Real-time digital simulation of a VSC-connected offshore wind farm

Patrick P. T. Groenewoud, Delft University of Technology, Netherlands, Patrick.Groenewoud@movares.nl
Ralph L. Hendriks, Delft University of Technology, Netherlands, R.L.Hendriks@tudelft.nl
Bart C. Ummels, Delft University of Technology, Netherlands, B.C.Ummels@tudelft.nl
Wil L. Kling, Delft University of Technology, Netherlands, W.L.Kling@tudelft.nl

Abstract — Multi-terminal high voltage direct-current (MT-HVdc) technology could be an interesting technology for international submarine interconnectors. Synergies may exist between energy trade and the connection of large-scale offshore wind power to onshore grids, since the capacity utilization of the system can be increased.

This paper presents a simplified simulation model of a VSC-connected offshore wind farm for the real-time digital simulator (RTDS). The RTDS works in continuous sustained real-time and is therefore able to perform the simulations fast. The converter bridge is modelled by the assumption of ideal sources. All other components (converter transformer, phase reactors, dc capacitor, etc.) are modelled using their physical representation in standard library blocks. Different operational cases are simulated: normal operation and fault situations in the ac-system.

Index Terms — High Voltage Direct Current, Multi-terminal, Offshore Wind, Real-time Digital Simulator, Voltage-Sourced Converter.

1. INTRODUCTION

Offshore wind power has the potential to become an important source of renewable energy in Western Europe. The first projects have been constructed relatively close to shore (<25 km) and have power ratings up to 160 MW. These wind farms are connected to the power system through submarine power cables operated at alternating current (ac). The future holds projects that will be located further away from the shore and have higher power ratings, complicating grid connection. Besides, there is a growing need for electricity trade in Europe, also because of the liberalized electricity market. The combination of these two objectives—grid connection for offshore wind farms and new cross-border interconnection capacity—into a single infrastructure may lead to interesting cost savings. The capacity factor of an offshore wind farm is in the order of 40%; the proposed solution could improve the usage of the electrical infrastructure by facilitating energy transports at times of low wind production.

At transmission distances of about 80 km, the physical limits of ac transmission through submarine cables are reached. Connection through direct-current (dc) technology could overcome these restrictions and seems therefore an interesting technology for the proposed solution. Contrary to most existing HVdc-transmission schemes, the proposed infrastructure is multi-terminal (MT), see figure 1.

Thyristor-based line-commutated converters (LCC) have been used for the conversion between ac and dc for more than 50 years now, for power ratings up to and over 1500 MW. For offshore use this technology has several disadvantages: the converter stations have large space requirements and are therefore difficult to build on offshore platforms, operation is problematic without additional equipment providing a stable ac voltage, and operation at low power produces high valve losses and harmonic currents. DC transmission based on voltage-sourced converters (VSC) with forced commutated switches could overcome these disadvantages. The high switching frequency reduces the ac-side voltage and dc-side current harmonics significantly compared to the LCC, thus requiring less harmonic filters and resulting in a smaller converter footprint. The VSC has inherent black-start capability, enabling energizing of the remote wind farm grid. Besides, the independent control of active and reactive power provides STATCOM-like functionality making it easier to comply with grid connection requirements onshore. Also, more robust operation in MT-configuration is an advantage.

For the study of the behaviour of the MT-VSC transmission system as a part of a power system, various simulation frameworks are available. Delft University of Technology has a real-time digital simulator (RTDS) that enables the simulation of electric networks in real-time. This saves time and allows the user to change system parameters during the simulation. A library with detailed power system-component models is included in the RTDS software. This allows the user to set-up a model that closely resembles the real system. Typical application of the RTDS is the closed-loop verification of control and protection hardware. For real-time operation, the RTDS has a minimum step-size of 50 μs. This step-time limits accurate simulation of circuits switching at frequencies above 1 kHz. To simulate the proposed transmission scheme, reduced VSC models are required.

The remainder of this paper is organized as follows. In section 2, the operating principles of the VSC are described, after which the control of the VSC is explained in section 3. The RTDS model is discussed in section 4 and in section 5 are different operational cases simulated, regarding the normal operation and fault situations in the ac system.

