

# Combined Stability and Electro-Magnetic Transients Simulation of Offshore Wind Power Connected through Multi-Terminal VSC-HVDC

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**Abstract**—Offshore wind energy has a high potential especially in Northern-Europe. Future wind power plants may be situated further from the shore and therefore a high-voltage direct current connection based on voltage sourced converters is most suitable for grid integration. Connection utilization can be improved by interconnecting several wind power plants leading to multi-terminal schemes.

This paper describes a modeling approach that facilitates the incorporation of such (offshore) dc-systems into transient stability simulations. It enables the possibility to use a different simulation approach for each side of the converters, i.e. to represent the ac-side by complex phasors and the dc-side by electro-magnetic transients. Coupling between the ac and dc-sides is obtained by the active power balance. To study the interaction between the multi-terminal scheme and the onshore network an illustrative test-network has been taken. A chopper-controlled braking resistor that protects the dc-circuit against overvoltages has been included and is expressed as a variable resistance. Methods to distribute the wind power among the onshore converters are explored and operation without a supervisory dispatch controller has been studied.

**Index Terms**—VSC-HVDC, wind power, multi-terminal, stability simulation, EMT simulation.

## I. INTRODUCTION

In many regions, a growing share of renewable energy sources in the generation mix can be observed. In Europe, this has to a large extent been initiated by the European Commission's target of having 20% of all energy produced by renewable sources in the year 2020. Large-scale wind energy is considered a major contributor in achieving this target. Several factors have driven the development of wind energy offshore, among which legislation issues, spatial restrictions, and the higher energy yield. The next generation of offshore wind power plants (WPP) will be larger in size and situated further remote than projects that have been realized over the past years.

A major challenge when integrating offshore WPPs into the power system is the connection to the onshore network. For

long connection distances, high-voltage direct current transmission based on voltage sourced converters (VSC-HVDC) promises to be the most cost-efficient solution [1]. To improve the utilization ratio, future VSC-HVDC schemes might even include more than two terminals. When such a system has multiple connections to the onshore transmission system, it can also be used for energy exchange apart from evacuating produced wind power. In such a multi-terminal dc (MTDC) scheme, the way the power is dispatched across the scheme is more challenging than for a point-to-point (two terminal) connection. Preferably the scheme should be operated without fast communication between terminals, while still being able to absorb all produced wind power. These requirements complicate the operation of MTDC schemes. Simulation studies are an effective way of comparing different control approaches on beforehand.

The operation, control, and simulation of MTDC schemes has been of interest in many studies. Many publications focus on electro-magnetic transient (EMT) type of simulations that model the power electronic interface of the VSC in detail, and therefore require a typical time step size of 100  $\mu$ s or less. Although indispensable for the actual design of these systems, this modeling approach is often too detailed for a first assessment of the interaction between a VSC-MTDC scheme and the real power system, as is typically done in transient stability studies. Such simulations are performed considering complex phasors at fundamental frequency only, which are done using a much larger time step size (1–10 ms). The phenomena that occur in the dc-network are too fast for this type of simulation and are therefore disregarded in many studies. However, fast transients in the dc-network might trigger certain control and protection modes that may have an important impact on the interaction with the ac-system in the time scale of interest.

This paper describes an approach to incorporate a VSC-MTDC scheme into stability simulations. An averaged model for each VSC is applied that couples the converter with the ac-network, modeled using complex phasors, whereas the dc-network is modeled taking electro-magnetic transients into account and being simulated at a smaller time step size. To demonstrate the application of this modeling approach, it is shown how the power flow across the MTDC scheme can be controlled according to a direct-voltage droop characteristic. A small study network has been used to illustrate both the method of modeling and the operation of the MTDC scheme

This research is financially supported by SenterNovem, an agency of the Dutch Ministry of Economic Affairs, under the project North Sea Transnational Grid (NSTG). NSTG is a joint project of Delft University of Technology and the Energy Research Center of the Netherlands.

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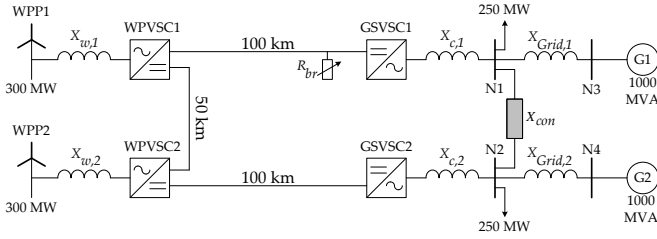


Fig. 1. Multi-terminal VSC-HVDC connection scheme.

in normal condition and during disturbances. To prevent direct voltage excursions during such disturbances, a braking resistor interfaced through power electronics is included.

