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Analysis of grid faults in offshore wind farm with HVDC connection

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Abstract

Future offshore wind farms are expected to be built farther away from shore and have larger capacities than today. This leads to new challenges related to grid connection. At distances longer than roughly 100 km, HVDC transmission is preferred over AC transmission due to large charging currents in AC-cables. Conventional LCC (line commutated converter) HVDC is not suited for connection to weak grids like offshore wind farms, and the less mature VSC (voltage source converter) HVDC technology is preferred instead. A future large offshore wind farm with full power converter turbines and three-terminal VSC HVDC grid connection has been modelled in PSCAD. With three terminals the HVDC link can be used for direct transmission between the onshore terminals in addition to transmission of wind power. Due to the power electronics interfaces, the system has low short circuit capacity and is missing inertia. Also, DC-cables are discharged very fast during faults. This leads to different fault responses than in conventional grids. This work focuses on fault responses and protection of a HVDC-connected wind farm, both within the wind farm itself and in the HVDC-link.

Keywords: offshore wind; grid connection; three-terminal VSC HVDC; full power converter wind turbines; fault response; protection

1. Introduction

The world needs carbon-neutral energy, and offshore wind power is an important answer to this need. Due to favorable wind conditions and less conflicts with other public interests, future offshore wind farms

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are assumed to be located farther away from shore than today. Both single wind turbines and total wind farm ratings are expected to increase. This will lead to new challenges related to grid connection. Up to now most offshore wind farms have been built relatively close to shore with conventional AC connection to the mainland grid. However, at long transmission distances the active power transmission in AC cables will be limited by the capacitive charging currents. The break-even distance above which DC-transmission is more economical than AC depends on e.g. power- and voltage level, but roughly said AC cables are suited for transmission only up to about 80-110 km [1],[2]. In the future, new transmission solutions like low frequency AC (lower than 50/60 Hz) might emerge [3].

Some of the largest offshore wind farms today are located in the UK; the 500 MW Greater Gabbard, the 576 MW Gwynt y Môr and the 630 MW London Array phase 1. Located 18-25 km from shore, all have AC cable connections to the mainland grid. There is a growing interest for HVDC for grid connection of offshore wind farms. VSC HVDC is suitable as it can, unlike the conventional LCC HVDC, be connected to weak grids. It also has smaller footprint due to less filtering requirements. North-west of Germany a number of VSC HVDC connections for grid connection of large offshore wind farms are already in operation or under construction. The 400 MW BorWin1 for grid connection of the BARD Offshore 1 wind farm has been in operation since 2012. The 800 MW BorWin2 and the 576 HelWin1 should both to be in operation by 2013, and will provide grid connection for some large offshore wind farms in the area [4],[5].

The focus of this work is fault response and protection of a HVDC-connected wind farm, both within the wind farm itself and in the HVDC-link. A HVDC connected wind farm will have different fault responses than conventional AC systems. Most literature discussing challenges related to protection of inverter dominated AC-networks are focusing on distribution/micro grids with small power electronics interfaced generation (DG) units, e.g. photo voltaic units. Tumilty et al. [6] states that use of conventional overcurrent protection is difficult due to the limited fault currents from the inverters, and suggests voltage based fault detection techniques. However, the voltage and power levels are much lower in distribution grids than in HVDC-grids, leading to different challenges. Protection methods for LCC HVDC are not relevant for VSC HVDC, and existing protection schemes for VSC HVDC is based on disconnection by conventional circuit breakers on the AC-side. This is not suited for multi-terminal grids, where it is desirable that the unfaulted part of the grid continues operation after a fault. Then fast fault detection and isolation of the faulted section by a DC-breaker is required. VSC HVDC is vulnerable to DC-side faults because although the semiconductor switches (e.g. IGBT) can block the fault current, the anti-parallel diodes will continue feeding current from the AC-side [7]. However, new converter topologies with built-in current interrupting capability can possibly be developed [8]. Many suggested DC-breakers for high power and voltage applications are also based on semiconductor switches [9]. For fault detection and location in HVDC-grids, Kerf et al. [10] state that conventional AC-protection, e.g. distance protection, is not suited, and suggests using transient wavelet-based protection. Descloux et al. [11] claim that sufficient selectivity can only be achieved using differential protection. This requires fast fibre optical communication between the two line ends, which can be several hundreds of km apart.

