Grid Integration of Offshore Wind Power and Multiple Oil and Gas Platforms

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Abstract—This paper investigates the possibilities of supplying offshore oil and gas platforms with power from the onshore power grid combined with offshore wind power. A system consisting of five oil and gas platforms connected to an offshore wind farm with a common VSC-HVDC link to the onshore power grid is studied. A model of the system is developed in MATLAB®/Simulink® and simulations are preformed for two critical system disturbances. The HVDC control system is designed and tuned in order to obtain stable offshore grid operation. The simulation results demonstrate that the system configuration is able to withstand severe dynamic events.

Keywords— HVDC transmission, VSC , power system stability, vector control

I. INTRODUCTION

The oil and gas industry is responsible for about 25% of the total greenhouse gas emissions from Norway [1]. Supplying oil and gas platforms with renewable energy from wind farms and from the onshore grid will greatly reduce Norway’s total CO2 emissions. Norway has committed to reduce the global greenhouse gas emissions by 30 %, compared to its own emissions in 1990, by 2020 [2]. About two-thirds of the cuts are to be made nationally. If these ambitious goals are to be reached, alternative power generation and supply solutions have to be considered. Today most of the offshore oil and gas platforms are self supplied with electric energy from gas fired turbines located on the platforms. These turbines typically have efficiency between 30 % - 40 % [3] and are the major source of emissions from the Norwegian continental shelf [4]. By replacing the energy from the gas turbines with renewable energy from offshore wind farms and hydro power from shore the greenhouse gas emissions can be reduced. This is however technically challenging because of the deep water and the long distance from shore in addition to the large costs associated with blackouts on the platforms.

Economical aspects and potential reduction in green house gases due to electrification from shore is investigated in [3]. Norwegian authorities have since 2007 required that power from shore must be considered for all new installations and major modifications on the continental shelf. To day the Troll A platform, and the fields Ormen Lange, Snøhvit, Gjøa, Valhall, and Goliat uses power from shore [5]. Associated with the increasing interest surrounding offshore wind power it has been suggested to supply oil and gas platforms with power from offshore wind farms. Several studies have been carried out investigating both economical aspects, possible fuel savings and emission reduction, as well as power system stability when a wind farm is connected to one or more oil and gas platforms in an isolated system [6] [7]. No systems like this are in operation today. A major challenge with such configurations is that a full backup power supply is needed in periods with no wind. In a system containing oil and gas platforms and offshore wind power connected to the onshore power grid there will be little or no need for power generation on the platforms. This also allows transfer of surplus power from the wind farm to the onshore grid. A system containing an offshore wind farm and an oil and gas platform with a common High Voltage Direct Current (HVDC) connection to the onshore power grid using Line Commutated converter (LCC) technology is studied in [8]. Similar systems to the one studied in this paper is investigated in [9] and [10]. These reports study a system using a Multi Terminal Voltage Source Converter (VSC)-HVDC system where the wind farm is connected on the DC side through a VSC. It is important to review different system configurations regarding both technical and economical aspects.

This paper will investigate the control and system stability of a power system containing an offshore wind farm connected to five oil and gas platforms through an offshore AC network. This network will be connected to the onshore power grid.
using a bipolar point-to-point VSC-HVDC connection, see Fig. 2.

A. Voltage source converter

For long distance submarine power transmission VSC-HVDC are proving to be a very promising technology for several reasons [11]. A schematic drawing of a two level, three-phase VSC is illustrated in Fig. 1. The voltages at the AC connections are a square wave switching between \(+V_{DC}\) and \(-V_{DC}\) depending on which switch is on. By using a switching frequency much higher than the fundamental frequency of the ac system a good impersonation of a sine wave can be constructed. The amplitude, phase angle, and frequency of the AC side voltage are usually controlled based on pulse width modulation (PWM). The voltage and phase angle on the AC terminals can be controlled separately. Hence active- and reactive power can be controlled individually by controlling the current through the phase reactance.

Fig. 1 Schematic drawing of a two level, three phase Voltage Source Converter

In 2010 Siemens introduced a multilevel VSC technology called HVDC Plus. At the same time ABB upgraded their HVDC Light system to utilize a similar technology. A multilevel VSC builds up the AC voltage in small steps by using several sub-modules consisting of IGBTs and a DC link capacitor holding a part of the DC link voltage. In this way the switching frequency of each semiconductor can be reduced hence reducing the switching losses in the converter and the total harmonic distortion [12].