The remainder of this paper is organized as follows: Section II describes the study network and the modeling approach. The selected method for multi-terminal operation is outlined in Section III, followed by simulation results that demonstrate the system behavior based on the derived model in Section IV. The paper ends with conclusions.

## II. SYSTEM DESCRIPTION

### A. Test Network

To illustrate the modeling approach and to study the control strategy for the VSC-MTDC scheme, a small demonstration network has been selected (Fig. 1). It contains four VSC terminals, having equal current and voltage ratings.

Two VSCs (WPSVC1, WPSVC2) are connected to wind power plants (WPP1, WPP2), each of which is aggregatedly represented as a single wind turbine generator equivalent. The series reactances  $X_{w,1}$  and  $X_{w,2}$  account for the wind power plant's main transformer and both high voltage and medium voltage cables. A simplified model of a variable-speed wind turbine generator has been applied [2]. Since the focus of this study is on transient stability for which the typical frequency range of 0.1–10 Hz is of interest, it is important that electromechanical phenomena are correctly modeled. Therefore, the model includes a quasi steady-state representation of the aero-mechanical energy conversion, as well as a two-mass shaft [3].

On the network side, two VSCs (GSVSC1, GSVSC2) feed the power into two separate connection nodes (N1, N2). At each node an equivalent transmission system model is coupled consisting of local loads of 250 MW, transmission lines modeled by equivalent reactances  $X_{Grid,1}$  and  $X_{Grid,2}$ , and slack generators (G1, G2) of 1000 MVA rating; simple exciter models and governor systems are included to approximate the transient behavior of a transmission network. By varying the reactance  $X_{con}$  of the branch between N1 and N2, two different scenarios can be studied: A high value of  $X_{con}$  represents a weak coupling, i.e. both converter terminals are assumed far apart. A low value represents the situation when both VSC terminals are in the electrical vicinity of each other.

The dc-network consists of two cables assumed 100 km long. The dc circuit is operated at  $\pm 150$  kV. Furthermore, to improve reliability a connection cable between WPSVC1 and WPSVC2 is foreseen, assumed 50 km long. At partial

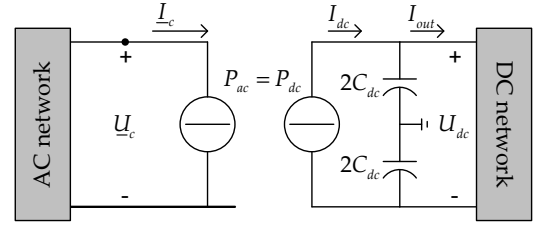


Fig. 2. Averaged VSC model; the converter is represented on the ac-side by a controlled current source.

load operation this cable also enables the transport of power between N1 and N2, thereby increasing the utilization of the whole infrastructure. All dc cables are represented by their  $\pi$ -equivalent circuit.

### B. Converter Model

VSCs have a switching frequency that is far above the fundamental frequency of the power system. By applying an appropriate modulation scheme, the converter can synthesize a voltage of arbitrary amplitude and angle, dictated by the control system. Transient stability is mainly linked to physical processes happening at frequencies far below rated, and therefore all phenomena at higher frequencies (e.g. harmonics) can safely be disregarded. Hence, an averaged model can be used in which the coupling between the ac and dc sides is established by active power balance only [4]. Usually, a cascaded control approach (often referred to as *vector control*) is chosen to determine the pulse patterns for the VSC: a fast inner current control loop regulates the converter current to a reference value, which is in turn provided by slower outer-loop controllers. These outer-loop controllers determine the operation mode of the VSC (active power control, direct voltage control, etc.). The bandwidth of the inner current control loop is so high, that reference values are achieved within a few milliseconds. This argues for neglecting this control mode and representing the ac side of the VSC as a controlled current source in transient stability simulations (see Fig. 2). The original outer-loop control functions are still represented and provide values for the current injection into the ac network.