The paper is organized as follows; the modelling of the wind farm and its grid connection topology is described in section 2. Fault response and detection in the wind farm AC collection grid is studied in section 3. Section 4 deals with ground-faults in the HVDC-grid, and investigates possibilities for fault detection. Finally, discussion and conclusions are given in section 5.

2. Offshore wind farm with HVDC connection to mainland grid

A case study of a thought future large offshore wind farm located far from shore has been defined. The wind farm is rated 1000 MW, and is located between two countries; 300 km from country 1 and 500 km from country 2. The long distances favours VSC HVDC grid connection, and a three-terminal solution connecting the wind farm to both countries is chosen. This allows for direct power transmission between the two countries in addition to transmission of generated wind power. The system is illustrated by Fig. 1.

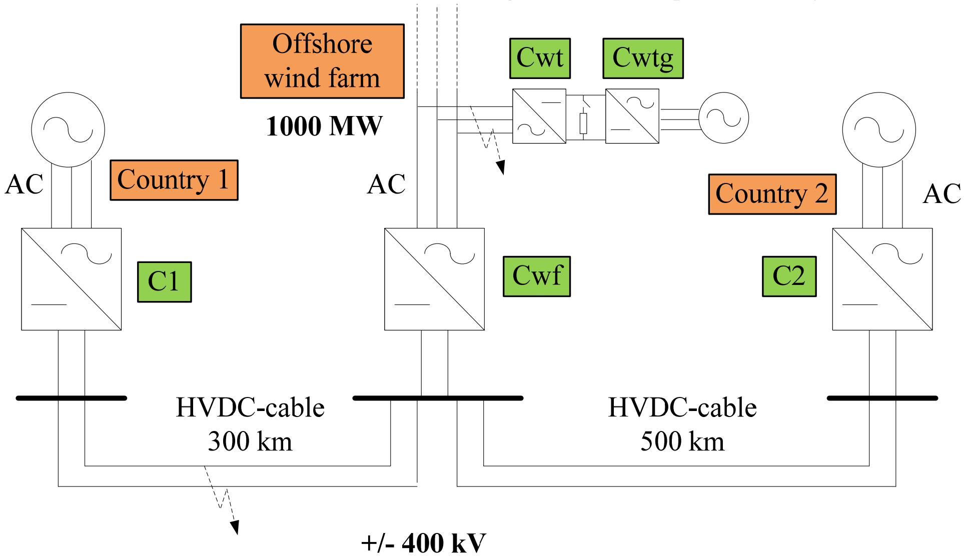

Figure 1: Offshore wind farm with three-terminal HVDC connection to the mainland grids.

All three HVDC terminals are rated 1250 MVA, which gives some reactive power capability at rated power. Different ratings for the separate terminals could however have been chosen depending on e.g. expected normal direction of power flow and need for direct transmission between the two countries. The HVDC transmission is done via two parallel cables operating at +/- 400 kV.

The wind turbines are full-power converter interfaced (back-to-back converters). All turbines have a chopper in the DC-link which is connected when the DC-voltage exceeds a certain level (1.2 pu). If the collection grid voltage drops the power generated by the turbine cannot be transferred to the grid, and the DC-link voltage will rise. Thus the purpose of the chopper is to consume excess energy in the DC-link during voltage dips, and thereby provide fault-ride-through capability. Each wind turbine is not modelled separately; instead one single 5 MW turbine is modelled and the rest of wind farm is represented by an aggregated model representing 199x5 MW turbines. The collection grid is a conventional AC-grid operated at 36 kV. A 1 km cable is added between the HVDC terminal and the single wind turbine.

The converters are two-level with LCL-filter at the AC-side and two capacitors at the DC-side. The capacitor mid-point is grounded. The currents through each of the switches are limited to 1.8 pu (referred to 1250 MVA), above which the switches are blocked. Conventional vector-oriented control with fast internal control loops for separate control of d- and q-axis current components is utilised [12]. Outer, slower control loops are added to control voltage and power. Referring to Fig. 1, converter C1 is controlling DC-voltage and reactive power on the AC-side. Converter C2 is controlling active and reactive power on the AC-side, but with DC-voltage droop on the active power controller. Converter Cwf is controlling AC-collection grid voltage magnitude and phase-angle.

