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# DolWin1 – Challenges of Connecting Offshore Wind Farms

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**Abstract**— Inherent properties of offshore AC grid with high penetration of wind generation present a number of challenges when connecting the wind turbine generators to the main onshore grid via HVDC. The paper focuses on discussing these challenges based on the experience gained by ABB during the execution of DolWin1 project and other previous offshore projects.

**Index Terms**—Offshore grid, HVDC, interaction, inrush current, fault currents.

## I. INTRODUCTION

Wind farms are today being installed in large scale in many countries. Germany, as a leader in wind energy in Europe, had 39.165 GW of installed wind capacity at the end of 2014, of which 1.049 GW was offshore, accounting for 9% of the country's net electricity consumption [1]. According to [1], a further 268 offshore wind turbines totaling 1.218 GW are scheduled to be online in 2015. The Renewable Energy Sources Act (EEG) in Germany, which came into force in 2000 and amended in 2012, set a cumulative target of 6.5 GW for offshore wind by 2020 [1]. Offshore wind is an essential component of Europe target of sourcing 20% of its energy consumption from renewables by 2020 [2].

Many of the planned offshore wind farms have a large power and considerable cable length to the receiving grid. The Voltage Source Converter (VSC) HVDC technology makes the connection of remote wind farms more feasible, there are no technical limitations to the length of the cable that can be used for transporting the energy. In AC transmission, the charging current of the cables takes a significant portion of the cable current carrying capability, which worsens with increased cable length. This implies that the AC cable must be rated for the capacitive charging current, in addition to the transmitted active current. The capacitive charging current is proportional to the voltage, the capacitance and the length of the AC cable. Beyond a certain distance, called the critical length i.e. 100 – 150 km depending on the cable type [3], there will be no capacity left for the active power transmission [5]. The classical way to increase the transmission capacity is to

increase the voltage level, but the reactive power increases with the square of the voltage, so the result is that the critical length will be reduced with increased voltage and power [4]. In HVDC there is no charging current in the cables since the voltage polarity doesn't change continuously, i.e. all the current carrying capacity is available for active power transmission. HVDC cables with XLPE insulation are lighter than other cables, making their installation offshore more effective and cheaper. Their lower weight per unit lengths allows the transport of longer sections, which translates in fewer cable joints, reduced installation time and reduced risk of failure. VSC HVDC converters have the inherent capability of independent control of active and reactive power flow. Furthermore, HVDC converter is able to control and stabilize the frequency and voltage of the wind farms. This enables and supports the smooth and reliable operation of the offshore wind farms. VSC HVDC links for wind farms are able to decouple the AC faults in the onshore grid from the wind farm by their DC chopper fast energy absorption capability. The DC link decouples the wind farms from faults, oscillation and electrical transients that may occur on the main grid, thereby reducing the mechanical stress on the equipment in the wind turbines.

DolWin1 project is one of the world largest HVDC links for connecting offshore wind farms. On July 27<sup>th</sup> 2015 ABB handed over the link to the Dutch-German grid operator TenneT offshore after successful completion of the project. DolWin1 is an important piece in the German transition to renewable energy and will provide 800 MW to the German grid when all wind turbines have been connected in 2018. The DolWin1 project was the first ABB project to implement the further improved VSC HVDC system.

The project started in July 2010 when TenneT awarded ABB the contract for the DolWin1 project. The project has been executed with overall lead from ABB in Västerås, Sweden. The HVDC link was designed and built by ABB in Ludvika, Sweden and the sea and land cables were manufactured and installed by ABB in Karlskrona, Sweden. The offshore platform was built under supervision of ABB in

Västerås by Heerema Fabrication Group in Zwijndrecht, Netherlands. The experiences ABB gained from the execution of the BorWin1 Project, the first offshore wind connection based on HVDC technology and awarded to ABB in 2007, have been very valuable and provided important lessons learned. DolWin1 will eventually connect three offshore wind farms to the German grid; Merkur Offshore, Trianel wind farm Borkum and Borkum Riffgrund 1.

