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Projects BorWin2 and HelWin1 – Large Scale Multilevel Voltage-Sourced Converter Technology for Bundling of Offshore Windpower

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SUMMARY

Within the projects BorWin2 and HelWin1 two interconnectors are realized which apply voltage-sourced converter (VSC) technology to integrate offshore windpower into the German AC system. Each system is designed to receive power from two different offshore windfarms resulting in total power levels of 800 MW and 576 MW which are beyond todays operational experience in VSC transmission.

This paper gives an overview of design aspects and electrical performance of the transmission schemes. Special focus is on the power capability of the converter stations which are based on modular multilevel converter (MMC) technology. The further discussion relates to the background and benefits of new concepts such as the implementation of an onshore braking chopper in MMC technology or a transformer configuration dedicated to offshore applications. After an outline on manufacturing, laying and testing of the AC and DC cables results of stability investigations for the onshore and offshore networks are discussed.

KEYWORDS

HVDC systems – VSC transmission – multilevel converter – HVDC power cable – HVAC power cables - offshore windfarm – performance – rating – fault ride through - blackstart

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1. INTRODUCTION

The integration of offshore wind power is posing new challenges ranging from remote power generation to onshore AC network interconnection. For the overall concept HVDC interconnections using VSC converter technology play a major role since they are the only solution for three main tasks to be solved:

a) Generation of isolated offshore AC systems,
b) Realisation of an economic power transmission and
c) Stabilization of onshore AC networks.

Due to the implementation of the German act to speed up infrastructure planning procedures, TenneT has the instruction to develop and manage grid connections to offshore wind farms in its German transmission grid area since December 2006. TenneT Offshore, a subsidiary within the TenneT Group, is responsible for this specific task. Acting on behalf of TenneT, TenneT Offshore takes care of the design, planning, construction and management of offshore connections to onshore grid connection points, while TenneT itself is responsible for managing the offshore grid.

The first realised offhore wind farm DC connection project was BorWin1. In 2010 TenneT has awarded the BorWin2 and the HelWin1 projects to a consortium of manufacturer of converter stations and power cables to supply a feed-in for several upcoming offshore wind farms. The BorWin2 project has a power rating of 800 MW with a DC transmission voltage of +/-300 kV. It will interconnect the two windfarms Global Tech 1 and Veja Mate which are located approximately 125 km offshore – northwest of the island of Borkum. The wind power will be transported via submarine and land cable to Diele near Papenburg, through a 75 km land cable route, where an onshore substation will reconvert it from DC to AC for further transmission and distribution within the 400-kV AC grid.
The HelWin1 power rating of 576 MW is realized at a DC transmission voltage of +/-250 kV. Two windfarms NordseeOst and Meerwind which are located about 85 km offshore are foreseen to be connected to the HelWin1 transmission system. The onshore point of interconnection with the onshore substation is in Büttel, that is approx.45 km distant from the submarine cable landing point.

This paper is organized as follows. Section 2 introduces the modular multilevel converter topology and gives an overview of overall system design and operational aspects of the converter stations. AC and DC cable technology are summarized in section 3 and section 4. Section 5 highlights results of joint stability investigations which were performed for the BorWin2 and HelWin1 interconnectors.

2. ELECTRICAL DESIGN OF CONVERTER STATIONS

2.1 Design Issues of Modular Multilevel Converter Technology

The Trans Bay Cable Project in California, USA, represents the first commercial VSC installation utilizing modular multilevel converter (MMC) technology. Within this project MMC was realized as a HVDC PLUS system with a power rating von 400 MW operated at a DC voltage of +/-200 kV [1]. BorWin2 and HelWin1 rely on the same overall design concept. Fig. 1 and Fig. 2 show the project locations and an overview of the HVDC PLUS transmission schemes with their offshore AC interconnections.

Fig. 1 Location of BorWin2 and HelWin1 projects (stations marked in yellow) together with further windfarm interconnectors.

