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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**—The present study attempts to collect relevant research on the subject of synthetic inertia control strategies for VSC-HVDC transmission links, particularly those connected to offshore windfarms. A number of ideas have been proposed in literature. First, various control strategies at the grid side converter interfacing the DC link with the AC power system are presented. This includes strategies exploiting the power-frequency relationship that naturally exists in AC systems with a high X/R ratio. Other strategies utilize the voltage-frequency relationship that exists when the DC link capacitor is asked to provide active power injection or absorption in response to frequency deviations. Then some coordinated strategies are outlined which build upon and combine other strategies (including those associated with traditional synchronous machines) in order to enhance the operational capability of the decoupled non-synchronous system with respect to synthetic inertia services. Some options for communication are also identified.

## I. 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. It should be emphasised that the inertia of the directly coupled synchronous generators determines the system frequency.

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 rates 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 by way of active power injection and absorption at the Grid Side Voltage Source Converter 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. One method is also given which coordinates between traditional directly coupled rotor inertia and a converter synthetic inertia method and therefore influences steady state frequency deviation.

The paper is organized as follows. Section II introduces the concept of synthetic inertia from individual wind turbine generators. Section III then introduces the VSC-HVDC link and the prospect of synthetic inertia from offshore windfarms. Section IV presents some frequency control strategies that may be implemented at the grid side voltage source converter of a VSC-HVDC connected offshore windfarm. Section V describes some strategies that have been proposed integrating some of the previously mentioned concepts as well as the traditional direct coupling method. A table is then given which summarizes the strengths and weaknesses of the various options. Section VI closes the paper with the more recent idea of multi-terminal HVDC. This subject is beyond the scope of the present work but illustrates the significance of the various communication methods presented. Section VII summarizes the survey by offering a hypothesis of an optimal synthetic inertia controller and discusses where further research may be relevant.

## II. 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 been proposed. 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].

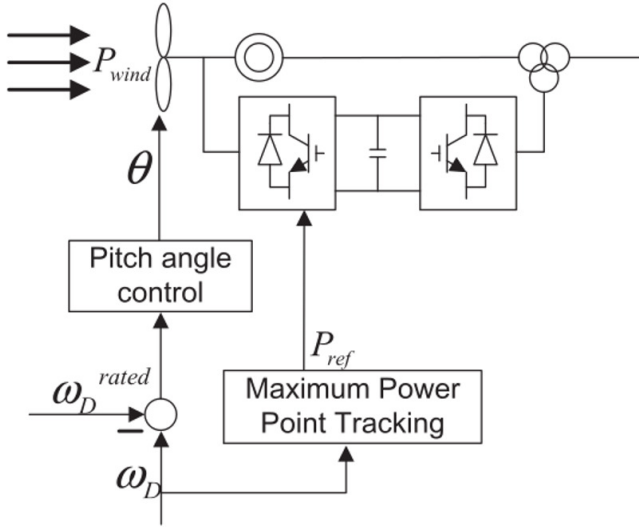


Fig. 1. Synthetic Inertia from WTG by Active Power Control [4]

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. In the case of VSC-HVDC connected OWF's, variable frequency operation of the AC collection grid is then possible. [5] mentions that since the windfarm AC collection grid likely has no loads connected to it, changes in frequency may be accomplished fairly easily. [2] then describes that rapid, reliable communication may be set up with the onshore AC grid through a chain-link coordination of voltage droops. This is essentially an artificial coupling of the two AC grids. Refer to Section VI-A for more information on this topic.

This method may have disadvantages as well. While instantaneous surges of active power may be available for mimicking a short-term inertial response, this may be followed by more prolonged periods of reduced power output while the rotor kinetic energy supply is recharged. This may further compromise system stability during more serious disturbances [1]. WTG's also tend to have a limited inertia time constant when used for this purpose.

### III. PROBLEMS AND OPPORTUNITIES WITH VSC-HVDC CONNECTED OFFSHORE WINDFARMS (OWF)

Due to its fast power transfer capability, 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 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. There is therefore 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.

### IV. 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 converter at the Point of Common Coupling (PCC). [9] proposes three methods; Fixed Frequency, Power-Frequency, DC Voltage-Frequency. The authors of [9] conclude that frequency performance is significantly improved by these methods, especially in isolated power systems. This section also includes a fourth method referred to as Inertia Emulation Control.