3. Fault in wind farm AC collection grid

The wind farm collection grid has only power electronics interfaced components. Therefore the dynamic characteristics are governed by the converters and corresponding controllers, and are highly different from conventional grids. Most important, the grid is inertia-less, and the short-circuit current capability of the converters is only slightly larger than the nominal current. In this section the response to faults within the AC collection grid is studied.

3.1. Fault-ride-through capability during short circuit

The response of a single wind turbine to a two-phase short-circuit in the AC collection grid, 0.5 km away from its terminals, is shown in Fig 2, and the corresponding response to a three-phase short-circuit is shown in Fig. 3. Both fault starts at 1 s and last for 100 ms.

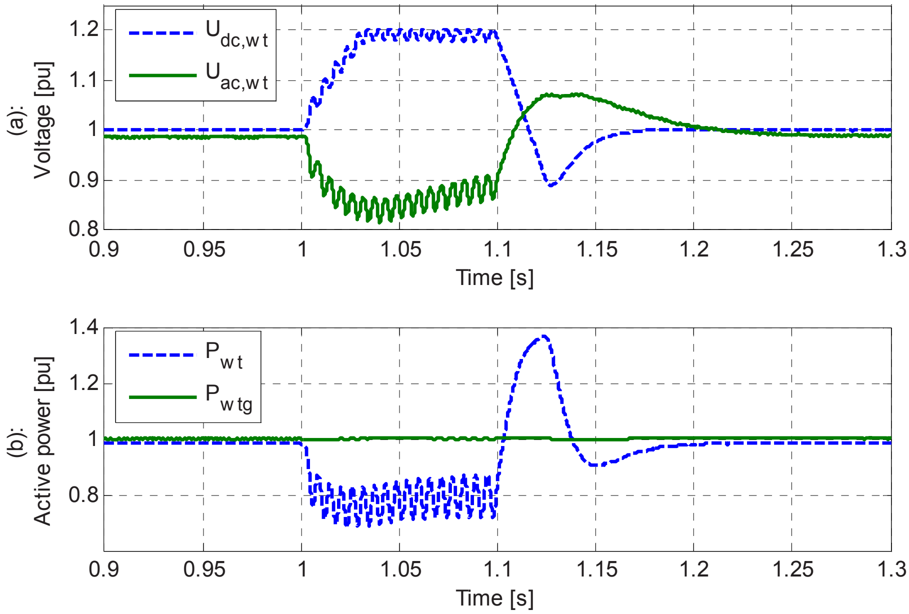

Figure 2: Response to two-phase short-circuit. (a): Wind turbine DC-link voltage (Udc,wt) and collection grid side AC-terminal voltage (Uac,wt). (b): Active power on collection grid side (Pwt) and turbine side (Pwtg) of a single wind turbine converter.

Figs. 3 and 4 (a) show that the AC-terminal voltage drops down to about 0.82 pu and 0.2 pu during the two-phase and three-phase short-circuits, respectively. The DC-link voltage in both cases increases to 1.2 pu, which is the value where the DC-chopper is connected. The (b) plots show that the active power delivered to the grid drops down to about 0.75 pu and 0 pu due to the voltage dips in the grid. The active power on the wind turbine side is however not disturbed by the faults due to the action of the DC-chopper. The wind turbine returns to normal operation after both faults. In this case the fault-ride-through capability is determined by the converter characteristics, and not by the inertia as for a conventional generator directly connected to the grid. Due to the chopper in the DC-link, the wind turbine is transient stable despite of lacking inertia on the grid side. The oscillations seen during the two-phase short-circuit are caused by the presence of negative sequence components.