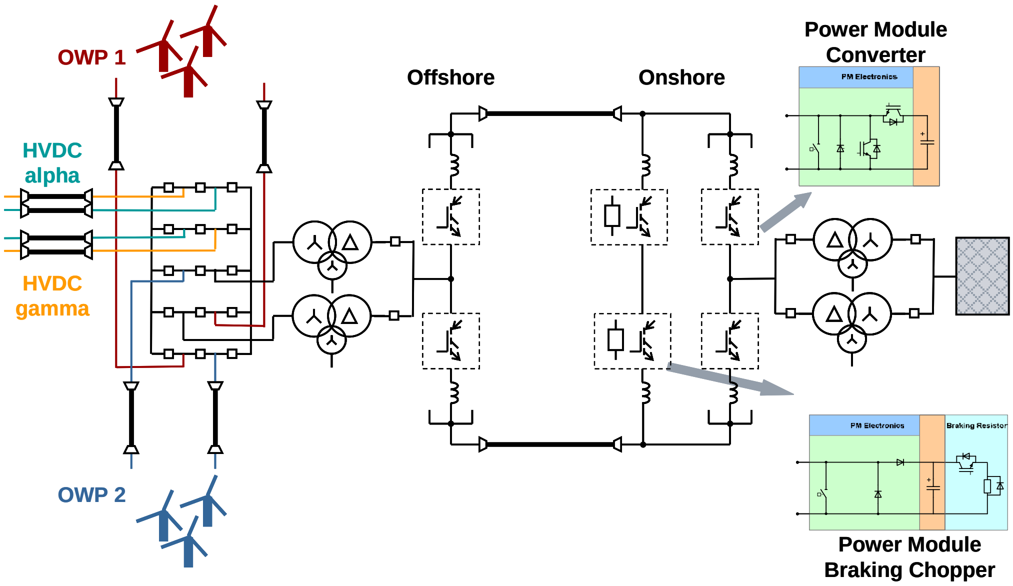


Fig. 2 Overview of HVDC transmission scheme with AC connections to offshore windfarms and adjacent HVDC stations. The number of outgoing AC interconnecting cables varies for various projects due to number of OWP and adjacent HVDC stations.

The HVDC PLUS converters are constructed from six converter modules. Each of the converter modules is made up from a series connection of individual power modules and operates as a controllable voltage source. For BorWin2 and HelWin1 the HVDC PLUS technology is adapted from Trans Bay Cable to European network requirements and towards higher power ratings by following main changes.

The key element of MMC technology is the use of power capacitors which are integrated within the converter modules. The main task of the storage capacitors is to serve as an

intermediate energy storage which realizes per power cycle a balance of a constant DC power flow and an oscillating AC power flow. As compared to a network frequency of 60 Hz in USA the storage capacity is increased for operation at 50 Hz by more than 20% accounting for balance of AC and DC powers during longer power cycles.
As for Trans Bay Cable Project 4.5 kV module IGBTs are used for BorWin2 and HelWin1. For higher power ratings loss-optimized IGBTs are used which can handle higher steady state operating currents. The maximum turn-off current of the IGBTs is increased to 3.0 kA for coordination of converter station internal fault currents.

BorWin2 and HelWin1 are operated at DC transmission voltages of +/-300 kV and +/-250 kV. For HVDC PLUS converters a new installation concept is introduced for which each converter module is constructed from a series connection of identical converter towers. Fig. 3 shows the assembly of a converter tower. Each converter tower has two external electrical connections which are located at its lower and its upper end. For up to 96 individual power modules the converter tower provides an internal helical electrical connection. This connection assures equal electrical stresses between the individual power modules. The converter towers are adjusted to different transmission voltages simply by choosing adequate base insulators.

