Faults Mitigation Control Design for Grid Integration of Offshore Wind Farms and Oil & Gas Installations Using VSC HVDC
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Abstract—This paper presents an analysis and new fault mitigation methods of grid integration of offshore wind farms and oil & gas installations using Voltage Source Converter (VSC) HVDC transmission system. On the fault occurrence in the onshore AC grid, the proposed DC link voltage controller initiates fast output power drop of the wind farm, in order to avoid the overvoltage in the DC transmission link. On the faults occurrence in the oil & gas installation, the proposed control employs a voltage-dependent limiter, to limit the maximum amount of active power from the offshore VSC. Simulation results in PSCAD / EMTDC show the satisfied performance of the proposed control strategy for the case of one 300 MW VSC transmission system connecting an offshore wind farm and oil & gas installations to the grid.

Keywords—Voltage Source Converter (VSC), Offshore wind farm, Oil & Gas Installation, Grid Integration.

I. INTRODUCTION
Offshore wind farms promise to become an important energy source in the near future, because of several favourable characteristics such as higher wind speeds, less turbulence and availability of large areas. However, long distances from wind farms to the shore pose challenges to the design of offshore power transmission links, such as the requirements on low electricity loss and the high grid faults toleration ability, which are critical for the economic feasibility of huge offshore wind projects.

Since the most of planning offshore wind farms are 100 km away from onshore, HVDC transmission solutions will be feasible and more competitive than the AC solutions [1].

Two major HVDC solutions for the offshore power transmission are the Line-Commutated-Converter (LCC) HVDC transmission system using thyristors and VSC HVDC system using IGBTs. The LCC HVDC solution has relatively less loss and longer commercial operation experience. However, the huge size and weight of LCC converter station is the major drawback for offshore applications [1] [2]. The VSC HVDC has recently gained growing interest due to its simplified modularity, the independence of AC network, and the decoupled active and reactive power control capability.

The configuration and control topologies of the VSC-HVDC transmission system for the offshore wind farms were presented in previous publications [3] [4]. Because some oil and gas installations are geologically close to high wind resource areas [10]. It is feasible to integrate the offshore oil & gas installations and the wind farms using single HVDC transmission link to onshore grid, which potentially can abate significant CO₂ emission caused by gas turbines or diesel generators at oil & gas installations.

In [5] [6], the control and performance of VSC HVDC system during a balanced phase to ground fault at onshore AC grid were studied, however, it is hard to find any detailed study on the offshore AC grid balanced faults.

Furthermore, in some of previous publications, the wind farm with variable speed wind turbines is simplified as a controlled current source or synchronize generator. Obviously, the operation and response of variable speed wind turbines under network disturbance will be significantly different from any current source, for example, the wind turbine drive train oscillations may cause oscillating power variations to the grid. Thus the model presented in this paper consists of wind air dynamic model and two mass drive drain model, which can be used for studying how the wind speed variations and mechanical oscillations influence the offshore AC grid.

This paper is organized as follows: First, a VSC HVDC transmission topology is proposed for grid integration of oil & gas installations and offshore wind farms. Second, the HVDC system mathematic model and the control strategy during the normal operation will be presented. Third, the control approaches to ride through various faults both in offshore and onshore AC grid will be investigated. At last, some simulation results in PSCAD will be presented to illustrate the stable performance of the proposed several control strategies to override faults.

I. SYSTEM CONFIGURATION
Figure 1 shows the single line diagram of the VSC HVDC system for the control strategy analysis. It comprised a wind farm with variable speed wind turbine, several oil & gas installations, and a VSC HVDC link.

![Fig. 1 Single line diagram of the VSC HVDC transmission system for the control strategy analysis](image-url)
The oil & gas installation has both passive loads and induction machines. The offshore side VSC collects and transmits active power to onshore grid side VSC by dc cables.

The variable speed operation of wind turbines can be achieved with the back-to-back converter and pitch control. A crowbar is connected to the convert to protect DC capacitor over voltage and rotor over current. Stator voltage-oriented vector control method is used to control the back-to-back converter [7]. The detailed control strategy of wind turbine with Doubly Fed Induction Generator (DFIG) will not be explained in this paper, since it was well documented in several references [3] [7].

An equivalent model of wind farms is developed based on aggregating wind turbines, which consists of air dynamic and mechanical model, generator and power converter control [8], as shown in Figure 2. The parameters of each power system component will be presented in the simulation results session.