2. VSC OPERATING AND MODELLING PRINCIPLES

A VSC is a power electronic device that can convert power from the ac to dc side and vice-versa by switching power electronic switches in a controlled manner. The ac side of the
VSC is theoretically able to produce any preferred voltage waveform, only limited by the direct voltage and the switching frequency. For grid purposes, a sinusoidal voltage needs to be produced with the same frequency as the grid’s. To produce this waveform, in most cases a pulse-width modulation (PWM) scheme is applied. The VSC is able to exchange active as well as reactive power. To exchange power with the grid, the produced voltage should differ from the ac-grid voltage. “From a system point of view, it acts as a zero-inertia motor or generator that can control active and reactive power almost instantaneously” [1]. In figure 2 a single-phase VSC is shown. The inductance between the grid and the ac side of the VSC is often the leakage inductance of a transformer, or a separately installed converter reactor [2]. For the power electronic switches in VSC transmission systems mainly insulated gate bipolar transistors (IGBT) are applied, and occasionally gate turn-off transistors (GTO) [3]. In case PWM with an infinite switching frequency and ideal switches are assumed, a sinusoidal voltage could be produced by the VSC. Since the minimum step size of the RTDS allows no detailed modelling of the converter bridge, the VSC has been modelled by ideal voltage and current sources. For the ac side, controlled voltage sources are used and a controlled current source has been used for the dc side, whereby the power $P_{ac}=P_{dc}$. See figure 2 for the schematically represented VSC.

$$P = \frac{V_g V_{conv}}{\omega L_g} \sin \delta$$

$$Q = \frac{V_g (V_g - V_{conv} \cos \delta)}{\omega L_g}$$

in which $\delta$ is the angle between $V_g$ and $V_{conv}$.

3. CONTROL OF THE VSC

For controlling the VSC, direct control (in which the converter voltage angle $\delta$ and amplitude $V_{conv}$ are changed independently) and vector control [5] can be used. Vector control allows developing a controller that is able to control the active power $P$ and the reactive power $Q$ independently. The active and reactive current components are decoupled, which implies consequently no offset in the steady state. (Note: this is not possible with direct control, since a change in the converter voltage angle $\delta$ does influence both $P$ and $Q$, as does a change in $V_{conv}$; see (1) and (2)). Vector control is therefore used in this work.

With vector control, the $dq$-currents will be tracked to appropriate reference values. For this, the grid-side voltages $v_{gd}$ and $v_{gg}$ are measured and values for converter voltages $v_{convd}$ and $v_{convo}$ are calculated in such a way that the desired reference values $i_{dref}$ and $i_{qref}$ are reached. The required converter voltages are then transformed back to the abc-reference frame and submitted as an input to the PWM mechanism. An overview of this process is presented in figure 3.

$$V_{conv} = PV$$

and

$$I_{conv} = PI$$

in which $P = AB$, which is the orthogonal Park transformation

$$P = \begin{bmatrix} \frac{1}{2} \sqrt{2} & \frac{1}{2} \sqrt{2} \\ \frac{1}{2} \sqrt{2} & -\frac{1}{2} \sqrt{2} \end{bmatrix} \begin{bmatrix} \cos \left(\theta - \frac{2\pi}{3}\right) & \sin \left(\theta - \frac{2\pi}{3}\right) \\ \sin \left(\theta - \frac{2\pi}{3}\right) & -\cos \left(\theta - \frac{2\pi}{3}\right) \end{bmatrix}$$

with $P^{-1} = P^T$.

The angle $\theta$ is measured by a phase-locked loop (PLL) system. A d-q-z grid control circuit could be used, which is known to perform robustly: “The d-q-z type of grid control circuit has excellent immunity from either loss of synchronizing voltages or harmonic distortion on the synchronizing voltages” [6].

After the transformation to $dq$-quantities, the voltages $v_{convd}$ and $v_{convo}$ have to be calculated by the current controller. To synthesize the current controller, first the network equations of the ac side will be derived with Kirchhoff’s circuit laws, see figure 4.

![Figure 3 Schematic overview of current control.](image)

![Figure 4 Basic Circuit for the derivation of circuit equations.](image)
Voltages will be in their vector representation

\[ V = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix}, \quad V' = \begin{bmatrix} V_x' \\ V_y' \end{bmatrix}, \quad V = PV' \]

The same holds for \( I \).