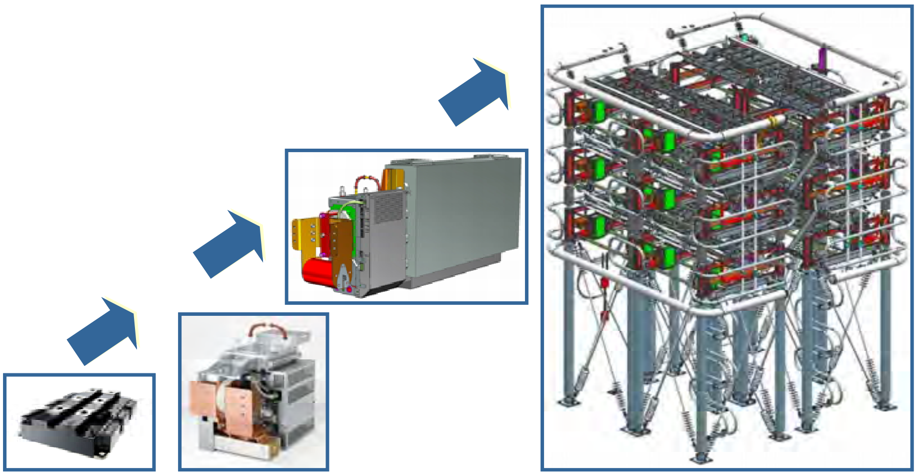


Fig. 3 Construction of HVDC PLUS converter towers from individual power modules.

2.2 Onshore Braking Chopper

When connecting offshore wind parks (OWP) via a VSC transmission system to the onshore AC network the OWP represent an isolated electrical system. This is beneficial for the onshore network since any faults occurring within the OWP will not be transferred by the VSC. However, in case of onshore AC faults the OWP power can not be fed into the onshore network and the excess power offshore will yield in a shutdown of the OWP. In order not to transfer the fault from the onshore to the offshore side a dedicated chopper is installed between the DC plus and DC minus pole at the onshore converter station. It dissipates the incoming power and thus enables an undisturbed operation of the OWPs during onshore faults. As the HVDC PLUS converter the braking chopper is realized as shown in Fig. 2 in a modular design for which each power module is combined with an individual braking resistor. A smooth operation of the braking chopper is realized since the individual control of the braking chopper modules results in an easy adaption to the actual load flow. Thus, high changes in dU_{DC}/dt and dI_{DC}/dt are prevented and negligible interference of the DC link with adjacent infrastructure such as pipelines and telecom equipment occurs.

2.3 Transformer Concept

Transformer concepts for HVDC systems play a major role since they determine operational features such as system losses, reliability, availability and maintenance. For BorWin2 and HelWin1 a parallel connection of three phase three windings YN0d5yn transformers is used. The converter side winding is connected in Delta in order to balance unsymmetrical AC network faults towards the converter side. A dedicated grounding device as described in [1] is used to serve as a reference for the DC voltages and to prevent DC voltage stresses of the converter side winding. The tertiary winding provides the HVDC station auxiliary power which is essential to realize the offshore station as an autonomous power system. The converter transformers have a nameplate rating of 70% of the total apparent power of the HVDC system. Transformer overload capability is designed to achieve 100% HVDC apparent power without aging and one transformer in operation.

Applying parallel operation of converter transformers to a VSC transmission scheme is a new concept which was developed with focus on the offshore station. Since shipping of transformers should be avoided as far as possible an in-built transformer redundancy which can be configured from onshore is an effective measure to assure highly reliable transmission systems.

2.4 Offshore Requirements and Auxiliary Systems

Due to its offshore environment the platform represents a highly integrated system which has to cope with multiple demands, e.g.:

- Safety for platform staff and facilities in a remote location: A comprehensive concept ranging from adequate training of personnel to safety systems is mandatory for working offshore.
- High reliability and availability of power transmission are of major priority since a shutdown of the HVDC system does not only result in zero power infeed of all OWP connected to the HVDC but also in a deficit of auxiliary power which is needed for the HVDC station and for the OWPs in stand-by mode. As a fallback solution Diesel generators take over auxiliary power supply.
- The offshore environment calls for special measures regarding material selection and surface coatings. In case of BorWin2 and HelWin1 all equipment is located indoor thus offshore conditions are essentially limited to the steel structure. The ventilation system is designed to protect all HV equipment and electronics from humidity and salt by adequate filtering of fresh air and by keeping an overpressure.
- Ancillary services of the platform include its function as a service location, storage location for spare parts and landing point for boats and helicopters.