B. Outline

This paper will start by presenting the system, how the different components are modeled and what simplifications that are made. Then results from two simulation cases, loss of all wind power and connection of a large load, is presented. The results of the simulations are discussed based on the grid code [13] and the simplifications made in the model before a conclusion is drawn.

II. MODELING THE SYSTEM

An overview of the system can be seen in Fig. 2. If a system like this is to be realized it can not be built at the expense of the stability of the onshore power grid. The onshore connection is therefore thought to be at a strong point in the Norwegian main power grid. The grid connection is modeled as a Thevenin equivalent with phase-to-phase rms voltage equal to 300 kV, the frequency is 50 Hz, and the short-circuit level is set to 2500MVA. From the onshore converter the energy is transmitted through a 220 km HVDC bipolar transmission link. The DC submarine cables are modeled as a PI equivalent using typical values and the DC voltage is set to \(\pm 120\) kV. The transformers are modeled using a model referred to as the exact equivalent circuit in [14] and typical values are used. The offshore converter station and the AC bus bar are thought placed on an offshore platform. Five oil and gas platforms with different load and one offshore wind farm are connected to the AC bus bar. The distance from the converter platform to the oil and gas platforms and the wind park vary between 50 km – 80 km, the voltage is set to 90 kV, and the frequency is 60 Hz. All the AC cables are modeled with a PI-equivalent and data are taken from [15]. To reduce complexity in the model the oil and gas platforms are modeled as a pure R and L load. In reality the platform load will be far more complex consisting of a mix between converters, induction machines, and passive loads. This simplification has to be taken into account when analyzing the results.

Fig. 2 Overview of the system.

A. Converters

This paper aim to demonstrate how the HVDC transmission system, the wind farm, and the oil and gas platforms interact, and how control of the HVDC transmission influence the system dynamics. Converter losses and harmonic filters are not a focus point in this study. By utilizing a PWM modulated VSC with sufficiently high switching frequency or a multilevel VSC with a high number of steps the output approaches a pure sinusoid and harmonics can be neglected. This means that the converter can be modeled like a controlled voltage source generating the average AC voltage over one cycle of the switching frequency. This type of model is often referred to as an average model. It does not represent harmonics, but the dynamics cased by the controllers and the power system interaction is preserved. The average model can also be used with larger time steps compared to a model including switches, hence reducing simulation time. Fig. 3 shows the VSC model used in this study. It is an ideal model so the active power on
the AC side is always equal to the active power on the DC side as described in (1).

\[ V_{conv,a} + V_{conv,b} + V_{conv,c} = V_{DC} I_{conv} \]  

(1)

**A. Control principle**

The control of the VSCs is realized by using vector control based on a synchronous rotating dq-reference frame. Using the dq transformation the voltages of the converter can be described as:

\[
\begin{align*}
    v_{g,d} - v_{d,conv} &= Ri_q + L \frac{di_d}{dt} - \omega Li_q \\
    v_{g,q} - v_{q,conv} &= Ri_q + L \frac{di_q}{dt} + \omega Li_d
\end{align*}
\]

(2)

where \(v_{g,d,conv}\) and \(v_{g,q,conv}\) and \(i_{dq}\) are the d and q part of the AC grid voltage, the converter input voltage, and the line current respectively [16]. R and L are the resistance and the inductance between the converter and the AC grid connection point. The d-axis of the rotating reference frame is aligned to the AC voltage vector. In this way it is possible to control the active and reactive power independently by controlling the d- and q-axis current [17]. A cascaded control system is used consisting of a fast inner current controller, controlling the d- and q-part of the current, and a slower outer controller. In the wind farm the outer controller is set to control the active and reactive power, and the outer controller on the onshore converter is set to control the DC voltage.

The offshore converter uses a simple yet robust control system to keep the voltage and the frequency on the offshore AC bus bar stable. A three-phase reference signal with fixed amplitude and frequency is sent to the VSC model. This is equivalent to having a constant modulation index and a fixed frequency in the PWM control signal. As long as the voltage on the DC terminals on the converter is constant it will produce a constant voltage on the AC terminals.