Applying Kirchhoff’s circuit laws and applying the Park-transformation results in

\[ V_g = RI + L \frac{d}{dt}(I) + V_{\text{conv}} \]

\[ PV' = RPI' + L \frac{d}{dt}(PI') + PV_{\text{conv}}' \]

\[ V_{g'} = P^{-1}RPI' + P^{-1}L \frac{d}{dt}(PI') + V_{\text{conv}}' \]

\[ V_{g'} = R' I' + P^{-1}L \frac{dP}{dt} I' + P^{-1}L P \frac{dI'}{dt} + V_{\text{conv}}' \]

\[ V_{g'} = R' I' + L' P^{-1} \frac{dP}{dt} I' + L' P \frac{dI'}{dt} + V_{\text{conv}}' \]

\[ \begin{bmatrix} V_{g'd} \\ V_{g'd} \\ V_{g'd} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_l \\ i_q \\ i_0 \end{bmatrix} + \begin{bmatrix} 0 & -oL & 0 \\ oL & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_l \\ i_q \\ i_0 \end{bmatrix} \]

\[ + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \begin{bmatrix} \frac{d}{dt} i_l \\ \frac{d}{dt} i_q \\ \frac{d}{dt} i_0 \end{bmatrix} + \begin{bmatrix} V_{\text{conv}} \\ V_{\text{conv}} \\ V_{\text{conv}} \end{bmatrix} \]

The VSC is connected to the grid through a \( \Delta Y \)-transformer where the converter-sided Y-winding is grounded. The converter star point is not grounded hence no zero-sequence currents can flow in the converter. Because of the delta winding at the grid side of transformer, no zero-sequence currents can flow and will therefore be neglected in the remainder. If \( i_l \) and \( i_q \) are chosen as state variables, the remaining equations are

\[
\frac{d}{dt}i_l = \frac{1}{L} v_g - \frac{R}{L} i_l - oL i_q - \frac{1}{L} v_{\text{conv}}
\]

\[
\frac{d}{dt}i_q = \frac{1}{L} v_g - \frac{R}{L} i_q + oL i_l - \frac{1}{L} v_{\text{conv}}
\]

In these equations the terms \( oL i_q \) and \( oL i_l \) cause a cross-coupling between both state variables. For the current controller, these factors will be regarded as external disturbances and fed forward. Two new control inputs can be introduced

\[ x_d = v_{g'd} - oL i_q - v_{\text{conv}} \]

\[ x_q = v_{g'q} + oL i_l - v_{\text{conv}} \]

From the original expression follows that

\[ x_d = (sL + R)i_l \]

\[ x_q = (sL + R)i_q \]

in which \( s \) is the Laplace-operator. Now two independent first-order models result that can be controlled by PI-regulators. The current controller is depicted in figure 5.

---

**Figure 6** System and controller overview.
Current references $i_{d,ref}$ and $i_{q,ref}$ are obtained from outer controllers. The following control modes can be distinguished (see figure 6):

- Direct-voltage control ($i_d$);
- fixed amount of active power $P (i_q)$;
- AC-frequency support ($i_q$);
- fixed amount of reactive power $Q (i_d)$;
- AC-voltage support ($i_d$).

For reliable operation, at least one of the VSCs in the scheme should control the direct voltage, thus securing power balance in the dc-network. In case only one direct-voltage controlling element is present, direct-voltage control can be implemented as proportional-integral (PI) control. The dc-voltage will then consequently reach the defined reference value after a system disturbance. In case more then one VSC is configured as a direct-voltage controlling element, all direct-voltage controllers need to be implemented as P-control only to prevent unexpected system behaviour. In this work, although only one VSC is configured as a voltage-controlling element, proportional control is applied according

$$i_{q,ref} = (v_{q,ref} - v_d) k_p$$

In this work VSC1 (as in figure 1) will be in active power-control mode, VSC2 will regulate the direct voltage, and VSC3 is in ac frequency-support mode to ensure that all power produced by the wind farm is injected into the dc system. In case of a fault at the grid side of VSC2, the direct voltage will become incontrollable. VSC2 is not able to exchange sufficient power between the ac and the dc grid. Hence, the direct-voltage will either increase or decrease quickly. The rate of change of the direct voltage depends on the set point of the power controller of VSC1 and the power that is supplied by the wind farm. The direct voltage rises if the set point of the power controller of VSC1 is positive and drops if this set point is negative (in case no power is supplied by the wind farm). Moreover, due to the fast dc-system dynamics, the direct voltage reaches unacceptable values within only a few milliseconds.