Within the design of BorWin2 and HelWin1 platforms special attention is paid to the auxiliary systems. The design of the electrical auxiliary system has a high degree of redundancy since it can either be supplied by one of the converter transformers or by one of two 2 MVA diesel generators. A third small scale diesel generator is installed to supply platform loads in case the HVDC system is shutdown. The platform internal cooling systems use heat exchangers towards a central sea water cooling system. The system is designed to establish a permanent flow of sea water to prevent aggregation of dirt or marine animals.

For BorWin2 and HelWin1 the platform consists of a baseframe which is anchored to the sea bed and serves as a foundation to the topside comprising the HVDC station. The topside is designed as a floating, self-lifting installation which will be towed by tugs to its destination at sea. The legs are an integral part of the topside. For erection the legs are immersed and fixed to the preinstalled subsea baseframe. Thus, by virtue of its design a large heavy-duty crane vessel is not needed to lift the topside onto its foundation. The topside of BorWin2 as shown in Fig. 4 has dimensions L x W x H of 72.5 x 51 x 25 m^3.
Within the OWP clusters in the German North Sea BorWin, HelWin, SylWin and DolWin it is planned to install future HVDC platforms directly adjacent to existing HVDC platforms to allow for synergies of ancilliary servives but also to realize possible interconnections at the 155 kV AC side as shown in Fig. 2.

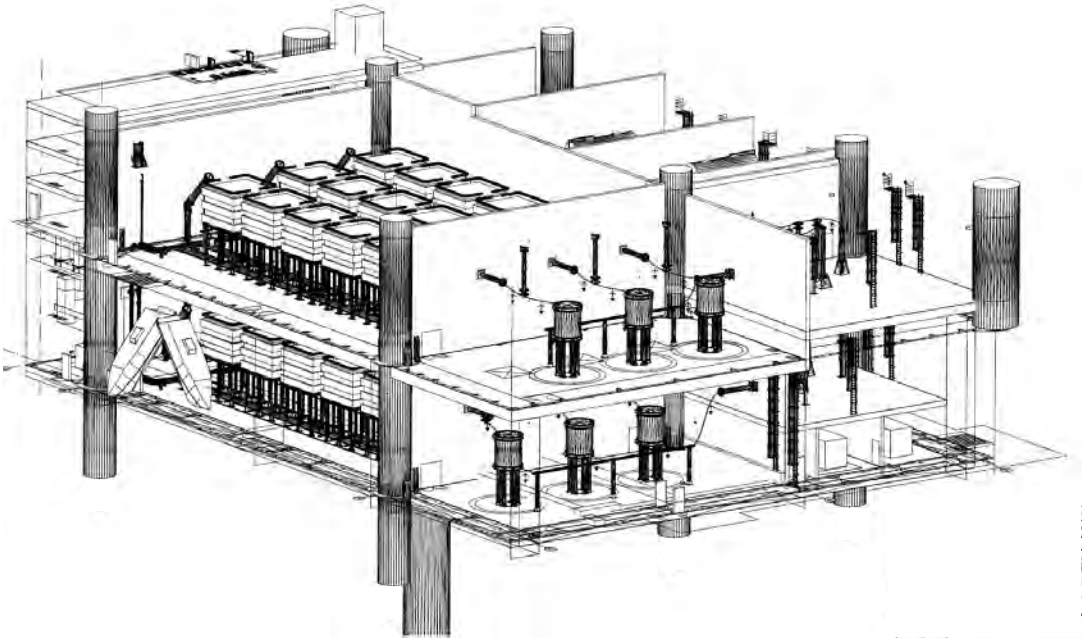


Fig. 4 Crossectional view of offshore platform BorWin2 with HV equipment.