**IV. Simulations Results**

The simulations were performed using the toolbox SimPowerSystems in MATLAB®/Simulink®. Two cases were simulated: loss of all wind power, and connection of platform 3. The system will be evaluated on whether the power system stabilizes after these disturbances and the voltages, and frequency keeps within the acceptable limits [13]. IEC 61892 is the norm regarding offshore electric installations. The allowed transient and static voltage and frequency variations on oil and gas platforms are stated bellow:

<table>
<thead>
<tr>
<th>Platform parameter</th>
<th>Per Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient voltage limits</td>
<td>0.8 – 1.2</td>
</tr>
<tr>
<td>Stationary voltage limits</td>
<td>0.9 – 1.06</td>
</tr>
<tr>
<td>Transient frequency limits</td>
<td>0.9 – 1.1</td>
</tr>
<tr>
<td>Stationary frequency limits</td>
<td>0.95 – 1.05</td>
</tr>
</tbody>
</table>
The most important results from the simulations are given in TABLE 2.

### TABLE 2 Results of simulation. All values are given in per unit values.

<table>
<thead>
<tr>
<th></th>
<th>Loss of all wind power</th>
<th>Connection of platform 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recovery time</strong></td>
<td>0.1 s</td>
<td>0.2 s</td>
</tr>
<tr>
<td><strong>DC cable</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{\text{min}} - V_{\text{max}}$</td>
<td>0.98 – 1.02</td>
<td>0.98 – 1.02</td>
</tr>
<tr>
<td><strong>AC bus bar</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{\text{min}} - V_{\text{max}}$</td>
<td>1.07 – 1.02</td>
<td>1.10 – 0.99</td>
</tr>
<tr>
<td>$f_{\text{min}} - f_{\text{max}}$</td>
<td>0.997 – 1</td>
<td>0.997 – 1</td>
</tr>
<tr>
<td><strong>Platform 4</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{\text{min}} - V_{\text{max}}$</td>
<td>0.98 – 0.93</td>
<td>1.01 – 0.90</td>
</tr>
</tbody>
</table>

### A. Loss of all wind power

In the first simulation case the wind park is set to deliver 50 MW before tripping the park. The HVDC-VSC transmission system will then have to react quickly to increase the delivered power. When the wind farm is disconnected the power to the loads will be reduced. This will cause the AC voltage to drop which again will cause a drop in the DC voltage. The onshore converter should sense that voltage drop and increase the injected power into the DC cable to restore the voltage to its reference value.

Measurements on the DC cable on the offshore terminals are displayed in Fig. 5 and Fig. 6.

### Fig. 5 DC voltage on offshore converter terminal during disconnection of the wind farm ($V_{\text{bus}}=240$ kV).

### Fig. 6 Active power into offshore converter during disconnection of the wind farm ($S_{\text{bus}}=30$ MVA).

The frequency on the bus bar drops around 0.2 Hz when the wind farm is disconnected but is reestablished after around 0.1 s. This is shown in Fig. 10. It can also be noted that the steady state frequency is 57.97 Hz. The frequency is well within the limits given in [13].

### TABLE I shows the grid codes on the platforms. Platform 4 has the largest voltage drop and hence the lowest voltage. The voltage on platform 4 during the disconnection of the wind farm is shown in Fig. 11. There are some fluctuations before the voltage stabilizes. The voltage is within the limits in [13].

### Fig. 7 Current from offshore converter to the bus bar during disconnection of the wind farm ($I_{\text{bus}}=1.925$).

### Fig. 8 Voltage on the bus bar during disconnection of the wind farm ($V_{\text{bus}}=90$ kV).

### Fig. 9 Active power from the offshore converter to the bus bar during disconnection of the wind farm ($S_{\text{bus}}=300$ MVA).

### Fig. 10 Frequency on the bus bar during disconnection of the wind farm.
B. Connection of platform 3.

In this simulation case platform 3 is suddenly connected to the system. Platform 3 is a RL load of 50 MW at $\cos \phi = 0.9$ inductive. Prior to the connection of the platform all the other platforms and the wind farm are running at their rated levels. The VSC-HVDC system will have to react quickly to supply the extra power needed. A part of the load on platform 3 is inductive. When the inductive load is connected energy will start to oscillate between the capacitance in the cables and the inductive load. This will cause the current to oscillate which again will produce fluctuations in the DC voltage. It is important that the control system is able to dampen these oscillations.