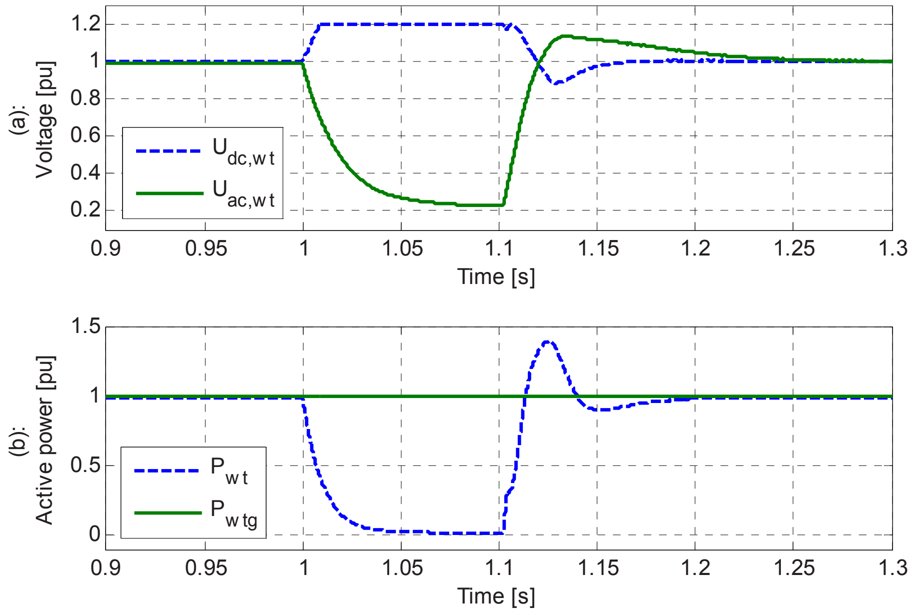

Figure 3: Response to three-phase short-circuit. (a): Wind turbine DC-link voltage (Udc,wt) and collection grid side AC-terminal voltage (Uac,wt). (b): Active power on collection grid side (Pwt) and turbine side (Pwtg) of a single wind turbine converter.

Wind turbine converters can be controlled to have different types of behaviour during voltage dips. Grid codes commonly require the wind turbines to provide as much reactive power as possible to support and help recovering the grid voltage. One strategy can be to control the active power down to zero so that reactive power corresponding to the full converter rating can be provided as long as the grid voltage is below a certain value. This type of fault-ride-through strategy was not implemented in the model used in this work. Such a control strategy anyhow relies on having a chopper in the DC-link, which has been implemented.

3.2. Fault detection and protection

Faults should be detected and disconnected fast enough so that the wind turbines can operate stable through the faults. It is therefore interesting to investigate the possibility of detecting faults in a grid with very low short circuit currents. Distance protection is the most common main short-circuit protection of transmission lines and cables, as well as for meshed distribution networks [13], and is therefore of particular interest. Overcurrent protection, which is commonly used for protection of radial high voltage distribution grids, is assumed unsuitable due to the limited short-circuit currents. Modern numerical distance relays can have different characteristics, but the basic principle for detection is that the impedance seen by the relay changes from a large to a small value. In addition the impedance angle generally changes from reflecting the load angle (mostly resistive) to the line/cable angle (mostly inductive) during fault. The impedances seen from the wind farm HVDC terminal (Cwf) for the same faults as in Figs. 3 and 4 are shown in Fig. 4.