2.5 Control & Protection and Operation of HVDC PLUS transmission scheme

Coming from point-to-point interconnectors between stable AC networks it is straight forward to locate the DC power control offshore where the OWP output power is to be absorbed and to assign the onshore converter to control the DC voltage.
Regarding the AC network at the onshore station three different operating modes are feasible: control of AC voltage, infeed of constant reactive power or infeed at a constant power factor. For operation in AC systems the control of AC voltage is the most practical case. In addition to the steady state control the performance upon AC network faults is a valuable feature of VSC converters. According to grid code requirements [2] the onshore converter is designed to support the AC network during faults with the injection of reactive currents resulting in increased stability of AC network voltage.
The onshore braking chopper is equipped with an own current control which receives its order value in normal operation via the onshore converter. Additional external control signals are used to trigger the braking chopper as an emergency power limitation by system operator.
On the offshore side the converter changes the DC power in order to keep balance with the actual OWP power resulting in a stable offshore AC frequency. The reactive power is adjusted to keep the AC voltage at its desired value.
The most important internal protection functions of HVDC PLUS converters rely on fast overcurrent detection of the converter modules. Furthermore power module voltage levels and

redundancy of available power modules are observed for protective setting. These basic functions are complemented by numerous AC and DC protective settings.
Automated sequences are used to run the HVDC transmission link in predefined operating states. The bays of the network side offshore GIS are energized and de-energized individually in order to allow for flexible configuration of the offshore network.
The HVDC sequences cover also the operation of the onshore station in a decoupled state, i.e. the onshore station operating in reactive power control mode without the DC cable connected. This is a valuable operating mode of the VSC station especially during commissioning and training phase since station tests can be carried out completely independent from the offshore station and actual power infeed of OWPs.

3. AC POWER CABLE TECHNOLOGY

The interconnection scheme of AC cables is shown in Fig. 2. The AC submarine transmission is realized by means of three-core cables, XLPE insulated, designed for the nominal voltage $U_0/U/U_m$ = 90/155/175 kV. Depending on length of AC cables compensating reactors are installed at the OWP side of the AC cables to adjust a ratio of compensation of 0.45 p.u.

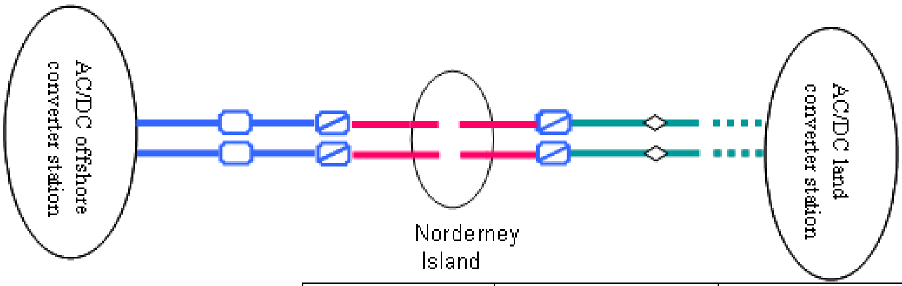
In the BorWin2 project the cables are 800 mm2 copper conductor sized and are suitable to transmit 200 MW each; they connect respectively the future OWP Veja Mate (2x11.4 km) and the OWP Global Tech 1 (2x30 km) to the AC/DC offshore converter station Borwin Beta. An AC bridge connection towards the existing converter platform BorWin alpha with short lengths of 30 m is also included.
In the HelWin1 project the cables are 400 mm2 copper conductor sized and are suitable to transmit 144 MW each; they connect respectively the OWP Nord See Ost (2x4.2 km) and the OWP Meerwind (2x7.6 km) to the AC/DC offshore converter station HelWin1. Provisions for AC connections to the future HelWin2 station are included.

The three core submarine cables have the typical construction as widely used for HV AC export cables in offshore wind parks. The cables are produced in Italy. Quality and integrity of cables are checked with factory acceptance tests and after installation tests. Furthermore a type test program in accordance with the Cigrè recommendations reported in Electra N°189 and 171 has been set up.

