF makes up for this by supplying the power no longer provided by the synchronous generation sources. There is also an instantaneous offset in all of the waveforms at the moment of load increase. This is due the manual excitation assumption used for simplified stability design of the onshore AC grid reference circuit. Since no automatic voltage regulation is present in the AC system, a voltage dip occurs at the moment of load change. Power is not independent of voltage and an instantaneous power

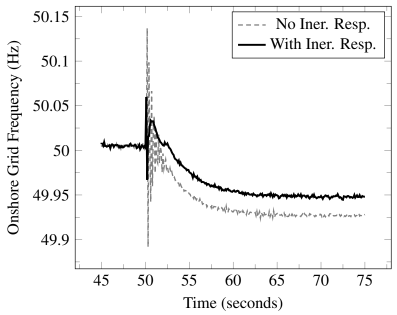

Fig. 5. OWF Contributes to Inertial Response (H_{DC} = 0.92)

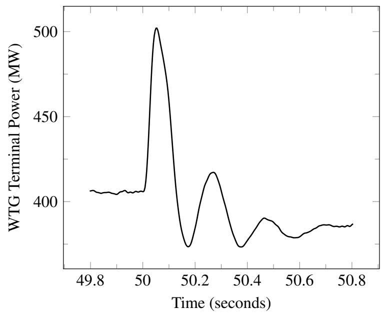

Fig. 6. OWF Synthetic Inertia Request (H_{DC} = 0.92)

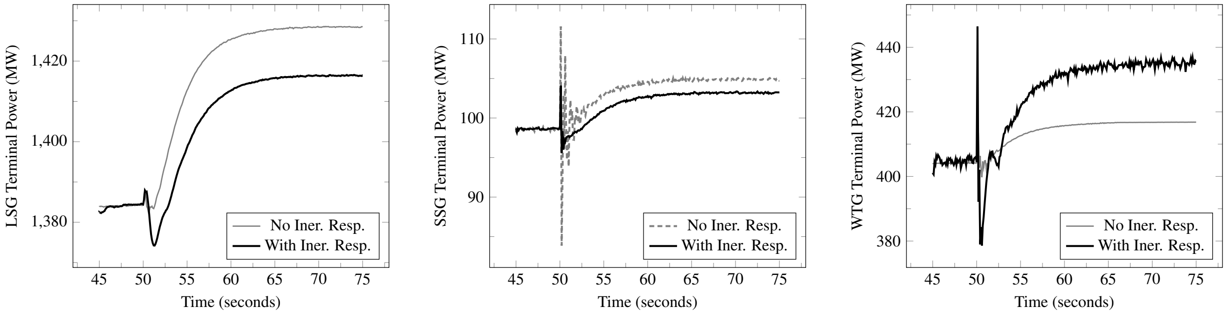

Fig. 7. OWF Contributes to Inertial Response (H_{DC} = 0.92)

offset is therefore observed. Load frequency control of the AC system also couples frequency to power creating an instantaneous offset in the frequency waveform. Further investigation on this topic is required and the influence of automatic voltage regulation needs to be explored.

The instantaneous power contribution from the WTG that creates the AC grid frequency filtering effect can be observed up close in Figure 6. It is a fine tuned application of the SSG inertial response power waveform superimposed over the primary response waveform from the communication-less channel. Since this study models the WTG as an ideal voltage source, this waveform is a request to an upstream wind turbine level control algorithm. In order to meet the instantaneous requirement of this request, the wind turbine level algorithm can employ strategies such as rapid braking action or dynamic deloading of the turbine. The OWF can also be designed with a windfarm power reserve as described in Section 1.1.

3.5. *Optimizing and Interpreting Synthetic Inertia Response*

As demonstrated in Section 3.4, according to PSCAD/EMT$^{\text{TM}}$ simulation, application of gain and time delay to an inertial response signal may have significant effect on AC system dynamic stability. For the present study, gain multiplier and time delay were optimized by observing the effect on the onshore AC system frequency. Figures 8 & 9 are frequency plots for a range of gains and delays. Figure 8 represents step one of the optimization process for this study. Gain was held at 1.0 and a spectrum of delays were plotted. A time delay of 0.01 seconds was then chosen because it had the optimal damping effect. Time delay smaller than 0.01 seconds exhibited no additional damping effect. Time delay was then held constant and a spectrum of gains were plotted. A gain multiplier of 2.0 was then chosen as having the optimal damping effect. Gain beyond a multiplier of two resulted in additional harmonics.