The voltage and power in the DC cable at the offshore converter terminal during the connection of the load is illustrated in Fig. 12 and Fig. 13.

The active- and reactive power from the wind farm into the bus bar is displayed in Fig. 17 and Fig. 18. The reactive power is due to the capacitances in the cable and the small change is due to the static voltage drop.
The frequency on bus bar during the connection of platform 3 is illustrated in Fig. 19. There is a small dip on around 0.1 Hz and the steady state frequency is 59.96 Hz. The frequency is well within the limits in [13].

![Fig. 19 Frequency on the bus bar during connection of platform 3.](Image)

From the simulations it can be seen that the system was able to reach a new stable state after both disturbances. In the case where platform 3 suddenly was connected the voltage and power oscillations were more severe and the system used longer time to reach a new steady state than for the case where the wind farm was disconnected. The voltage variations on the platforms were within the limits in both cases, however there were some oscillations.

These simulations are performed using an average VSC model which has no time delay. A real converter will have a time delay given by the switching frequency. This time delay combined with other delays associated with real life system will decrease the stability margins. However the time delay in the converter is small. A detailed VSC model will also introduce harmonics in the AC voltage and ripple in the DC voltage but this will to a large extent be removed by filters. Overall it is not expected that the use of a detailed VSC model would have much effect on the results in this paper.

The control parameters have a big influence on the dynamics of the system. Different control parameters might reduce the fluctuations in the voltage. Providing the offshore converter with a more sophisticated AC voltage control may also help dampen the oscillations in the AC voltage on the offshore bus bar, assuming that the control is fast enough to react on the oscillations in the DC voltage. It is also possible for the wind farm to support the AC voltage by providing dynamic reactive power.

The platform load in this study are modeled as a RL load, hence the load will vary with the voltage on the platform. In reality the platforms will behave more like a constant power load. A more constant load profile will most likely affect the transient behavior of the system and have a negative effect on the systems stability. More detailed load models may lead to a different result.

Direct start of a large induction motor may cause a large inductive current that may prove to be challenging to the control. However most large induction motors use a frequency converter or other arrangements to limit the starting current. A sudden connection of a load on 50 MW $\cos \phi =0.9$ is also not realistic but will give a good indication to how the system will react to large disturbances in the system and how the control is able to respond.

This project uses an aggregated wind farm model consisting of a VSC connected to a fixed DC source. In reality a sudden increase in load, like the case of connecting platform 3, might cause a dip in the DC voltage in the wind farm converter. This will in turn affect the voltage on the AC bus bar. The dip in the DC voltage is believed to be small and taking into account that the wind farms influence on the bus bar voltage is far less significant than the HVDC transmissions system the simplifications in wind farm model is considered valid for the simulation cases presented in this paper.

There are some uncertainties regarding the frequency measurements. The simulations were done using a discrete model with sampling time on 50 $\mu$s. This may lead to an inaccuracy in the frequency measurement which can explain the static variation from the fundamental frequency shown in Fig. 10 and Fig. 19. The transient behavior is also uncertain because of the limited number of voltage periods during the transient. The frequency in the system was however well within the limits in both simulation cases as expected given the nature of the control of the offshore converter.

V. DISCUSSION

A model of the power system and the control system has been made and simulations have been performed in order to study if this system configuration is a feasible way to integrate oil and gas platforms and offshore wind power to the onshore grid.

The control system develop is working as intended. The DC voltage controller is able to track the voltage reference during the disturbances simulated in the study. However some oscillations in the DC voltage were observed during connection of platform 3. The control of the wind farm was able to control the active- and reactive power injected into the grid. The control system was able to keep the voltage and frequency variations within the offshore grid code and the system reached a new steady state within 0.2 s. in both simulation cases.

The results of the simulations indicate that the system configuration reviewed in this paper is feasible. However more detailed studies needs to be done before a clear conclusion can be made. This could include development of a more sophisticated control for the offshore converter and a more detailed load model for the oil and gas platforms.
REFERENCES


[13] IEC 61892, "Mobile and fixed offshore units –Electrical installations".