II. SYSTEM CONTROL

The control objective of VSC transmission system are: 1), to collect and transmit power according wind generation and oil & gas installation load situation, 2), to maintenance DC link voltage to a reasonable range, and 3), to provide reactive power compensation if necessary. 4), to regulate the offshore AC grid voltage and frequency.

To achieve the above mentioned objectives, there are different control strategies for offshore side VSC and onshore side VSC. The offshore side VSC regulates the voltage and frequency of the offshore AC grid, while onshore side VSC maintains DC link voltage and provide reactive power.

Comparing with LCC HVDC solutions, one of the advantages of VSC HVDC is the bi-direction power transmission; in another word, the power transmission can change its direction automatically according the offshore wind generation supplying and load demanding situation, as simulation result shown in Fig. 7.

A: Normal operation

As the control strategy of onshore side VSC has been well explained in several references [5] [7], this paper focuses on several controllers employed in the offshore VSC-HVDC system, shown as follows:

Offshore AC Frequency Controller

Several frequency control strategies of VSC-HVDC systems were proposed in [9]. However, the fixed frequency control strategy is favorable for transmitting the offshore wind energy. First, with the fixed offshore AC grid frequency, the offshore VSC behaves as infinite voltage source and absorb the fast changing wind power generation, so a bi-direction power transmission can be achieved. Second, with the fixed frequency the extra power control loop is not needed, therefore, the fast communication system among the offshore wind farms, the oil & gas installation and VSC is not necessary.

The diagram of the frequency control strategy for the offshore side VSC is also shown in Figure 3. A fixed nominal frequency (f_{ref}) is supplied to the VSC output voltage (V_{VSC}); therefore, the VSC is controlled as a voltage source with constant frequency and phase angle. The AC voltage controller consists of one PI regulator and feedback from measurement, as shown in Fig. 3.

B: Onshore AC Grid Fault Mitigation Control

It is critical to supply continuous power to oil & gas installations, which requires offshore AC grid to ride through certain onshore grid faults.

During onshore grid fault, the active power transmitted to onshore by DC cable will be significant reduced due to onshore AC voltage dip, while the wind farm keeps on supplying active power to offshore VSC, the HVDC DC link voltage dynamic can be shown in equation [1]:

\[ C_i \frac{dV_{DC}}{dt} = 2P_w - 2P_c - 2P_p = \Delta P \] (1)

Where \( \Delta P \) is the surplus power generated by wind farm, and where \( P_w, P_c, P_p \) is active power of wind farm, offshore VSC, and oil platforms respectively. If no any control on DC link implemented, the HVDC DC link voltage will increase rapidly, which will be out of reasonable range and bring equipments damage.

There are several methods for grid fault ride-through mentioned in [6]. It is possible either to use DC chopper to dissipate superfluous power by breaking resistors, or to reduce wind farm output power after detecting the DC link voltage surge. The wind power deduction method will be used in this paper, because the variable speed wind turbines facilitate the possibility of energy storage into the rotating rotor, thus the surplus energy can be stored into the rotor instead of being dissipated to the breaking resistors.
The proposed HVDC DC Link Voltage Controller (DLVC) is shown in Fig. 4. The Fig. 9 shows a comparison between systems with the DLVC controller and without DLVC controller basing on simulation results. Normally the wind power reference $P_{Wref}$ is decided by maximal power track calculation. When DC link voltage ($V_{DC}$) exceeds certain value ($V_{DC \_ref}$), the $V_{DC}$ deviation loop is activated by sending its output to wind turbine power reference. By this way, the wind power output will be reduced by change modulation index to Rotor Side Converter (RSC). Thus, a new power balance will be established to regulate the HVDC DC link voltage.

Another alternative option of DC link voltage regulation is to reduce the current from wind farm by frequency control, which is mentioned in [6]. However, the fast deviation of frequency is hard to be detected in a short period, so it might be not feasible for this response speed demanding application.

C: Offshore AC Grid Fault Mitigation Control

The offshore side VSC collects and transmits the wind power to oil & gas installations and onshore, while maintaining the AC grid voltage ($V_{ac}$) and frequency. Figure 3 shows the control structure of the offshore side VSC.

The offshore AC grid faults most likely occur in oil & gas installations than in wind farm. During the fault, there will be a voltage drop with a low retained voltage at the offshore AC bus. Therefore, a large transient current caused by power balance will most probably occur, which might damage the IGBTs and other equipments.

