Asymmetrical Fault Analysis at the Offshore Network of HVDC connected Wind Power Plants

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***Abstract*—Short-circuit faults for HVDC connected Wind Power Plants (WPPs) have been studied mostly for dc link and onshore ac grid faults, while the offshore ac faults, especially asymmetrical faults, have been mostly omitted in the literature. Requirements related to the offshore asymmetrical faults have been kept as future development at national levels in the recent ENTSO-E HVDC network code. In this paper offshore ac faults are studied using the classical power system fault analysis methods. It is shown that suppression of negative sequence current flow is not applicable and negative sequence current has to flow during the asymmetrical offshore faults, which implies that the offshore WPP and the HVDC offshore converter are required to provide flow of negative sequence current. The steady-state fault analysis is verified with time-domain simulations.**

***Index Terms*—Power system faults, wind energy integration, HVDC transmission, converters, current control.**

I. INTRODUCTION

A number of today's offshore wind power plants (OWPPs) are being connected via HVDC links, and more are already planned to be installed in the near future [1]. Despite the wide interest in analysis of these HVDC connections mainly in terms of control design and impact on grid stability and protection, offshore asymmetrical faults have been analyzed only in few studies until now [2] - [4]. The ENTSO-E HVDC network code [5], which has recently been published in the Official Journal of EU, has left the requirements for fault-ride-through capabilities and asymmetrical current injection in case of asymmetrical faults to be specified by the relevant system operator in articles 19 and 25 for the "DC-connected power park modules" and "remote-end HVDC converter stations". Only in the recent grid code from Germany, negative sequence current injection is required from Wind Turbines (WTs) [6]. In accordance with the grid code requirements (both onshore and offshore) and rapidly increasing offshore installations, state-of-the-art full-scale converter-based (type 4) WTs and Voltage Source Converter (VSC) based HVDC converters are equipped with enhanced control capabilities such as fault-ride-through and independent control of active and reactive currents both in positive and negative sequences [7], [8].

In conventional onshore power systems, owing to conventional synchronous generators with high short-circuit current contribution in positive sequence to symmetrical faults and also in negative sequence to asymmetrical faults, the protection systems are able to detect and securely clear the faults, despite the relatively high share of WPPs. However the existing fault ride-through response of the WTs is not designed or optimized for secure protection system operation in a network without synchronous generators, such as offshore ac network of HVDC connected WPPs. Short-circuit faults at the offshore ac network of HVDC connected WPPs have been studied for symmetrical faults in [9] and asymmetrical faults in [2] and [3], where it is shown that positive and negative sequence current control capabilities of the OWPP and HVDC converters can be utilized to minimize active power and dc-link voltage oscillations and to increase the active power transfer. In [4], impact of positive sequence current injection from OWPP on the fault detection during offshore asymmetrical faults has been studied.

In this paper asymmetrical (single-line-to-ground, line-to-line, double-line-to-ground) faults at the offshore network of HVDC connected WPPs are analyzed focusing on the impact of positive and negative sequence current injection from the OWPP and the HVDC converter. A fundamental faulted network analysis is performed first utilizing classical power system fault analysis method based on symmetrical components rather than purely relying on time-domain simulations. The main purpose of the paper is to explore the required current injection behavior for OWPP and HVDC converters during offshore asymmetrical faults and guide towards the future grid code requirements and control solutions. By analyzing the limitations with basic theoretical tools, better and more realistic requirements can be generated.

II. FAULTED NETWORK ANALYSIS

The studied system is shown in Fig. 1, which is a simplified generic network, with parameters in appendix. The

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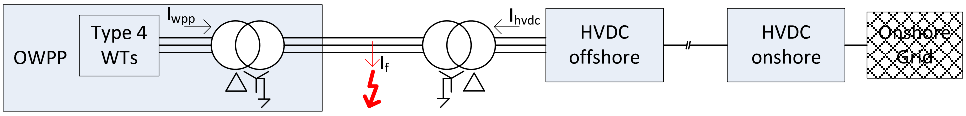


Figure 1. Generic network diagram for HVDC connected offshore wind power plant.

cable between the two transformers (OWPP and HVDC) is modeled as series resistive-inductive impedance. Shunt components (e.g. cable capacitance, filters) are not considered, which will be discussed again in section IV. Asymmetrical faults occurring in the middle of the cable are analyzed below. As explained above, the main focus is on fundamental analysis of fault current injection from the OWPP and the HVDC converter; hence, detailed analysis of controls during steady-state periods or power flow to the onshore side are not within the scope of this study; moreover, for this initial analysis it is assumed that controls are able to meet the desired performance.