Fig. 3 shows the positions of the current and voltage phasors at the terminals of the VSC with respect to the internal voltage of G1, which is taken as the reference ( $xy$ -frame). For the VSC terminal voltage phasor  $\underline{U}_c$  it holds

$$\underline{U}_c = u_{c,x} + ju_{c,y} = U_c e^{j\theta_g} \quad (1)$$

with  $U_c$  being the RMS-value and  $\theta_g$  the angle difference with the reference. For the purpose of control a second reference frame is introduced ( $dq$ -coordinates) that aligns with the VSC terminal voltage phasor  $\underline{U}_c$ . For the converter current phasor  $\underline{I}_c$  can be written

$$\underline{I}_c = i_{c,x} + ji_{c,y} = (i_{c,d} + ji_{c,q}) e^{j\theta_g} \quad (2)$$

For the active and reactive power drawn from the network by

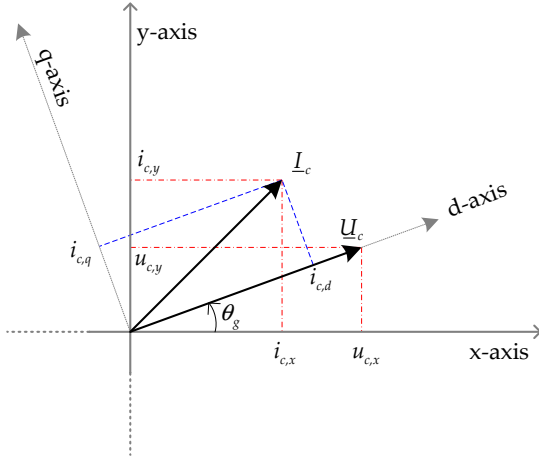


Fig. 3. Phasor diagram of the VSC terminal voltage and current.

the VSC now yields

$$\begin{cases} P_{ac} = u_{c,d}i_{c,d} \\ Q = -u_{c,d}i_{c,q} \end{cases} \quad (3)$$

This implies that active and reactive power can be controlled independently by regulating  $i_{c,d}$  and  $i_{c,q}$ . The coupling with the dc-network is achieved by injecting a direct current according to the active power balance across the VSC

$$I_{dc} = \frac{P_{dc}}{U_{dc}} = \frac{u_{c,d}i_{c,d}}{U_{dc}} \quad (4)$$

in which  $U_{dc}$  is the direct voltage. This representation is based on the assumption of a lossless converter. If converter losses need to be taken into account, these could be represented through external resistances included on the ac and/or dc-side. Moreover, the ac-network is presumed to be balanced, i.e. only positive-sequence voltage and current phasors have been considered.

The dc-side dynamics are governed by

$$C_{dc} \frac{dU_{dc}}{dt} = I_{dc} - I_{out} \quad (5)$$

where  $I_{out}$  is the direct current that is exchanged between the VSC and the dc-network and  $C_{dc}$  represents the sum of the aggregated dc cable capacitance and the installed converter capacitance. In the proposed model, (5) is solved together with the remainder of the dc-network by the EMT network solver.

Because the stability part and the EMT part of the network are simulated using different time-step sizes, i.e.  $\Delta t_{ts}$  and  $\Delta t_{emt}$ , respectively, attention should be paid to the way the coupling interface within the converter model is established. Both parts are solved sequentially according to the *serial protocol* [5]: relevant ac-network quantities are passed on to the EMT network solver at the end of the stability section calculation. The value of the direct voltage is provided to the transient stability network solver after the last EMT time step. This sequence is repeated until termination of the simulation. Since  $U_{dc}$  is not passed on to the stability section until the last time step of the EMT solver, inaccuracies may occur when  $\Delta t_{ts}$  is large compared to the dc-network time constants. This issue can be overcome by either representing the network of

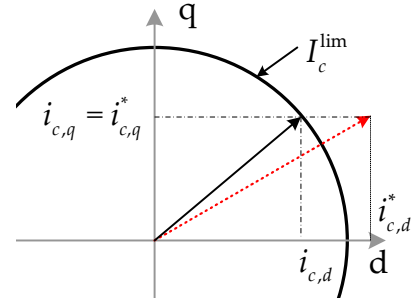


Fig. 4. Priority limiter that gives precedence to the reactive current, i.e. the  $q$ -axis component.