To avoid the situation where the direct voltage reaches an unacceptable level, an extra direct voltage controller is added to VSC1, which is only activated when the direct voltage is out of a specified interval. The function of the outer controller shifts from power controller to direct voltage controller if direct voltage is out of this interval. If normal operation is restored and the direct voltage is within the operating boundaries again, VSC1 will change back to power-control mode again. An overview of this process is presented in figure 7.

4. MODEL SET-UP FOR THE RTDS

The transmission system will be implemented for the Real-time Digital Simulator (RTDS) system. The RTDS is a powerful computer that works in continuous, sustained real-time. Hence, simulation of events is just as fast as their occurrence in practice. This saves time, in comparison to other off-line tools, where the simulation of one second would take much more calculation time.

The complete model for the RTDS is shown in figure 8. ACgrid1 is connected via a three-phase circuit breaker and a $\Delta Y$-transformer to the ac side of VSC1. The dc side of VSC1 is referred to as “1” in the model section labeled “DCgrid”. This also applies for the other VSCs. By changing values for the blocks labeled “RRL” (which are part of a benchmark model for HVdc-transmission systems [7]) the ac grids can represent different short-circuit ratios. The right-hand side of the dc model is used to model energizing of the dc system, as will be explained later. Component values are given in table 1 and are taken from [2].

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated system power</td>
<td>$P_{nom}$</td>
<td>300 MW</td>
</tr>
<tr>
<td>Rated direct voltage</td>
<td>$v_d$</td>
<td>150 kV</td>
</tr>
<tr>
<td>Phase reactor inductance</td>
<td>$L$</td>
<td>35 mH</td>
</tr>
<tr>
<td>AC equivalent resistance</td>
<td>$R$</td>
<td>0 Ω</td>
</tr>
<tr>
<td>DC-capacitance</td>
<td>$C$</td>
<td>40 μF</td>
</tr>
<tr>
<td>DC equivalent resistance</td>
<td>$R_{dc}$</td>
<td>60 kΩ</td>
</tr>
<tr>
<td>AC-system rated frequency</td>
<td>$f$</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

4.1. Offshore wind farm and collection system

A wind farm consisting of direct drive turbines has been assumed, with a rated power of 300 MW. This wind farm is represented by one VSC. Because of the relatively short simulation time, a constant wind speed has been assumed. The VSC (“direct drive wind farm”, figure 8) has been placed in series with two $\Delta Y$-transformers. The rated voltage of equivalent wind turbine is 3.5 kV; this voltage is transformed to 20 kV-level in the collection system. From 20 kV, the voltage is transformed to 150 kV.
The offshore VSC (VSC3, figure 8) should provide and maintain a stable voltage in the offshore grid. For the generation of the desired system voltage and frequency at the ac-side of the VSC, takes care of the generation of a fixed voltage behind the ΔY (150/23 kV) transformer.

4.2. Energizing of the dc grid and system start-up
The dc system has to be energized before the MT-VSC transmission system can start operation. If the VSC is connected to the ac system without additional measures, high charging currents will flow that could damage the converter. By inserting a current-limiting resistor at system start-up, the converter is protected. When the direct voltage is at its rated value, the resistor is bypassed. The right-hand side of the dc circuit in figure 8 is added to simulate this start-up sequence.

To energize the dc-system the following procedure is followed:
1. Energize the dc grid, close BRK1 (figure 8);
2. Start the PWM of all VSCs and synchronize to the grid voltages;
3. apply a reference for the direct voltage to the direct voltage-controlling VSC;
4. open circuit breaker BRK1 (figure 8); and
5. apply a power reference to the power-controlling VSC.

5. SIMULATION OF SELECTED CASES
In this section different cases will be simulated in order to evaluate the performance of the system. First the power flow during normal operation is evaluated and then different fault situations are considered.

5.1. Power flow during normal operation
During normal operation different power flows in the transmission system can take place. The following power flows are possible:
1. In case the system is only used for energy trade between both interconnected system: from VSC1 to VSC2 or from VSC2 to VSC1;
2. In case wind power is transported to one interconnected system only: from VSC3 to VSC1 or from VSC3 to VSC2;
3. A combination of option of 1 and 2.