#### A. Fixed Frequency Control Strategy

Fixed frequency is the simplest 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].

#### B. Power-Frequency Control Strategy

In this method, the frequency control loop is added to the outer active power loop at the PCC. 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].

The system dynamics equation can be adapted to include the effects of the converter. In general, grid connected synchronous generator interaction with system wide frequency deviations can be described with the swing equation:

$$2H \frac{df}{dt} = P_m - P_e, \quad (1)$$

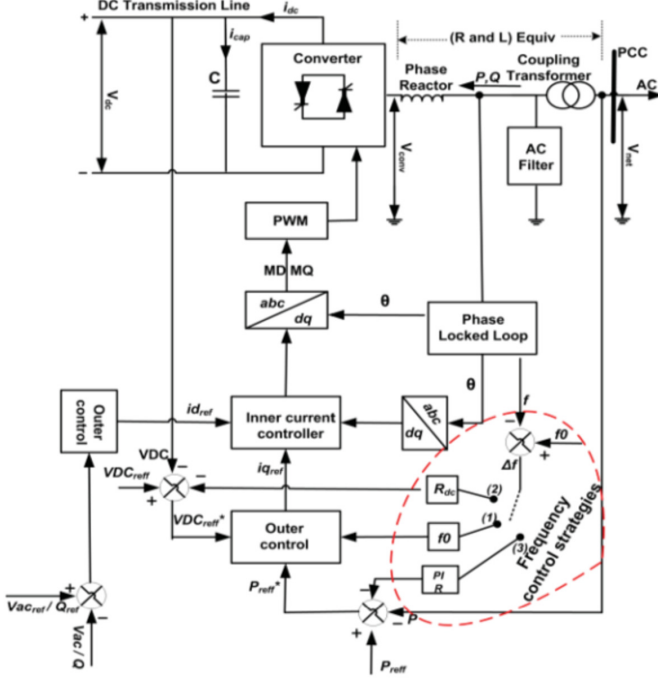


Fig. 2. VSC-HVDC Frequency Control Methods [9]

where  $H$  is the inertia time constant in seconds,  $f$  is the grid frequency in Hertz,  $P_m$  is mechanical power in per unit and  $P_e$  is electrical power in per unit. The frequency dynamics of a grid connected VSC may be described similarly:

$$K_{DC} \frac{df}{dt} = P_{DES} - P_{DC}, \quad (2)$$

where  $P_{DES}$  is the desired change in power and  $P_{DC}$  is the actual change in power through the VSC due to a grid disturbance.  $K_{DC}$  is the slope of the P-f droop. (2) can now be solved for  $P_{DC}$  and added to (1) for a generalized dynamics equation that includes the effects of synchronous generation as well as the converter dynamics:

$$(2H + K_{DC}) \frac{df}{dt} = (P_m + P_{DES}) - P_e. \quad (3)$$

A phase-locked loop is then used at the PCC to estimate the frequency and feed that information to the frequency controller [9].

### C. $V_{DC}$ -Frequency Control Strategy

In this method, the frequency control loop is added to the outer DC voltage loop at the PCC. Then when system frequency changes, instantaneous power is required from the DC link capacitor. This in-turn influences the DC voltage across that capacitor.  $V_{DC}$ -Frequency Control uses this DC voltage change and the capacitor energy equation to govern the dynamics of this interaction with a droop control [9]:

$$W_{cap} = \frac{1}{2} C V_{DC}^2 \quad (4)$$

where  $W_{cap}$  is the capacitor energy in per unit of rated power,  $C$  is the capacitance of the DC link capacitor in per unit and  $V_{DC}$  is the DC link voltage in per unit. The instantaneous power deviation can be included in this equation as the time derivative of energy:

$$\Delta P = \frac{dW_{cap}}{dt} = \frac{C}{2} \frac{dV_{DC}^2}{dt}. \quad (5)$$

Now, if we let (3) be represented by the standard P-f droop definition  $\Delta f / \Delta P = -R_{Pf}$  and combine with (5), we arrive at:

$$\Delta f = -R_{Pf} \frac{C}{2} \frac{\Delta V_{DC}^2}{T_{\Delta}}. \quad (6)$$

The new voltage-frequency droop relationship is then

$$f - f_0 = -R_{Vf} \left[ V_{DC}^2 - V_{0,DC}^2 \right] \quad (7)$$

where

$$R_{Vf} = \frac{R_{Pf} C}{2T_{\Delta}} \quad (8)$$

and is a function of the size of the DC link capacitor [9]. Notice the frequency deviation is proportional to the square of the voltage deviation. This non-linear relationship adds complexity to the small signal analysis of the system.