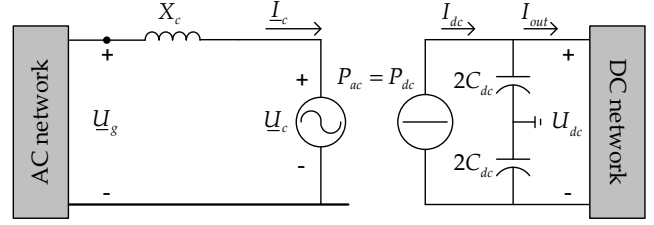


Fig. 5. Averaged VSC model operating as a stiff voltage source on the ac-side.

the stability part in the EMT part by an appropriate equivalent model, or by averaging the interface variables properly [6]. In this study however, this method has not been applied as the difference in time-step size between both model sections has been kept relatively small, namely  $\Delta t_{ts} = 10\Delta t_{emt}$ .

The currents injected into the ac-network are provided by two PI-controllers that continuously regulate the direct voltage and the RMS-value of the converter voltage by setting  $i_{c,d}^*$  and  $i_{c,q}^*$  respectively

$$i_{c,d}^* = K_{p,d}(U_{dc}^* - U_{dc}) + \frac{1}{\tau_{i,d}} \int (U_{dc}^* - U_{dc}) dt + i_{c,d}^0 \quad (6)$$

$$i_{c,q}^* = K_{p,q}(U_c^* - U_c) + \frac{1}{\tau_{i,q}} \int (U_c^* - U_c) dt + i_{c,q}^0 \quad (7)$$

The fact that VSCs hardly have overcurrent capability, leads to the necessity of a proper limiting strategy in case the total converter current  $\sqrt{i_{c,d}^{*2} + i_{c,q}^{*2}}$  exceeds the current rating of the converter,  $I_c^{lim}$ . This limiting can be done in different manners, giving precedence to the active current  $i_{c,d}$  or to the reactive current  $i_{c,q}$ , or a combination of both. In this paper, precedence is given to the reactive current, as this is considered to be beneficial for voltage support during and after disturbances. The priority limiter is shown in Fig. 4.

The output of the limiter,  $i_{c,d} + ji_{c,q}$  is rotated over an angle  $\theta_g$ , yielding the converter current given by (2).

In a wind park there is no fixed voltage reference and the control of the VSC is slightly different than described before. In our model, the VSC has to fulfill the function of a stiff voltage source, ensuring that all produced wind power is adequately absorbed. Therefore, the WPVSC cannot be represented by a controlled current source but must be modeled as a controlled voltage source instead (Fig. 5).

By adjusting the amplitude and angle of the converter voltage, control of the WPVSC can be established. In this

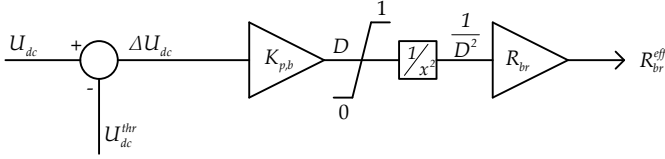


Fig. 6. Dynamic braking resistor control system.

study, a fixed wind park frequency, and hence voltage angle are assumed. Only voltage magnitude control is applied by

$$U_c = K_{p,u} (U_g^* - U_g) + \frac{1}{\tau_{i,u}} \int (U_g^* - U_g) dt + U_c^0 \quad (8)$$

For the wind park's ac-network, the WPSVC voltage phasor angle is chosen as the reference. The coupling between the ac and dc-side is realized in the same manner as with the controlled current source.

### C. DC-circuit protection

An important issue regarding the application of VSC transmission for offshore wind power is the challenge to let the scheme remain connected to the grid also in the event of network faults. Due to the current limit of the VSCs, at a reduced network voltage a lower amount of power can be supplied to the onshore grid. As the WPP network is decoupled by the VSC link, the wind turbines continue to inject the prefault power into the dc-grid, causing the direct voltage to rise rapidly. This can be overcome by either reducing the output power of the wind turbines very quickly, or by installing a controlled device that dissipates the excess power [7]. A dynamic braking resistor, which is interfaced through a chopper, is such a device.

In this study, a braking resistor is used to let the VSC-HVDC scheme ride through an onshore fault. For simplicity, this resistor is modeled as a variable resistance based on averaging of the detailed power electronic model. This is shown in Fig. 6. Above a threshold voltage  $U_{dc}^{thr}$  the protection system starts to operate by increasing the duty cycle  $D$ .