4. DC POWER CABLE TECHNOLOGY

The portion of DC transmission is realized by means of single core XLPE insulated cables.
In the BorWin2 project the DC link is designed to transmit 800 MW at the nominal rated voltage U/U_m = 300/315 kV, while in the HelWin1 project the transmitted power is 576 MW at the rated nominal voltage U/U_m = 250/262 kV. The cable schemes are shown in Fig. 5.

Extruded cables for DC have been widely developed and tested up to 320 kV. A further qualification at 320 kV is ongoing to fully cover all offshore connections in the German North Sea which are currently under construction. Cables for submarine applications have a construction as shown in Fig. 6 below.



BorWin 2	Deep water	Shallow water	Norderney	Land
Section length(km)	113.7	4.5+5.2	1.5	75
Conductor cross section (mm2)	1000 Cu	1700 Cu	1700 Cu	2400 Al
Cable diameter (mm)	122	131	110	122
Cable weight (kg/m)	35	44	32.4	15.7

HelWin 1	Deep water	Shallow water	Norderney	Land
Section length(km)	68	17	-	45.5
Conductor cross section (mm2)	875 Cu	1200 Cu	-	1800 Al
Cable diameter (mm)	112	118	-	110
Cable weight (kg/m)	30	35.3	-	12.3

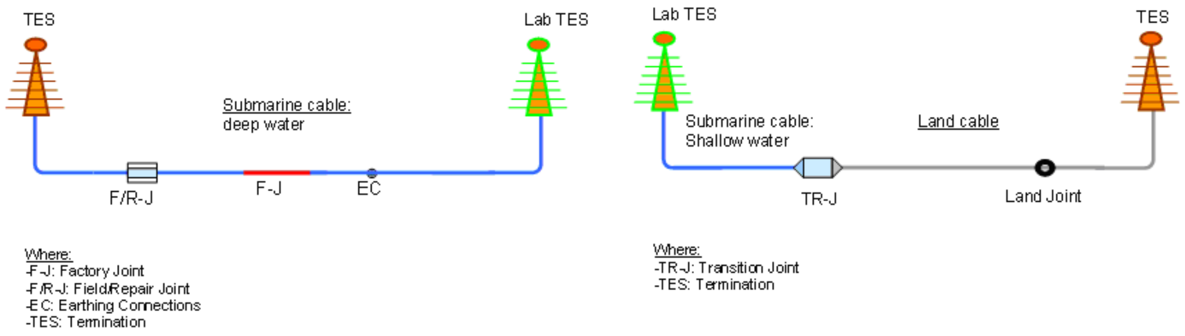
Fig. 5 DC cable data for BorWin2 and HelWin1 project.

1.Conductor, Copper compact stranded, waterblocked
2.Conductor screen
3.Insulation, extruded DC insulation
4.Insulation screen
5.Longitudinal water barrier
5.Lead sheath
6.Poliethylene sheath
7.Bedding
8.Armour
9.Serving

Fig. 6 HVDC cable from offshore converter platform to land.

Land cables, as shown in Fig. 7, have typically aluminum conductors, similar insulation package as submarine cables, but their outer layer are simply made with a thick aluminium foil longitudinally welded, which is a fully impervious layer against water and moisture penetration, and a PE outer sheath.
The submarine cables are produced in Arco Felice (ITA) and Pikkala (FI) factories. The land cables are manufactured in Delft (NL) and Pikkala (FI) factories. The cables are subjected to the factory acceptance test and after installation test. A type test program according to Cigrè recommendations reported in TB 219 and Electra N°171 has been set up on the loops shown in Fig. 8.

Fig. 7 HVDC land cable to onshore station.



Loop 1 Loop 2

Fig. 8 Testing loops for DC cables.

Land Installation

The open-trench installation technique will be implemented for the major part of the land routes, apart from specific areas Horizontal Directional Drilling will be necessary for crossings with roads, rivers, dikes, dunes and other obstacles. The HVDC power cables are installed in flat formation inside the trench.
Installation methodologies and the related activities planning are aligned with installation windows, local regulations and other environmental constraints present along the land routes.