### D. Inertia Emulation Control (INEC)

This method takes the DC Voltage-Frequency strategy one step further by allowing a desired emulation inertia to be specified. The derivation is also slightly different. The power dynamics between the AC and the DC side are calculated as follows [1]:

$$P_{in} - P_{out} = V_{DC} (I_{in} - I_{out}) \quad (9)$$

$$\Delta P = V_{DC} \Delta I_{DC} \quad (10)$$

where  $P_{in}$  and  $I_{in}$  are input from the VSC to the DC link capacitor and  $P_{out}$  and  $I_{out}$  are output from the DC link capacitor to the VSC.  $V_{DC}$  is the DC link voltage. Replacing  $\Delta I_{DC}$  with the capacitor dynamics equation gives:

$$\Delta P = V_{DC} C \frac{dV_{DC}}{dt}. \quad (11)$$

In the per unit system, (11) can now be equated to the swing equation and an emulation inertia time constant  $H_{VSC}$  defined (see also (1)):

$$\frac{1}{f_0} \left[ 2H_{VSC} \frac{df}{dt} \right] = \frac{1}{S_{VSC}} \left[ V_{DC} C \frac{dV_{DC}}{dt} \right]. \quad (12)$$

Integrating both sides yields:

$$\left[ \frac{2H_{VSC}}{f_0} \right] \int df = \left[ \frac{C}{S_{VSC}} \right] \int V_{DC} dV_{DC} \quad (13)$$

and

$$\frac{2f H_{VSC}}{f_0} = \frac{C V_{0,DC}^2}{2 S_{VSC}} + K_0, \quad (14)$$

where  $K_0$  is referred to as the integration constant. Finally, according to [1], by solving for  $K_0$  the following relations can be made:

$$K_0 = 2H_{VSC} - \frac{C V_{0,DC}^2}{2 S_{VSC}} \quad (15)$$

where

$$H_{VSC} = \frac{f_0}{2\Delta f} \frac{C V_{0,DC}^2}{2 S_{VSC}} \left[ \left( \frac{\Delta V_{DC}}{V_{0,DC}} + 1 \right)^2 - 1 \right]. \quad (16)$$

Then  $R_{Vf}$  from (7) can be replaced by:

$$R_{Vf} = \frac{C f_0}{4 S_{VSC} H_{VSC}} \quad (17)$$

As with the DC Voltage-Frequency Control Strategy, a non-linear droop relationship exists. This adds complexity to the task of system design and analysis. The designer must 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  $\pm 15\%$  to preserve stability [10]. Also, [1] explores the prospect of emulation inertia time constants in the range of zero to four seconds for capacitors of size 2mF and 5mF. Then for a larger emulation inertia time 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.

## V. COORDINATED CONTROL STRATEGIES

### A. VSC-HVDC Coordinated Control Strategy

This strategy combines the WTG Synthetic Inertia method described in Section II with the GS-VSC Inertia Emulation method (INEC Controller) described in Section IV-D. 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 chain-link coordination of voltage droops as described in Sections II and VI-A. However, this time 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.

Simulation suggests the capacitor size was not improved and that further research is therefore required [4].

### B. Wind-Thermal-Bundled DC Modulation

This strategy explores a coordination between the proportional power-frequency droop method of a VSC-HVDC described in Section IV-B 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 in both islanded and interconnected mode. In contrast, mode 2 is found to yield the best results under fault conditions [7].

## VI. MULTI-TERMINAL HVDC (MTDC)

Although the topic of Multi-Terminal HVDC is beyond the scope of the present study, it serves as a good tutorial about the relevant communication methods that are currently being researched. As the system becomes more complex the researcher is further prompted to evaluate which method of communication is most efficient and reliable.