In one aspect, the transient current should be limited to avoid the equipment damage. In another aspect, the VSC should supply over current as much as possible within its limitation, in order to allow protection system detect and trigger the faults in time.

Since there is no inner current control loop implemented in offshore side VSC, the AC voltage of VSC ($V_{ac}$) has to be appropriately limited. Therefore, an offshore AC grid voltage independent limiter is implemented in the ac voltage control loop via the modulation index (M) of the VSC, shown in Figure 3. When the faults occur, the low offshore AC grid voltage ($V_{ac}$) is detected, and the $V_{ac}$ is set to a low value, in order to limit the VSC current. During the faults recovery period, the VSC voltage $V_{ac}$ limitation increase linearly with the offshore AC voltage, as shown in Figure 5.

The exact design of the $V_{ac}$ versus $V_{ac}$ curve in Figure 5 is depends on the detailed VSC design and how fast the wind generation recovers from faults, in order to reach the active power balance in the offshore AC grid.

III. SIMULATION RESULT

To evaluate the proposed control system, a model of VSC-HVDC transmission system is simulated in PSCAD / EMTDC, shown in Figure 1. The simulated topology consists of a 300 MW variable speed wind turbines based wind farm and a 100 MW oil & gas installation, which is connected to VSC-based HVDC transmission system of 150 km length and transmission voltage of ± 120 kV.

A: Normal operation simulation

System control and operation during normal operation with series step change of both wind speed and oil & gas installation load were simulated. The simulation events are listed at table 1. The Fig. 9 shows the simulation result.

At $t = 2$ s and $t = 4$ s, the wind speed changes from 11 m/s to 12 m/s, and changes back to 11 m/s, the active power generated by wind farm and power transmit to onshore were changed correspondingly. Notice that there is no any affection on power supplying to oil & gas installation. At $t = 3$ s and $t = 5$ s, the load switching of platform shown in Fig. 6 (d) have no affection on wind farm power output as shown in Fig. 6 (b). Fig. 6 (c) shows that the power transmitted to onshore grid reduces and increases correspondingly with platform load variation. The Fig. 6 (g) and Fig. 6 (h) clearly shows the regulation of offshore AC voltage and frequency during variation of wind speed and platform load.

TABLE I SIMULATION EVENTS

<table>
<thead>
<tr>
<th>Sec.</th>
<th>Events</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>Wind speed increases from 11 to 12 m/s</td>
</tr>
<tr>
<td>3</td>
<td>An oil installation rated 60 MW (0.12 pu, pf 0.85 ) is connected</td>
</tr>
<tr>
<td>4</td>
<td>Wind speed decreases to 11 m/s</td>
</tr>
<tr>
<td>5</td>
<td>An oil installation rated 60 MW (0.12 pu, pf 0.85 ) is disconnected</td>
</tr>
</tbody>
</table>

Furthermore, the wind step change was replaced by the existing wind source for 10 seconds, with mean wind speed = 12 m/s at hub height and a random noise generation, shown in Fig. 7 (a). The active power of wind farm varies correspondingly with certain delay, shown in Fig. 7 (b).

Because of the proposed fix control strategy in offshore AC grid, the surplus power is absorbed and transmitted by offshore side VSC. If the wind power generation is less than the load of the oil & gas installations, the power flow in VSC-HVDC reversed from the onshore grid to the offshore automatically.
Further study focuses on the operation and performance during a solid three phase to ground fault on onshore AC grid, and the simulation results are shown in Fig. 8.

The fault was applied at 1.5 s and cleared at 1.6 s. When the fault occurred, Onshore AC voltage collapsed to 0.11 p.u., shown in Fig. 8 (a). During the fault, the active power transmission reduced significantly as shown in Fig. 8 (c), while wind farm still produce power as illustrated in Fig. 8 (b). During the faults, the power consumption of oil & gas installation keeps on normal value, to guarantee the continuous oil production. When the fault is cleared, the onshore AC voltage and HVDC DC link voltage recovers after some transient. The power transmission resumes and HVDC DC voltage return to nominal value.

Simulations were carried out using DLVC controller mentioned in section II. When the HVDC DC voltage increases to 1.05 p.u., the extra control loop shown in Fig. 4 will be activated. The control signal is sent to wind farm power reference to reduce its power output. As we can see in Fig. 8 (b), the active power generation of wind farm is reduced from 0.88 p.u. to 0.65 p.u., while the HVDC DC link voltage (Fig. 8 (g)) keeps in a reasonable range.
The wind turbine rotating speed will be increased, because the unbalanced mechanical torque and DFIG air-gap torque leads to acceleration of wind turbine rotor.