The stabilizing effect of this optimized inertial response signal might be quantified by setting $H_{WTG} = H_{SSG}$. The associated kinetic energy represented by this would then be (see section 11.1.3 of [12])

$$KE_{WTG} = KE_{SSG}\,\frac{S_{WTG}}{S_{SSG}} = H_{SSG}\,S_{WTG} = 3.525 sec \times 400 MW = 1410 MWs\,. \tag{8}$$

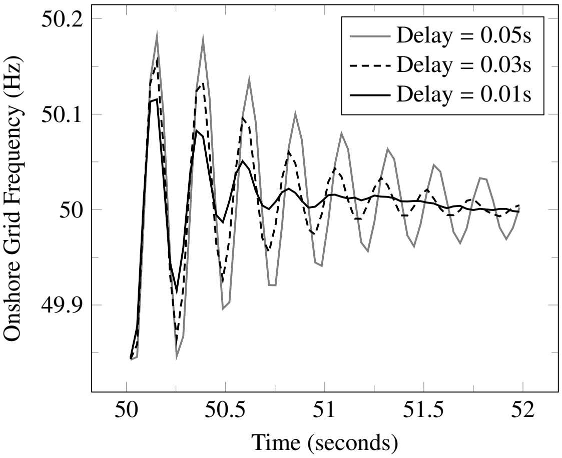

Fig. 8. OWF Contributes to Inertial Response (1.0 Gain, 0.92 H_{DC})

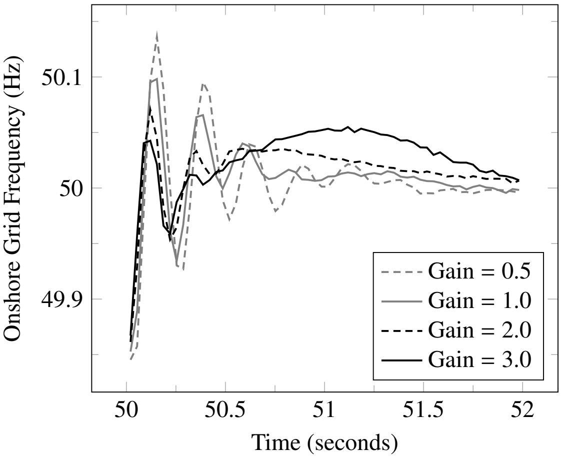

Fig. 9. OWF Contributes to Inertial Response (0.01s Delay, 0.92 H_{DC})

However, since this is not mechanical inertia, the time rate of change of kinetic energy is a more meaningful way to express the synthetic inertia response power waveform. This waveform is given in Figure 6 and occurs in the fiber-optic channel at the bottom of Figure 2. It can be expressed analytically as

$$\frac{d}{dt} KE_{WTG} = \frac{K}{1 + s\,\tau}\, P_{iner} = \frac{K}{\tau}\, P_{iner}\, \mathbf{e}^{-t/\tau} = \frac{2.0}{0.01}\, P_{iner}\, \mathbf{e}^{-t/0.01} = 200\, P_{iner}\, \mathbf{e}^{-100\,t} \tag{9}$$

where K is the gain multiplier, τ is the time delay and P_{iner} is the inertial response power measurement at the SSG.

4. Conclusion

This paper explores various control strategies that have been proposed that enable VSC-HVDC connected offshore windfarms to provide synthetic inertia services to the onshore AC grid through active power injection. This includes dedicated control strategies at the grid-side VSC as well coordinated methods which utilize a combination of strategies across the decoupled asynchronous system to accomplish the desired outcome. Based on this survey, an optimal control strategy might have a synthetic inertia response which allows the designer to specify the inertia constant. The designer would have the freedom to increase the size of the inertia constant while keeping the DC link capacitor size within reason and without much dependence on DC voltage deviation limit. Ideally, this constant would be completely independent of capacitor size and DC voltage deviation. The method would also be able to contribute to the minimization of the steady state frequency deviation. The synthetic inertia design would be accomplished with minimal cost to the owner/operator and would not be site specific.

Generator Response Following is presented as a possible design solution which includes some of these desired characteristics. The method is demonstrated with two communication channels functioning independently of each other. In this design scenario, system effects typically associated with inertia constant are accomplished by manipulating an inertial response measurement from the SSG. These effects can be amplified or reduced depending on design requirements and are independent of DC link capacitor size. Since the method is implemented with a separate communication channel for primary response, it can also impose an influence on steady state frequency deviation.

For installation feasibility or economic reasons, a real world implementation of the concept may be different from the above. For example, the installation of a SSG at the PCC for the sole purpose of providing inertial support to the OWF may not be economically practical. In this case, a synchronous condenser or a pre-existing synchronous generator located near the PCC might be used. This paper has demonstrated the GRF concept using a SSG with a power rating of 25% × OWF power capacity. However, prior experience suggests that the SSG can have a power rating as low as 5% × OWF power capacity and still be effective. A torque measurement at the shaft to separate primary response information from inertial response information also may not be realistic when weighed against the stability needs of the interconnected AC grid. Other possible implementations include a simple power measurement at the machine terminals or a real-time calculation of a synchronous power flow response rather than ”following” a measurement from another machine. However, it should be emphasized that less complex and less robust implementations of the method may have less of a stabilizing effect. In summary, Generator Response Following is a promising method that can offer design flexibility for balancing economic needs with stability concerns when frequency support services are required from VSC-HVDC connected offshore windfarms.

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