Currently, there are no MTDC systems in operation however MTDC grids are becoming more accepted as an alternative solution to point-to-point connections. This is mainly because they provide higher flexibility of dispatch power, reduced intermittency of renewable sources and general redundancy of power supply during DC disturbances compared to point-to-point VSC-HVDC [1], [2].

### A. Communication-less

According to [2], communication independent control schemes which rely only on local measurements must be

TABLE I  
CONTROL STRATEGIES FOR THE PURPOSE OF SYNTHETIC INERTIA FROM VSC-HVDC CONNECTED OWF'S

Method	Description / Implementation	Advantages	Disadvantages
Synthetic Inertia from WTG's	Artificial Coupling of Synthetic Inertia Through the HVDC Link	Much Research Available with Onshore Windfarms	Communication Required, Must Recharge Rotor Kinetic Energy
VSC Fixed Frequency Control	Implemented at the GS-VSC	Simple Design and Implementation	Intended for Small Isolated Systems, No Synthetic Inertial Response
VSC Power-Frequency Control (Proportional or PI)	Implemented at the GS-VSC	Simple Design and Implementation, PI can Influence Steady State Frequency	Very Little Synthetic Inertial Response
VSC Voltage-Frequency Control	Implemented at the GS-VSC	Some Synthetic Inertial Response	Synthetic Inertia Limited by Capacitor Size and Voltage Deviation Limits
Inertia Emulation Control	Implemented at the GS-VSC	Some Synthetic Inertial Response, Time Constant can be Specified	Synthetic Inertia Limited by Capacitor Size and Voltage Deviation Limits
VSC-HVDC Coordinated Control	Combine Inertia Emulation Control with Synthetic Inertia from WTG's	Some Synthetic Inertial Response, Time Constant can be Specified	No Improvement of Inertia and Capacitance Evident, Communication Required
Wind-Thermal-Bundled DC Modulation	Combine VSC Power-Frequency (Proportional) Control with Directly Coupled SG at WF-VSC	Good Inertial/Synthetic Inertial Response, Synchronous Generation Influences Steady State Frequency	Expensive and Site Specific because Synchronous Power Plant Required

developed. Rapid, reliable communication may be set up with the onshore AC grid through a chain-link coordination of voltage droops. This includes an f-V droop at the GS-VSC of the onshore AC grid. Then a V-f droop at the WF-VSC of the offshore AC collection grid. In this way, frequency deviation information is transported from one AC grid to another with a voltage droop. Frequency regulation loops at the wind turbine level are then used to provide power increases or decreases based on AC collection grid frequency variations. This artificial coupling of the OWF to the main grid allows it to provide frequency support services as a traditional onshore windfarm would [2].

### B. Fiber Optic Communication

This method requires using the fiber optic communication channel already embedded in the sub-sea cable connection of a VSC-HVDC link to an OWF. The communication link is between the onshore frequency measurement and the offshore WF-VSC's. This solution arises from a need for communication to multiple onshore locations where the frequency is different at each of those locations. Therefore the frequency support requirement is different at each of those locations. A weighted sum of the various frequencies is then used as the frequency for the OWF. The authors demonstrate that the transient frequency deviation of the onshore AC system can be improved over the communication-less method in the case of under-frequency trouble [5].

According to [2], communication solutions are prone to performance and reliability issues such as time delay, reduced data rate or complete loss of connection. As the complexity of the system grows (ie: from point-to-point systems to MTDC

systems) coordination of communication channels will become more difficult as well. For example, if a power in-feed to the system is required, decision making algorithms will have to be developed to determine which AC grid will be chosen to deliver the power and at which terminal.

## VII. 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 by way of active power injection and absorption. 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. Each method has advantages and disadvantages as can be seen in the Table I summary.

Based on the results of the present survey, a hypothetical optimized control strategy would have a synthetic inertial response which allows the designer to specify the inertia time constant. The designer would have the freedom to increase the size of the inertia time 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. All these items suggest there is still plenty of opportunity for research in this area. Furthermore, motivation is provided by the ever increasing need for non-synchronous generation

to contribute to the stability of the AC system as a directly coupled synchronous plant would.

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