When an infinite switching frequency is assumed, the effective value of the braking resistor can be derived using the power dissipated by the braking resistor

$$P_{diss} = \frac{(DU_{dc})^2}{R_{br}} = \frac{U_{dc}^2}{R_{br}^{eff}} \Rightarrow R_{br}^{eff} = \frac{R_{br}}{D^2} \quad (9)$$

where  $R_{br}^{eff}$  is the value of the effective resistance applied in the model and  $R_{br}$  the physical resistance value of the chopper.

## III. DIRECT-VOLTAGE CONTROL

An important constraint with respect to the application of HVDC can be found in maintaining the direct voltage close to the rated value. Moreover, a well-controlled direct voltage is an indication of a power balance in the dc-system. The deviation of the direct voltage from its nominal value can therefore be used as a control input for distributing the power flow among the VSC terminals.

The control method to be applied is very much dependent on the connection scheme. When only two grid-connected VSCs

are considered, the power flow between the VSC terminals can easily be controlled by letting one VSC control the direct voltage with a PI-controller, while the other VSC controls the scheduled power exchange with an integral controller [8]. For a wind park it is difficult to control the active power set-point since it is constantly subjected to variations in wind speed and hence generated power. Therefore, the GSVSCs must control the direct voltage in the example VSC-MTDC scheme. Several control strategies can be chosen, which will be briefly outlined below, depending on the connection scenario.

### A. Weakly coupled AC grids

Simulation of this scheme can be obtained by assigning a large value to  $X_{con}$ . One of the GSVSCs controls the direct voltage with a PI-controller, acting as a dc-slack node. To prevent hunting actions, other VSCs may only be equipped with proportional direct voltage controllers, i.e.  $\tau_{i,d}$  set to infinity. A prescheduled power exchange between two separate ac-grids can be achieved by adding a feedforward term in the direct-voltage controller. This can be achieved by letting

$$i_{c,d}^0 = \frac{P_0}{U_c} \quad (10)$$

in (6), with  $P_0$  the active power set-point. This method yields, however, that all fluctuations in wind power go towards the PI-controlled GSVSC since it acts as a dc-slack node. A supervisory dispatch controller should therefore divide the generated wind power between the terminals by adjustment of  $P_0$  at discrete time intervals.

An alternative method to achieve this functionality would be controlling the direct voltage at all GSVSCs by proportional control alone. The steady-state operation of such scheme is realized by a dc-droop characteristic with a direct-voltage droop  $k_{p,d}$  and an offset  $i_{c,d}^0$  [9].

### B. Coupled AC Grid

A small value of  $X_{con}$  is selected to model a VSC-MTDC scheme that is connected with multiple terminals to the same ac-network. Distinction can be made between control strategies that make each GSVSC to supply a predefined share of the total wind power to the grid [10], and strategies that prioritize the power supply at one particular GSVSC [11]. The former method uses  $k_{p,d}$  as a control parameter for each GSVSC while  $i_{c,d}^0$  is used in the latter to shift the droop characteristic horizontally. More sophisticated methods must be employed when the amount of offshore applications in the same HVDC scheme increases. For instance the voltage-margin method, which combines adaptive control with an outer dispatch controller [12], [13], is a promising alternative.

## IV. SIMULATION STUDIES

The operation of the MTDC scheme shown in Fig. 1 is tested by simulation studies in the simulation software PSS<sup>®</sup>Netomac. This simulation program employs a solution method that is based on a fixed time-step for both stability and EMT sections. The wind parks and the converters are rated 300 MVA and have an overcurrent capability of 110%.

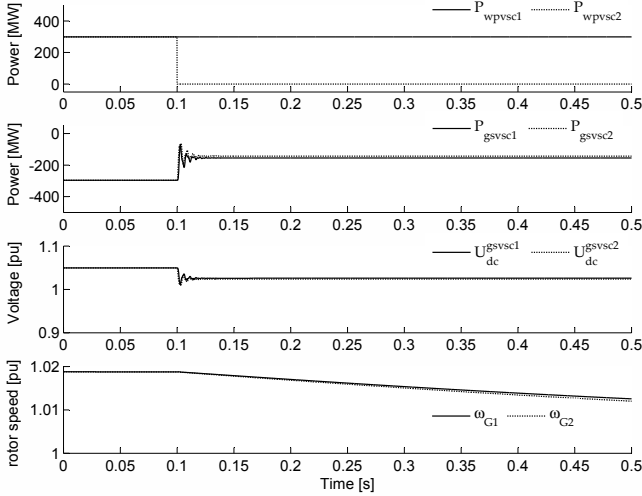


Fig. 7. Failure of WPVSC2. The transition to a new operating point is reflected by the direct voltage and the power of the VSCs. The bottom graph shows the rotor speed response of the onshore generators.