Fig. 9 Simulation results during a three phase fault on onshore side AC grid (Blue: without DLVC implemented, Green: with DLVC controller).

The simulation case has been repeated without the DLVC controller, as shown by blue curves in Fig 9. When the configuration without DLVC controller is used, the active power from wind farm (blue solid curve in Figure 9a) almost keeps unchanged, thus the dc voltage farm (blue solid curve in Figure 9a) surged to a high level (1.36 p.u.) until the fault clearance. At the same time, with DLVC controller presence, the HVDC DC voltage, offshore AC voltage and offshore AC frequency (green solid curves in Figure 9a and 9b) peak values are smaller than the configuration without DLVC controller.

C: Offshore AC Grid Fault Simulation

The simulations results of a solid three phase to ground fault on offshore AC grid are shown in Fig. 10. The fault is applied at 1.50 s and cleared at 1.60 s. When the fault occurs, the offshore AC voltage collapses to almost 0.1 p.u. as shown in Fig. 10 (a). During the fault, the wind farm active power output and HVDC active power transmission reduce significantly as show in Fig. 10 (b) and (c). When the fault is cleared, the offshore AC voltage recovers after some transient as the power transmission resumes.

Simulations were carried out implementing VDL mentioned in section II, which influences the recovery ramping of active VSC power. In this case, the wind farm power recovers faster than active VSC power. Therefore the power unbalance brought frequency surge after 1.70 second (Fig. 10 (h)). The active VSC power recovery ramping can be further adjusted to reach more accurate power balance and thus less frequency variation.

The simulations were repeated for different values of offshore VSC reference voltage limitation $V_vsc_{\text{max}}$. When the $V_vsc_{\text{max}}$ is equal to 1.5 times the rated VSC AC voltage, the offshore VSC current surged to 2.8 p.u. (Fig. 11 b). When the $V_vsc_{\text{max}}$ is equal to 1.1 times the rated VSC ac voltage, the offshore VSC current is within 1.0 p.u. during fault and surged to 1.5 p.u. during recovery period (Fig. 12 b). Simulation results in Figure 11 and 12 show that the VDL significantly affects the system dynamics during the fault and recovery period.

Simulations in Figure 11 and 12 also show that the wind farm DFIGs and induction motors in oil platforms will supply most of fault current, while VSC current was kept as relatively lower value. So it is interesting to see that how the fault current will be supplied if the wind turbine is equipped with full size converters, as over current capability of converter is limited close to the rating current. Furthermore, if the VSC supplies the offshore oil & gas installation, another potential challenge could be how to set the protection system parameters to distinguish the AC grid faults current from the motor start current in the oil installation.

In this extremely serious fault scenery simulated, the active power supplied to oil & gas installations has dropped to near 0 p.u. Therefore, the uninterruptible power supply needs to be installed in the platform to keep continuous operation.
IV. CONCLUSIONS

Several faults mitigation control strategies for the offshore VSC HVDC grid integrating offshore wind farm and oil & gas installations has been proposed and evaluated in this paper, for example, the DC link voltage controller for onshore grid faults and the voltage dependent limiter for offshore AC grid faults. First, the principle of the proposed VSC HVDC system and its control strategy has been described. The system dynamic performances during variable wind speed and load switching have been demonstrated by PSCAD simulation.

Second, the system performance during onshore AC grid three phases to ground fault has been studied. With the proposed DC link voltage controller, the system is likely to survive during such fault conditions.

At last, the offshore AC grid three phases to ground fault was studied, and the simulation results show the proposed VDL limiter implemented will help the system recovery by influencing the recovery ramping of active VSC power.

APPENDIX

<table>
<thead>
<tr>
<th>Table II</th>
<th>System Parameters</th>
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<tr>
<td>Rating (base) apparent power</td>
<td>300 MVA</td>
</tr>
<tr>
<td>Rating (base) voltage, offshore AC</td>
<td>115 kV</td>
</tr>
<tr>
<td>Rating (base) voltage, HVDC link</td>
<td>120 kV</td>
</tr>
<tr>
<td>System Frequency $f_{ref}$</td>
<td>50 HZ</td>
</tr>
<tr>
<td>Resistance per km</td>
<td>0.0217</td>
</tr>
<tr>
<td>Inductance per km</td>
<td>0.792mH</td>
</tr>
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</table>

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