A. Single-Line-to-Ground Offshore Fault

The equivalent sequence network connection during a single-line-to-ground fault [10] is shown in Fig. 2, where the superscripts 1, 2, and 0 represents positive, negative, and zero sequences, respectively; and Z_c is the cable impedance, $Z_{w\text{-}trf}$ and $Z_{h\text{-}trf}$ are WPP and HVDC transformer impedances respectively, and Z_{fault} is the fault impedance, which is taken to be zero as solid (bolted) fault. The wye-delta winding of the WPP and HVDC transformers isolate the converters from fault zero sequence network and the grounded neutrals on the cable side provides the path for the zero sequence fault current flow, which could also be provided via grounding transformer(s) as well [1]. For a conventional synchronous generator, the induced internal voltages are balanced pure positive sequence, while the negative sequence is pure impedance [8]. However, for the OWPP and (VSC) HVDC, both the positive and negative sequence currents are controlled during the fault, as represented by current sources (I^1_{wpp}, I^1_{hvdc} ,I^2_{wpp}, I^2_{hvdc}) in Fig. 2, whereas similar approach has been utilized for WT's onshore asymmetrical fault analysis in [11]-[14].

The equivalent sequence network in Fig. 2 implies that the positive, negative and zero sequence currents flowing into the fault have to be equal (and in phase) to each other [10]. It is important to note that the positive and negative sequence currents are provided by the converters (WPP and HVDC) in the offshore AC network. Hence, suppression of for instance negative sequence current implies suppression of the fault current and extremely high voltages in the other sequences, as will be analyzed with time-domain simulations. This phenomenon with the negative sequence current interruption can also be understood to be similar to zero sequence current interruption, which occurs in case of an ungrounded (or poorly grounded) power system, which results in floating neutral point due to high zero sequence voltage with respect to ground and close to nil fault current.

B. Line-to-Line Offshore Fault

The equivalent sequence network connection during a line-to- line fault [10] is shown in Fig. 3, where the zero sequence network does not appear. In case of line-to-line fault total positive and negative sequence currents are having equal magnitudes but in opposite phase. Similar to the previous fault case, suppression of negative sequence current during a line-to-line fault implies suppression of the positive sequence current as well. Hence, it becomes impossible to flow pure positive sequence current, which implies that converter controls would not be able to realize a pure positive sequence current reference.

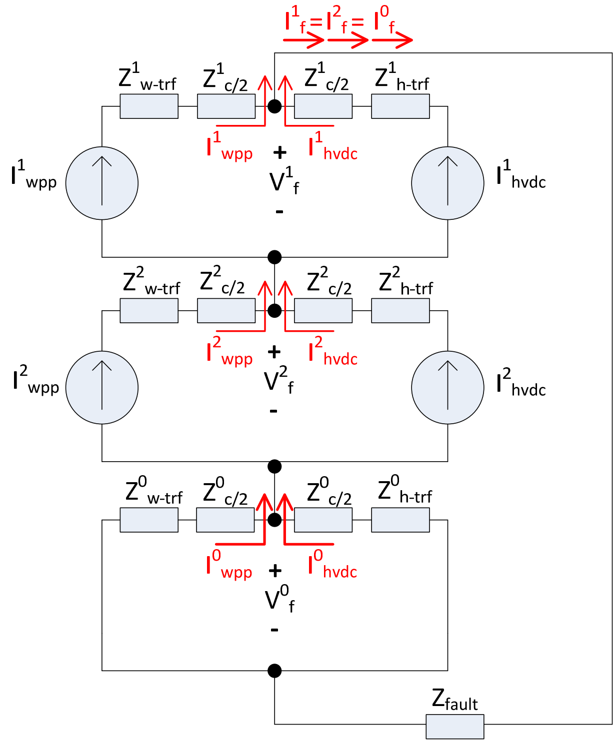


Figure 2. Single-line-to-ground fault equivalent sequence network.