The value of  $X_{con}$  will be varied to distinguish between a coupled ac-grid that has two VSC connection points, and two separate ac-grids with an HVDC link in between. A chopper-controlled braking resistor rated 330 MW is installed near GSVSC1, which is activated at  $U_{dc}^{thr} = 1.2$  pu. The wind is assumed constant to put emphasis on the behavior of the VSCs. In normal operation, GSVSC1 and GSVSC2 share an equal amount of the generated wind power, which is realized by the utilization of a direct voltage droop characteristic with  $K_{p,d} = 20$ ,  $U_{dc}^* = 1$  pu, and  $i_{c,d}^0 = 0$ .

#### A. Failure of a WPVSC

The operation of the control scheme can be illustrated by tripping WPVSC2, which could be caused by a disturbance inside the collection network. Both GSVSCs are considered connected to a different ac-system, i.e.  $X_{con}$  is very large. The system response is depicted in Fig. 7.

After the tripping event at  $t = 0.1$  s the dc circuit is subjected to a power imbalance that causes a reduced direct voltage according to the droop characteristic of the GSVSCs. A slight difference between the power distribution among both GSVSCs can be observed after the disconnection, compared to normal operation. This can be attributed to the location of WPP1, which is 100 km from GSVSC2 and 150 km from GSVSC1. This problem can be overcome by either changing the dc droop constant or by introducing an offset in the direct-voltage controller. These methods imply the necessity of a dispatch controller that constantly shifts the droop lines in order to match the scheduled exchange ratios, particularly in case the dc-network is larger than the test network used here.

#### B. Onshore Short-Circuit

To demonstrate the fault ride-through behavior of the VSC-MTDC scheme, the system is subjected to a 0.2 s-long, three-phase bolted fault at the terminals of G1. Both AC-grids are coupled now. By adopting two different values of  $X_{con}$  the

influence of the connection distance on the transient behavior is examined. A fault ride-through is considered successful if the scheme returns to its pre-fault operating point without violating the maximum allowable direct voltage, here assumed 1.4 pu.

First, a relatively weak connection is considered, i.e. the onshore connection sites are situated far apart. As can be seen in Fig. 8a, the voltage at N4 is hardly affected by the fault because of the weak coupling. Due to the fact that both WPPs remain connected and only GSVSC2 is able to supply power to the grid, the direct voltage starts to rise quickly. It is kept at a maximum of 1.35 pu by the dc-protection mechanism that partly dissipates the excess dc-circuit energy in the braking resistor. G1 and G2 respond differently to the onshore fault: G1 cannot draw power any longer, causing  $\omega_{G1}$  to decrease. Since GSVSC2 supplies more active power during the fault, G2 is forced to draw more power from the network and  $\omega_{G2}$  increases. After fault clearance, the system returns to its pre-fault operating point and hence fault ride-through has correctly been established.

Now,  $X_{con}$  is given a very small value, representing a strong connection between both ac-networks. The system is subjected to the same disturbance as with the weak connection and its response is shown in Fig. 8b. The voltage at N4 is now perceptibly affected by the short-circuit and GSVSC2 runs into its current limit more quickly than in the previous simulation. Furthermore, because of the reactive current precedence, the active power supply is curtailed in order to support the voltage. The dc-protection system is fully utilized and consequently, the excess energy in the dc circuit cannot be completely dissipated. This causes the direct voltage to reach an unacceptably high level in a short time. The fault ride-through requirement has not been fulfilled in this case. This issue might be resolved by either active power reduction in the wind park, increasing the rating of the dc-protection system, or both.

Either of the two simulation studies show the effectiveness of the applied modeling approach. If only transient stability simulation had been performed, the dynamics of the dc circuit would have been disregarded. Consequently, direct voltage fluctuations that could trigger the dc-protection system and cause different power dispatching along the VSCs, would not have been visible while their influence on the onshore network behavior is not negligible. On the other hand, application of EMT simulations alone would have implied a much longer simulation time.