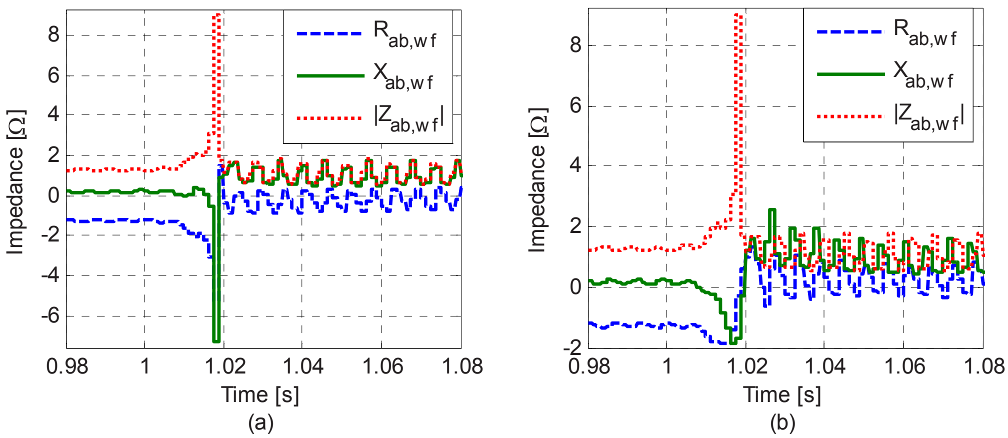

Figure 4: Impedance (a) two-phase short circuit (b) three-phase short circuit

During normal operation the relay sees an impedance of about 1.3 Ω in magnitude. During both faults the impedance is oscillating, but with mean values only slightly lower than the pre-fault value. The impedance angle is however changing from close to 0º in normal operation and closer to 90º during faults. The change in angle could allow for detection of the fault by choosing a properly fitted tripping characteristic. However, the very small change in impedance magnitude makes it doubtful to use distance protection in the wind farm collection grid.

4. Fault in HVDC grid

As for faults in the collection grid, fast detection and disconnection of faults within the HVDC-link is important to maintain stable operation of the wind farm. These faults are likely to be permanent, but the three-terminal solution allows for continued power transmission between two of the terminals despite of a fault. Phase-to-phase faults on the DC-cables are considered unlikely if the two phases are laid in separate cables with some distance in-between. Therefore a phase-to-ground fault has been studied here. Positive phase currents and voltages measured at the DC-side of the three HVDC terminals during a fault halfway between terminals C1 and Cwf (referring to Fig. 1) are shown in Fig. 5. The fault is a positive-phase-to-ground fault occurring at 1.4 s, and the cables between C1 and Cwf are disconnected after 15 ms (at 1.415 s.). 15 ms was found to be the longest allowable fault duration to ensure stability of the remaining network after the disconnection. There are some small time delays between the fault occurrence and the responses of currents due to the distances between the fault location and the measurement points.

In Fig. 5, I_{C1} is the current flowing from HVDC terminal C1 towards the fault, while $I_{Cwf\text{-}C1}$ is the current flowing from HVDC terminal C_{wf} towards the fault. $I_{Cwf\text{-}C2}$ is the current flowing from HVDC terminal Cwf towards terminal C2 and I_{C2} is the current flowing in the opposite direction, from HVDC terminal C2 towards terminal Cwf. I_{C1} and $I_{Cwf\text{-}C1}$ both have a steep increase when the fault occurs, and this is due to the discharging of the capacitors on converter terminals C1 and Cwf. After the discharge I_{C1} equals the current fed through the C1 converter from the grid side, $I_{Cwf\text{-}C1}$ equals the current fed through the Cwf converter from the wind farm grid plus the current from the third terminal, C2. In this case the current through the converters are only slightly higher than nominal, and there is no large current through the diodes. However this depends on the grounding on the grid-side. In this case there is a high-impedance grounded transformer on the grid-side, which effectively limits the fault current. If the transformer instead was solidly grounded, the fault current through the converter would be much larger, and this could be harmful for the diodes.