Marine Installation

Along the DC routes from the landing points up to the Converter Platforms, two HVDC power cables and one FO cable will be installed in a common trench at a target burial depth ranging from 1.5m to 5m, depending on different requirements and conditions due to traffic safety, HSE, permits.
Along the AC routes from the Converter Platforms up to the AC Transformer Platforms, two HVAC power cables will be installed along separated and almost parallel routes at a target burial depth of 1.5m.
Different burial equipments will be used: Vibro-plough, Vibro-sword, Hydroplow, Vertical injector, Trenching ROV, always in agreement with specific project requirements. Italian Cable-Ship Giulio Verne will operate together with other vessels and barges suitable for the related installation activities. Different cable protections are adopted (mattressing and rock dumping) at crossings with in-service utilities.

Fig. 9 Cable laying ship Giulio Verne.

5. ELECTRICAL PERFORMANCE

Faults in the offshore and onshore networks were investigated to evaluate the AC system stability using NETOMAC. The model includes the onshore HV network, detailed model of OWPs and the HVDC links BorWin2 and HelWin1. If available the representation of wind turbines and other converters rely on stability models provided by the individual manufacturers. Generic models which fulfil grid code requirements [2] are used as a fallback solution in case no detailed information is available. Within detailed study work a comprehensive set of fault scenarios was investigated from which two representative results are introduced within this paper.

5.1 Offshore network fault

For BorWin2 a scenario with full load operation at 800 MW of BorWin2 with both OWPs Veja Mate and Global Tech 1 connected is assumed. Fig. 10 shows the results for a 3-phase to ground fault which occurs on one export cable of Global Tech 1.
Upon fault occurrence the active power drops to zero. At the onshore side the system voltage is unaffected from the offshore fault. The lack of active power results in a minor drop of onshore frequency by <250 mHz for a limited duration of 100 ms demonstrating the stability of the onshore network. At the offshore side the fault is cleared by tripping out the faulty cable after 150 ms. The fast recovery of the offshore network voltage is followed by a stable ramp up of active power within 700 ms.

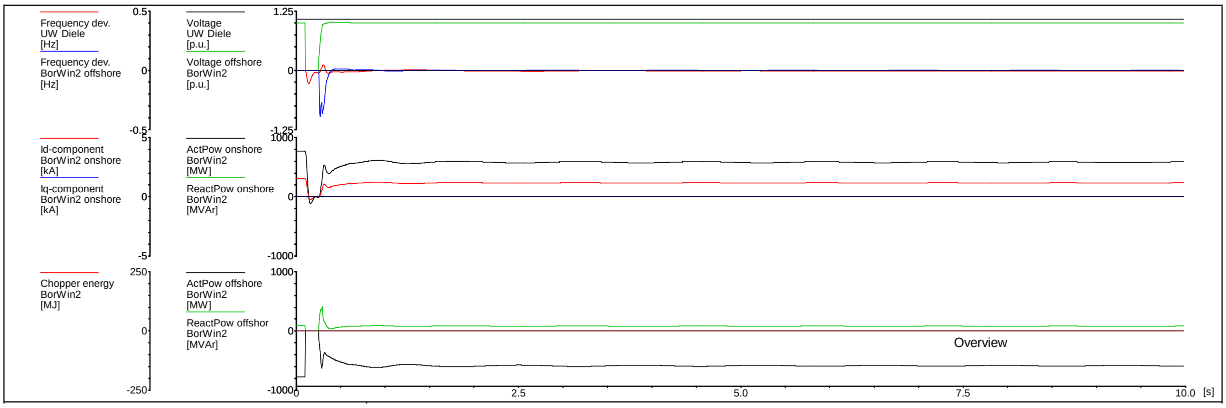


Fig. 10 Offshore 3-phase fault on one export cable of OWP Global Tech 1 feeding BorWin2.

5.2 Onshore network fault

Fig. 11 shows a 3-phase fault on single circuit line at the BorWin2 onshore station in Diele. The chopper effectively decouples the offshore network from the onshore fault which is nicely demonstrated by the undisturbed performance of the BorWin2 offshore converter and the associated OWPs. During the fault the onshore converter injects reactive current according to the grid code requirements. After fault clearing the onshore AC voltage shows a stiff recovery and active power is released immediately from the braking chopper. Due to the meshed onshore network the fault is also seen at the onshore connection point of HelWin1 in Büttel as a drop in system voltage by 0.08 p.u.