## V. CONCLUSION

In this paper, grid integration of offshore wind power by a multi-terminal VSC-HVDC scheme has been studied. For grid-interaction studies it is important to focus on transient stability. Existing stability models do not have the ability to accurately model the effect of protection mechanisms based on the direct voltage, because of the too large time-step size. In this paper a model has been described that uses phasor quantities at the ac-side while the dc-side is represented by its electro-magnetic transient behavior. Both network representations are linked by active power balance. VSCs that are connected to the onshore

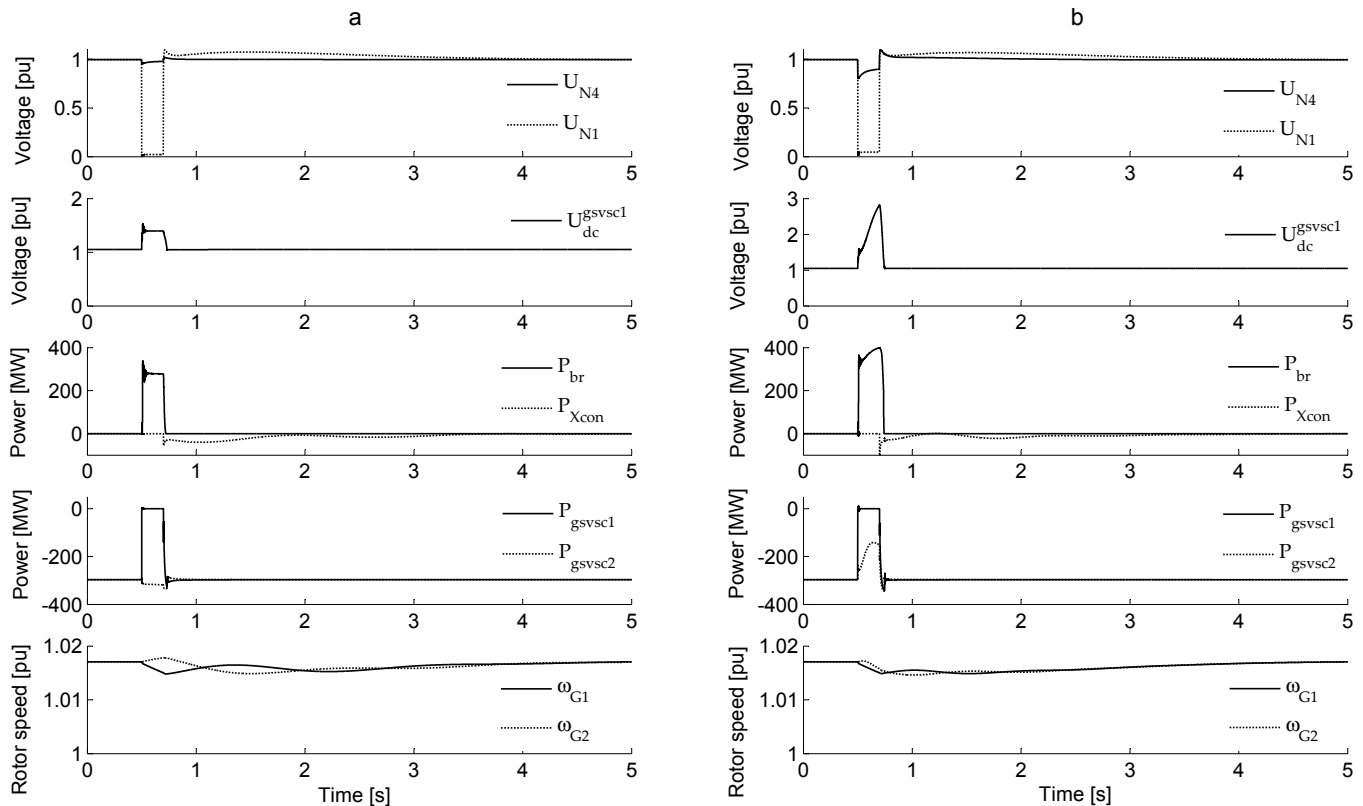


Fig. 8. System response after a short-circuit in the mainland grid for a weak coupling (left) and a strong coupling (right) between both onshore networks.

network can be represented by a controlled current source while VSCs that are connected to a wind power plant must be modeled as a controlled voltage source on the ac-side to absorb all wind power.