C. Double-Line-to-Ground Offshore Fault

As seen in Fig. 4, in case of double-line-to-ground fault, the positive sequence current is sum of the negative and zero sequence currents. Hence it is important to note that in case of double-line-to-ground fault, it is possible to suppress the negative sequence current and inject pure positive sequence current (which will create anti-phase zero sequence current flow on the zero sequence network). However, developing a control algorithm using this fact might require detection of the fault type, which might bring complexity. Moreover, depending on system grounding and fault location, the zero sequence impedance may be infinite and the same constraint as for the line-to-line fault would arise.

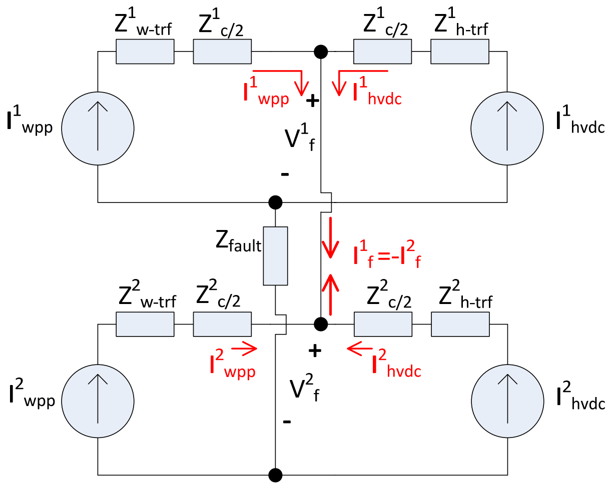


Figure 3. Line-to-line fault equivalent sequence network.

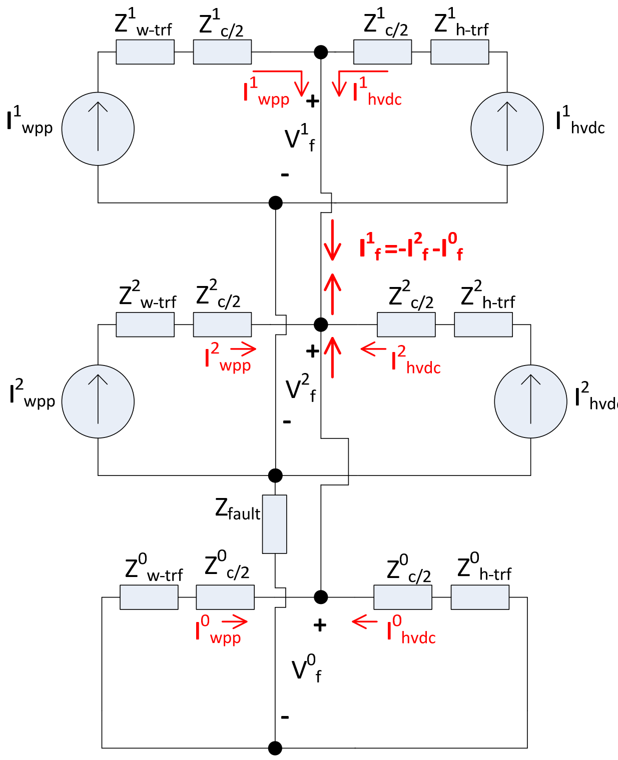


Figure 4. Double-line-to-ground fault equivalent sequence network.

III. TIME-DOMAIN SIMULATIONS

The generic network in Fig.1 is modeled in Simulink SimPowerSystems toolbox. In order to verify the fault sequence network analysis of the previous section without any impact of control dynamics, the OWPP and HVDC converters are modelled as ideal current (or voltage) sources, when positive and negative sequence currents are being injected during (steady-state period of) faults. Only single-line-to-ground fault (at phase-a) analysis is performed in this section, with the following responses from HVDC and OWPP converters:

i) Pure positive sequence voltage by the HVDC (reduced to limit current below 1pu)
ii) Pure positive sequence (1pu) current by the HVDC
iii) Equal (0.5pu) magnitude and in-phase positive and negative sequence currents by the HVDC and the OWPP

Results for case i, where the HVDC is generating balanced symmetrical voltages and OWPP does not inject any currents, are given in Fig. 5. As observed in Fig. 5 (a), voltage is reduced down to 0.1 pu in order to keep the current within limit, i.e. 1pu. Being not shown, positive, and negative and zero sequence fault currents are equal to each other. In this case, the HVDC converter behaves similar to a conventional synchronous generator but with limited current magnitude. Positive, negative, and zero sequence voltages appear in the network and sequence currents flow as dictated by the characteristics of the fault. Such a scheme might be a candidate for fault-ride-through scheme of offshore HVDC converter [15]; however any current injection scheme via setting positive and negative sequence current references (e.g. to minimize dc-link power oscillations) might not be applicable, as it will interrupt the circuit, as analyzed in the next case.