As an illustration, a simulation will be performed in which the system is used for energy trade (150 MW from VSC2 to VSC1) and wind power is produced. At a certain moment, the wind power goes up from 100 MW to 200 MW. VSC1 has been equipped with an outer power controller, in order to make sure that 150 MW is drawn by ACgrid1. VSC2 is equipped with a direct-voltage controller as outer controller and will therefore accept the fluctuations in wind power.

Starting value: After wind gust:
- $P_{VSC1} = -150$ MW
- $P_{VSC1} = -150$ MW
- $P_{VSC2} = +50$ MW
- $P_{VSC2} = -50$ MW
- $P_{VSC3} = +100$ MW
- $P_{VSC3} = +200$ MW

The result of this simulation is presented in figure 9a–b. The system works as expected regarding the power flows.

5.2. Three-phase to ground fault at the grid side of VSC2
In this section, different fault situations will be simulated in order to identify bottlenecks in the system. A three-phase to ground fault will be applied at the grid side of VSC2. As mentioned earlier, VSC2 is unable to control the dc-voltage during the fault and VSC1 should take over this task.
Power flow from VSC1 to VSC2

Figure 10a–g shows the system responses to a three-phase to ground fault at the grid side of VSC2, which is cleared after 100 ms. During the fault, the voltage at the grid side of VSC2 is zero (figure 10b). The voltage at the converter side of the transformer however, is not zero (figure 10b). The reason for this is that the current controller of VSC2 still tries to control the current in such a way that the reference value for the direct voltage is reached. This reference value cannot be reached, since ACgrid2 can not deliver power to VSC2. The current through VSC2 remains equal, but the power goes to 0 MW (figure 10e). The current through the valves of VSC2 temporarily reaches a value of 2 kA (figure 10d) at the moment that the fault is applied. It is questionable whether the IGBTs are able to survive this overshoot. A solution would be over dimensioning of the IGBT valves or installation of a larger converter reactor to decrease the rate of rise. The direct voltage increases fast (figure 10f) at the moment that the fault is applied. As can be observed in figure 10f, the outer controller of VSC1 quickly switches from active power-control mode to direct voltage-control mode.

After the fault has been cleared the system remains stable and is able to restore fast (figure 10a–g).

Power flow from VSC2 to VSC1

The same fault as was applied in the previous part will be simulated, but the power is now transported from VSC2 to VSC1. This means that the direct voltage will decrease after the fault has been applied, since VSC2 is the direct voltage-controlling converter. During the fault VSC1 will temporarily take over this function again. The direct voltage reaches a value below 250 kV. However, this is high enough for the system to remain in operation. Other phenomena that occur are similar to what has been explained above and therefore are not included here. The three-phase to ground fault does not result in the shut down of the system. The system remains stable and is able to restore fast.

6. CONCLUSION

According to the part of this study concerning steady-state situations, building a MT-VSC transmission system seems to be possible. For multi-terminal purposes, only one VSC can be commanded to control the dc-grid voltage, while the other VSCs are just adding or drawing power to this dc-grid. This interaction between the VSCs can function in a proper way, based on local measurements and without a need for telecommunication.

To control the power flow of each VSC, a current controller (which is able to decouple $P$ and $Q$, based on
vector control) with an associated outer controller has been applied to the two VSCs connected to an onshore ac-grid. The VSCs are able to exchange active as well as reactive power with the ac grid and can be used to support the ac grid voltage and frequency.

In order to handle fault situations, the scheme must be expanded in order to protect the VSC and dc-grid from over-voltages and -currents. This is because the defined basic control strategies that are developed in this paper and valid during steady state are not achievable in case a short circuit at the ac-side of the converter occurs, since the converter is simply not able to exchange power with the ac-grid. Thus, in case a short circuit occurs at the ac-side of the VSC controlling the dc-grid voltage, another VSC should control the dc-grid voltage. If this requirement is satisfied, the system is able to restore fast after the ac-short circuit has been cleared.

ACKNOWLEDGEMENT

This research was partly funded under the framework of the Dutch Ministry of Economic Affairs BSIK programme ‘Large-scale wind power offshore, towards an innovative and sustainable business’, with support from the We@Sea consortium (http://www.we-at-sea.org/).

The research presented in this paper was part of a M.Sc.-project at Delft University of Technology, conducted from December 2006 to August 2007.

REFERENCES