Several direct voltage control methods have been explored. To minimize the requirement of fast communications between the VSCs, the onshore converters are equipped with a controller that regulates the power exchange with the grid according to a direct-voltage droop characteristic. It appeared that the application of this control method depends on both the topology of the dc-network and the generated wind power. An additional supervisory controller could overcome these issues by continuously adapting the droop-characteristic to the required power exchange schedule.

A small study network has been taken to illustrate the operation of the VSC-MTDC scheme. The dc-circuit is protected against overvoltages by a chopper-controlled braking resistor. The power electronic interface has been disregarded by representing the protection scheme as a variable resistance. The connection distance between both GSVSCs has been varied. It was shown that for long distances between the onshore converters, the system could ride through an onshore fault successfully. It has been illustrated that fault ride-through was not fulfilled in case a stronger coupling between the onshore converters was present. This problem can be overcome by either designing the protection mechanism at a higher power rating, very fast curtailment by the wind power plants, or both.

## REFERENCES

- [1] P. Bresesti, W. L. Kling, R. L. Hendriks, and R. Vailati, "HVDC connection of offshore wind farms to the transmission system," *IEEE Trans. Energy Convers.*, vol. 22, no. 1, pp. 37–43, 2007.
- [2] J. G. Slootweg, S. W. H. De Haan, H. Polinder, and W. L. Kling, "General model for representing variable speed wind turbines in power system dynamics simulations," *IEEE Trans. Power Syst.*, vol. 18, no. 1, pp. 144–151, 2003.
- [3] J. G. Slootweg, H. Polinder, and W. L. Kling, "Representing wind turbine electrical generating systems in fundamental frequency simulations," *IEEE Trans. Energy Convers.*, vol. 18, no. 4, pp. 516–524, 2003.
- [4] J. Morren, S. W. H. De Haan, and J. A. Ferreira, "Model reduction and control of electronic interfaces of voltage dip proof DG units," in *Proc. IEEE Power Engineering Society General Meeting*, vol. 2, Denver, CO, Jun. 6–10, 2004, pp. 2168–2173.
- [5] V. Jalili-Marandi, V. Dinavahi, K. Strunz, J. A. Martinez, and A. Ramirez, "Interfacing techniques for transient stability and electromagnetic transient programs IEEE task force on interfacing techniques for simulation tools," *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 2385–2395, Oct. 2009.
- [6] J. Arrillaga and N. R. Watson, *Computer Modelling of Electrical Power Systems*, 2nd ed. Chichester, UK: John Wiley & Sons Ltd, 2002.
- [7] L. Harnefors, Y. Jiang-Hafner, M. Hyttinen, and T. Jonsson, "Ride-through methods for wind farms connected to the grid via a VSC-HVDC transmission," in *Proc. Nordic Wind Power Conference*, Roskilde, Denmark, Nov. 1–2, 2007.
- [8] L. Harnefors, "Control of VSC-HVDC transmission," tutorial presented at the IEEE Power Electronics Specialists Conference, Rhodes, Greece, Jun. 15–19 2008.
- [9] R. L. Hendriks, G. C. Paap, and W. L. Kling, "Control of a multi-terminal VSC transmission scheme for connecting offshore wind farms," in *Proc. European Wind Energy Conference*, Milan, Italy, May 7–10, 2007.

- [10] L. Xu, Y. Wang, L. Yao, and J. Rasolonjanahary, "Multi-terminal HVDC system for large offshore wind farm integration and transmission network support," in *Proc. 8th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, Bremen, Germany, Oct., 14–15, 2009, pp. 122–127.
- [11] L. Xu, B. W. Williams, and L. Yao, "Multi-terminal DC transmission systems for connecting large offshore wind farms," in *Proc. IEEE Power and Energy Society General Meeting*, Jul. 2008.
- [12] T. Nakajima and S. Irokawa, "A control system for HVDC transmission by voltage sourced converters," in *Proc. IEEE Power Engineering Society Summer Meeting*, vol. 2, 1999, pp. 1113–1119.
- [13] T. Haileselassie, K. Uhlen, and T. Undeland, "Control of multiterminal HVDC transmission for offshore wind energy," in *Proc. Nordic Wind Power Conference*, Rønne, Denmark, Sep. 10–11, 2009.



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