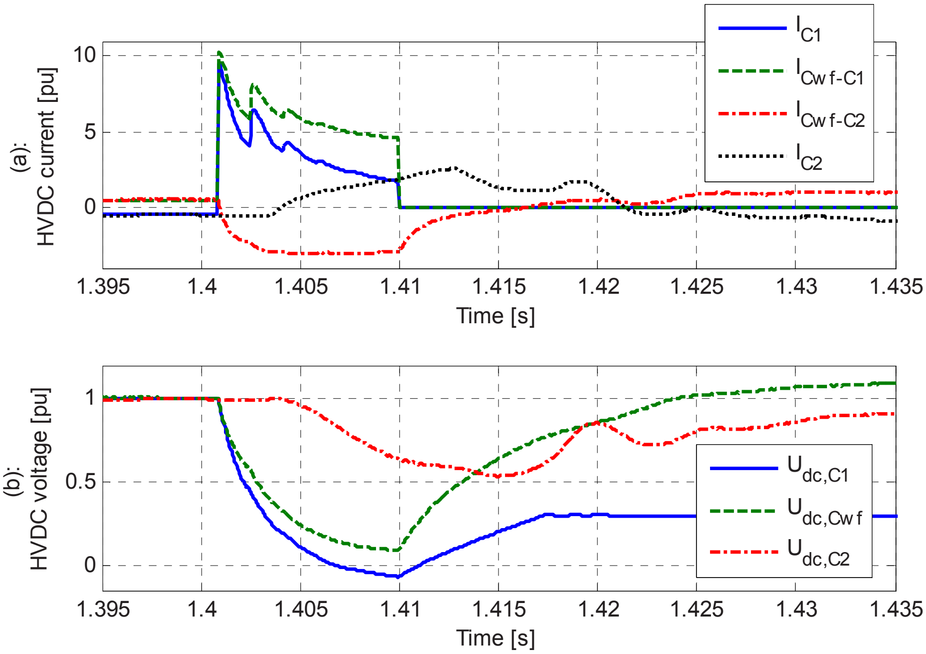

Figure 5: (a) HVDC cable currents, pu-basis is 1000 MW. (b) HVDC terminal voltages. As measured at the three HVDC-terminals C1, C2 and Cwf.

From the wind farm HVDC terminal the correct faulted branch can be identified by looking at the directions of the fault currents on the two branches. In addition the currents on the faulted line are significantly larger than the nominal directly after the fault occurrence, while the currents on the unfaulted line are not. The DC-voltages on each side of the faulted cable section decrease quite fast to values close to zero, while the voltage at terminal C2 is decreasing slower and only down to 0.5 pu. Thus the initial fault current levels can be utilised for fault detection together with the DC-voltage levels. As previously stated, the initial current peak is due to the capacitor discharging, and the two-level converter represents worst case in this matter. Multi-level converters can have smaller capacitor discharge currents since there are smaller capacitors associated with each level. This could make fault detection more difficult.

An alternative is to utilise the current derivative [14], shown in Fig. 6, for fault detection. The current derivatives on the faulted branch ($d(I_{C1})/dt$, $d(I_{Cwf\text{-}C1})/dt$) are initially very high, while the current derivatives on each side of the unfaulted cable section are relatively small. This allows for fast and reliable fault detection. The current derivatives on each side of the faulted cable section will however depend on the fault location, so it has to be investigated if reliable detection can be achieved for all fault locations. It also has to be assured that no normal load step changes can be confused with a fault condition.

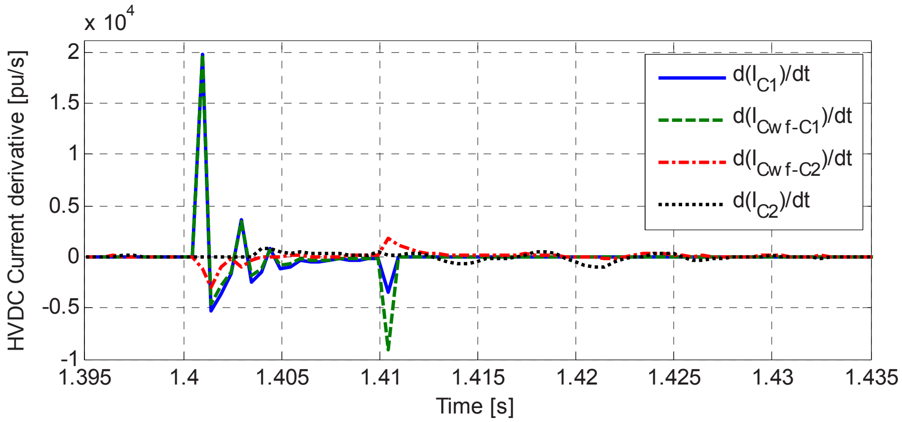

Figure 6: Derivative of HVDC currents with positive-phase-to-ground fault between terminals C1 and Cwf.

Fig. 7 shows the response in active power through the three HVDC terminals during the fault and after the disconnection of the link between terminals C1 and Cwf. After the disconnection, the active power through terminal C1 goes to zero while the power delivered to terminal C2 is increased accordingly. The change in active power through C2 is due to the DC-voltage droop on the active power controller if this converter. Thus the wind farm can continue the power generation without interruption.