Results for case ii, where only the offshore HVDC is injecting 1 pu balanced positive sequence current, are shown in Fig. 6. Fault current in Fig. 6 (a) is observed to be higher than 1pu due to the additional zero sequence current flowing through the grounded transformers. In Fig. 6 (b), fault phase voltages (thus HVDC voltages too) reach unrealistic values as high as 300 pu, which results from the fact that the negative sequence in Fig. 2 behaves as open circuit, as the converters are suppressing the negative sequence current in this case. It is important to note that simulation could converge only with using snubber resistance and capacitances for the inserted fault (in the simulation toolbox); otherwise no convergence has been obtained.

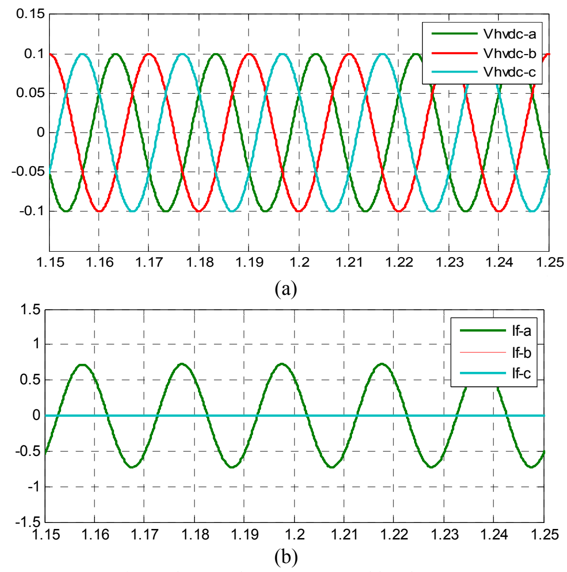
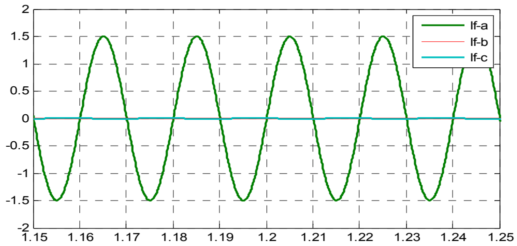
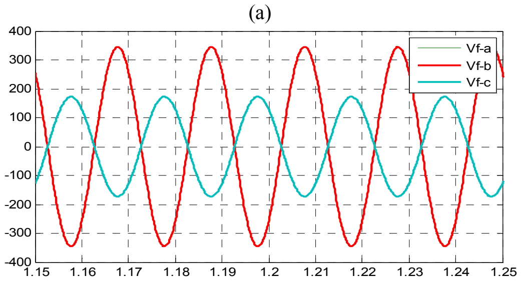


Figure 5. For case i (a) Phase voltages generated by the HVDC [pu] vs. time [s] (b) Fault phase currents [pu] vs. time [s].



(a)



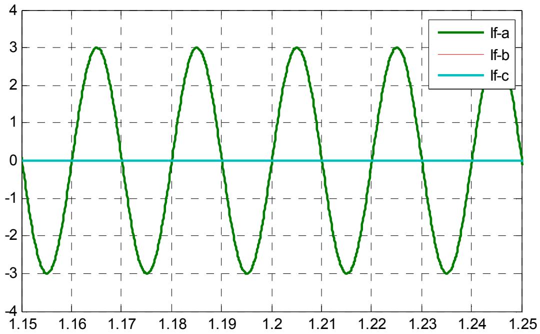
(b)

Figure 6. For case ii (a) Fault phase currents [pu] vs. time [s] (b) Fault phase voltages [pu] vs. time [s].