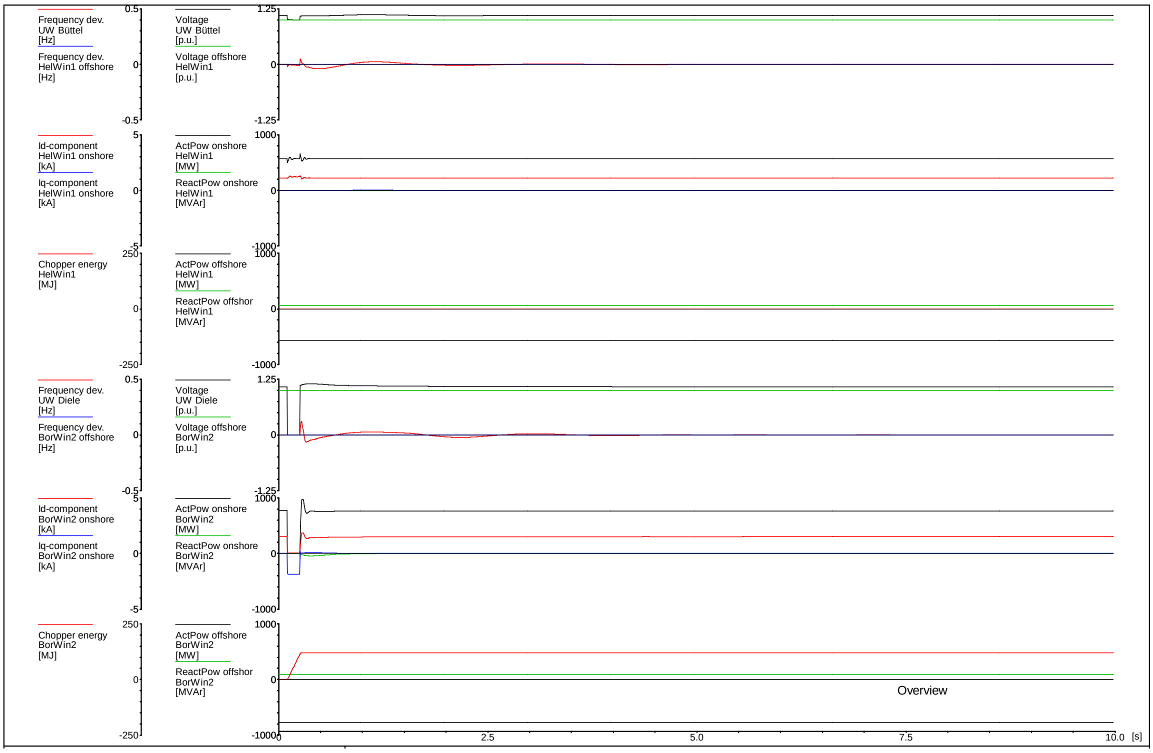


Fig. 11 Onshore 3-phase fault on a 400 kV line leaving BorWin2 onshore station

5.2 Stability of onshore and offshore AC system

The results highlight the stability of the onshore and offshore networks. Especially by the choice of network faults it is demonstrated that the system remains stable even under severe fault conditions. The stability is approved by the good recovery of system voltage and small deviations in network frequency. Furthermore, no power oscillations occur between onshore power generators due to the high short circuit power of the onshore system of 13 GVA even in weak system conditions. The BorWin2 and HelWin1 interconnectors exhibit a fast and reliable recovery upon offshore and onshore faults.

6. CONCLUSIONS AND OUTLOOK

The concepts developed for the projects BorWin2 and HelWin1 highlight the benefits of MMC converter technology for the interconnection of offshore windfarms. They will serve as a basis for two further projects SylWin1 and HelWin2 which have been contracted in 2011.

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