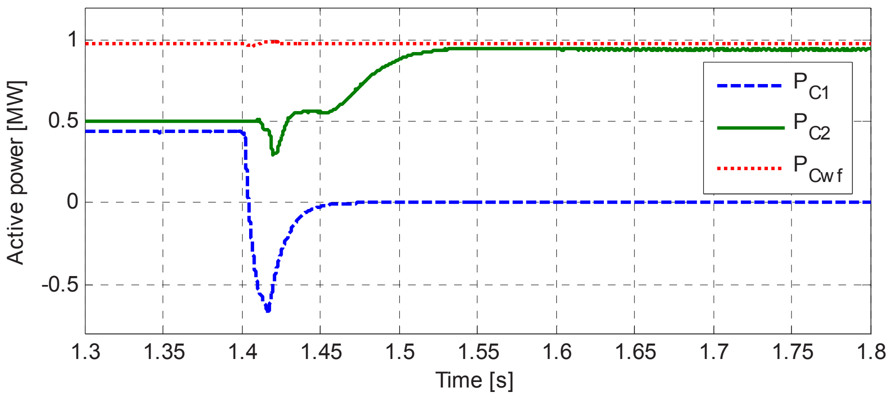

Figure 7: Active power through HVDC converters C1, Cwf and C2 with positive-phase-to-ground between terminals C1 and Cwf

5. Discussion and conclusions

Simulations showed that the wind turbines could operate stable through both two-phase and three-phase short circuits in the collection grid. This is due to the action of the DC-chopper, which absorbs excess energy in the DC-link when the collection grid voltage drops.

To assure that the unfaulted part of the grid can remain in operation after a fault, the faulted section has to be located and disconnected. Distance protection is the most common protection for AC-grids. However, the use of conventional distance protection in the converter interfaced AC-collection grid is doubtful since the change in impedance due to the fault is very small. The change in impedance angle could however allow for detection of the fault by choosing a properly fitted tripping characteristic. Differential protection however appears to be the most secure choice of short-circuit protection for the collection grid. This means that communication will be required. Fault analysis for various loading and fault locations should be carried out to draw safe conclusions.

The study of ground faults in the HVDC-grid showed that the faulted section has to be disconnected very fast in order to ensure stable operation of the remaining grid. For a fault halfway between terminals C1 and Cwf (150 km from each), the maximum disconnection time was found to be as short as 15 ms. Fast fault detection is possible e.g. based on rate-of-change of current together with DC-voltage level, but a fast DC breaker is required for disconnection. DC breakers for high voltage and high power have remained a challenge for a long time. Last autumn ABB claimed in a press release to have solved the problem by developing a DC-breaker capable of interrupting the power within 5 ms [15]. Significant experience from real-life installation is however still missing.

The very large capacitor discharge current makes it possible to detect the fault fast, but it is important to also consider the harmful effect this current is likely to have on the capacitor itself. Thus some protection or current limiting for the capacitor has to be provided. This can be done with snubbers, which limits the rate-of-change of current [8]. For a more accurate analysis of the DC-fault current, this should have been included in the model. Also, the capacitor discharge current and possibilities for fault detection with other topologies than the two-level should be studied, since the two-level is assumed to have the largest capacitors and discharge currents.

In addition to the capacitor discharge current, the response to a phase-to-ground fault in the HVDC grid is very dependent on the grounding of the converter AC-side. Fault current can flow from the AC-side via the anti-parallel diodes to the fault location. If there is a low-impedance grounded transformer on the AC-side, the fault current can be quite large, while an isolated neutral will give a small current. Thus to prevent damage of the diodes, an isolated neutral is advantageous. However, it was observed that isolated neutrals on all AC-sides lead to asymmetry in the DC-voltage after disconnection of the faulted HVDC cable section, which is also stated in ref. [7]. The HVDC-system is then floating relative to ground, and although the resulting phase-to-phase DC-voltage is close to nominal the positive phase-to-ground voltage is significantly less than nominal while the negative phase-to-ground voltage is significantly larger (in magnitude). The converter control system is only controlling the phase-to-phase DC-voltage, and is not able to bring the system back to symmetric operation after the unsymmetrical fault. With low-impedance grounding on the AC-side of one terminal the system remains symmetric. Finding an optimal grounding strategy or improving the control system in order to assure symmetrical operation after an unsymmetrical fault are possible topics of further study.

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