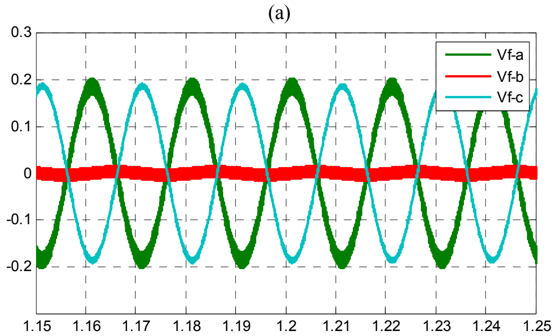
Results for case iii, where both the HVDC offshore converter and OWPP are injecting 0.5 pu positive and 0.5 pu negative sequence currents, are given in Fig. 7. It is not shown due to space limitations but OWPP and HVDC currents are adjusted with phase angles to be all in-phase at the faulted cable when they are transformed through the transformers' phase shifts. Similar to the previous case, fault current is getting higher with the additional zero sequence current flowing through the transformers' grounding; however the phase voltages at the fault (thus at converter terminals too) are reasonable, ca 0.2 pu. Even though it seems like injections in this case are ideally working stable, this cannot be a current injection scheme for the converters, since any deviation from identical current injection (due to control dynamics for instance) would result in non-convergence as in the previous case as the fault circuit requires exactly identical positive and negative sequence currents. It is not shown here but similar results as in Fig. 7 are obtained when only the HVDC was injecting equal magnitude (0.5 pu) and in-phase positive and negative sequence currents. The fault analyses for line-to-line and double-line-to-ground faults have been verified too, but could not be shown due to space limitations.

IV. Discussion and Future Work

The analysis here show that offshore asymmetrical faults have specific characteristics in terms of positive and negative (and zero) sequence current flow, which must be supplied by the OWPP and/or HVDC converters. It can be concluded that the positive and negative sequence current injection schemes from the OWPP and HVDC converter have to obey the characteristics of the asymmetrical fault, similar to the solid symmetrical fault case where the X/R ratio of the impedance from a generator to the fault dictates the active and reactive current flow. On the contrary to symmetrical fault cases, where the HVDC and OWPP converters can independently control their (positive sequence) current magnitudes, positive and negative sequence current flows from HVDC and OWPP converters are coupled to each other in asymmetrical fault cases. Hence any current injection scheme specifying strict positive and negative sequence current magnitudes for HVDC and OWPP converters during asymmetrical faults needs to be carefully analyzed. A scheme, where the HVDC converter behaves as a positive sequence voltage source allowing flow of negative sequence current (within the voltage and current limits) as in case i above, while the OWPP converters contribute with limited positive and/or negative sequence currents, can be a possible scenario.



(a)



(b)

Figure 7. Case iii (a) Fault phase currents [pu] vs. time [s] (b) Fault phase voltages [pu] vs. time [s].

Shunt components (e.g. cable capacitance) might possibly change the results but the authors believe that extremely high voltages as in Fig. 6 (b) would still be observed due to high impedance values of those shunt components, which stands as a future work. The analysis here applies also for a network, which is composed of very high share of power electronic converters, for instance a microgrid without synchronous generators.

The results imply that while implementing any negative sequence current injection schemes, for instance the recent German grid code [4], specific characteristics of the pure converter based offshore networks should be taken into account. Current injection schemes, which are setting the positive and negative sequence current references for the WTs and offshore HVDC, should be carefully designed. Voltage levels at converter terminals must also be analyzed to formulate clear requirements.

Once the fundamentals have been studied from a theoretical perspective, future work will also be directed towards the development of control schemes that can be applied in reality.

The analysis here is performed considering the state-of-the-art VSC type offshore HVDC station, which can control voltage and/or current at its terminals. A similar analysis for a diode rectifier unit (DRU) type offshore HVDC [7], which is being studied and prepared as a novel solution to possibly become more cost-effective and reliable, stands as a future work. Interesting results might appear since the passive diode rectifier would not be able provide specific currents. Additionally, similar analysis for meshed offshore networks stands as future work as well.

V. Conclusion

An important and interesting fact has been explored in this paper that positive and negative sequence current injection by the HVDC and OWPP converters in an offshore isolated network cannot be independently dictated for offshore asymmetrical faults as the asymmetrical fault characteristics dictates the characteristic of the current flow. In a conventional (onshore) power system, conventional power plants with the directly connected synchronous generators provide the path for the negative sequence current flow. However, in an isolated offshore converter-only network, the converters have to provide the negative sequence current flow or as minimum must not suppress it, in order to obey the characteristics of the specific asymmetrical fault.

The results are important to give insight for national implementation of the ENTSO-E HVDC Network Code, especially for the asymmetrical current injection requirement from the "DC-connected power park modules" and "remote-end HVDC stations"; and also for control and protection scheme development for offshore wind installations.

VI. Appendix

TABLE I. Data for the Generic Network in Fig.1

WPP rating	100MW	-	-	-
HVDC rating	120MVA	-	-	-
WPP transformer	120MVA	YgD1	155kV/33kV	Z=0.01+j0.1
HVDC transf.	120MVA	YgD1	155kV/320kV	Z=0.01+j0.1
Cable	-		-	Z=0.001+j0.01
Fault Impedance				Z=0

References

[1] CIGRE, "CIGRE Technical Brochure B4.55 HVDC Connection of Offshore Wind Power Plants", May 2015.

[2] S. K. Chaudhary, R. Teodorescu, P. Rodriguez, P. C. Kjaer and A. M. Gole, "Negative Sequence Current Control in Wind Power Plants With VSC-HVDC Connection," in *IEEE Transactions on Sustainable Energy*, vol. 3, no. 3, pp. 535-544, July 2012.

[3] A. Moawwad, M. S. El Moursi and W. Xiao, "A Novel Transient Control Strategy for VSC-HVDC Connecting Offshore Wind Power Plant," in *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1056-1069, Oct. 2014.

[4] M. Ndreko, M. Popov, M. A.M.M. van der Meijden, "Study on FRT compliance of VSC-HVDC connected offshore wind plants during AC faults including requirements for the negative sequence current control," International Journal of Electrical Power & Energy Systems, Volume 85, pp. 97-116, Feb. 2017.

[5] ENTSO-E Network Code on Requirements for Grid Connection of High Voltage Direct Current Systems and Direct Current-Connected Power Park Modules [online] Available: https://www.entsoe.eu/Documents/Network%20codes%20documents/NC%20HVDC/EC%20Regulation%20%28EU%29%202016%201447%20HVDC%20network%20code.pdf, 26 August 2016.

[6] Forum Netztechnik/Netzbetrieb im VDE (FNN), "VDE-AR-N 4120:2015-01 Technical requirements for the connection and operation of customer installations to the high-voltage network (TCC High-Voltage)," Jan. 2015.

[7] R. Teodorescu, M. Liserre, P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems,* Wiley Press, 2011.

[8] T. Neumann, T. Wijnhoven, G. Deconinck and I. Erlich, "Enhanced Dynamic Voltage Control of Type 4 Wind Turbines During Unbalanced Grid Faults," in *IEEE Transactions on Energy Conversion*, vol. 30, no. 4, pp. 1650-1659, Dec. 2015.

[9] S. Bernal-Perez, S. Ano-Villalba, R. Blasco-Gimenez and J. Rodriguez-D'Derlee, "Efficiency and Fault Ride-Through Performance of a Diode-Rectifier- and VSC-Inverter-Based HVDC Link for Offshore Wind Farms," in *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2401-2409, June 2013.

[10] H. Saadat, Power System Analysis, McGraw-Hill Press, 1999, pp. 421-432.

[11] V. Diedrichs, H. Lorenzen, I. Mackensen, and S. Gertjegerdes, "Asymmetrical current injection addressed by ENTSO-E draft network code" in *Proc. Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms,* 2012.

[12] I. Erlich, T. Neumann, F. Shewarega, P. Schegner and J. Meyer, "Wind turbine negative sequence current control and its effect on power system protection," in *Proc. IEEE Power & Energy Society General Meeting*, 2013.

[13] Ö. Göksu, R. Teodorescu, C. L. Bak, F. Iov and P. C. Kjær, "Impact of wind power plant reactive current injection during asymmetrical grid faults," in *IET Renewable Power Generation*, vol. 7, no. 5, pp. 484-492, Sept. 2013.

[14] M. Ndreko, M. Popov, A. A. van der Meer and M. A. M. M. van der Meijden, "The effect of the offshore VSC-HVDC connected wind power plants on the unbalanced faulted behavior of AC transmission systems," in *Proc. IEEE International Energy Conference (ENERGYCON)*, 2016.

[15] R. Sharma, "Electrical Structure of Future Off-shore Wind Power Plant with a High Voltage Direct Current Power Transmission," Technical University of Denmark, Lyngby, 2011.