The DolWin1 HVDC Light converter station was energized at the Dörpen West substation in Germany in the end of 2012. This was the first time a VSC converter station was operated at the new record DC voltage level of  $\pm 320$  kV. During the period up to energization of the whole link, the station was operated to test and evaluate the new technology.

After completion of the DolWin Alpha platform in 2014, the link was commissioned in August 2014. This was the first energization of a HVDC VSC link operation at  $\pm 320$  kV. During the latter part of 2014 wind turbines from two wind farms, Borkum Riffgrund 1 and Trianel wind farm Borkum, were connected to the DolWin1 link. During the first months of 2015 the DolWin1 link was kept in operation in order to allow connection of additional wind turbines. After several months there was enough wind turbines connected to allow a meaningful trial operation. Trial operation started mid-April 2015 and lasted until the end of June 2015. Provisional acceptance certificate (PAC) was given one month after end of trial operation. During the period until taking over by TenneT a maximum power of 400 MW has been transmitted.

An offshore AC grid, with its inherent properties, provides a number of challenges when connecting wind turbines to an HVDC link. The paper gives insight into these challenges.

## II. OVERVIEW OF DOLWIN1 TRANSMISSION SYSTEM

The transmission system of the DolWin1 project is shown in Fig. 1. The HVDC link connects the offshore wind farms located in North Sea to the German Grid at Dörpen West. The link has a total capacity of 800 MW at  $\pm 320$  kV DC voltage. The wind farms are connected with AC cables to an HVDC-Light converter station installed on an offshore platform (DolWin Alpha). The generated power is transformed here from AC to DC and transmitted via a 165 km XLPE insulated DC cable, comprised of a 75 km submarine part and 90 km land part, to an onshore converter station at the grid connection point in Dörpen West. The oil-free DC cables minimize the environmental impact at sea and on land, which is very important because DolWin1 cable route passes several sensitive areas. The power electronic converter is a cascaded two-level (CTL) that consists of several small two-level building blocks called cells. The CTL enables the creation of nearly sinusoidal output voltage from the converter and hence no AC harmonic filter is required. Thanks to the low switching frequency per cell, the insulated gate bipolar transistor (IGBT) switching losses and reactor

harmonic losses are significantly reduced. The total converter station losses are in the range of 1%. The CTL features together with the HVDC control are described in [6]. DolWin1 project has higher equipment redundancy level than in normal monopole HVDC system: it has parallel converter transformers, each capable of handling 800 MW. The DC chopper is for enhancing the ride-through capability during AC faults in the onshore grid. It prevents onshore disturbances from propagating to the offshore grid.

The offshore grid is comprised of Borkum Riffgrund 1, Trianel wind farm Borkum, and Merkur Offshore wind farms. The layout of the wind farms is shown in Fig. 2. Borkum Riffgrund 1 is a 277 MW wind farm which consists of 78 x 3.6 MW full converter wind turbine generators (WTGs) and it is connected to DolWin Alpha via two 11.4 km AC cables and two 155/33 kV, 180 MVA transformers. Trianel wind farm Borkum (in its first phase) consists of 40 x 5 MW full converter WTGs with a total capacity of 200 MW, and it is connected to DolWin Alpha via a 7.3 km AC cable and a 155/33/33 kV, 225 MVA transformer. Merkur Offshore is a 400 MW wind farm which consists of 66 x 6 MW full converter WTGs and it is connected to DolWin Alpha via two 13 km AC cables and four 155/33 kV, 120 MVA transformers. The individual WTG strings are not shown in the figure. Instead, the aggregation of the 33 kV cables and WTGs is shown. Trianel wind farm Borkum and Borkum Riffgrund 1 wind farms are in operation while Merkur Offshore wind farm is planned to be online by 2018.

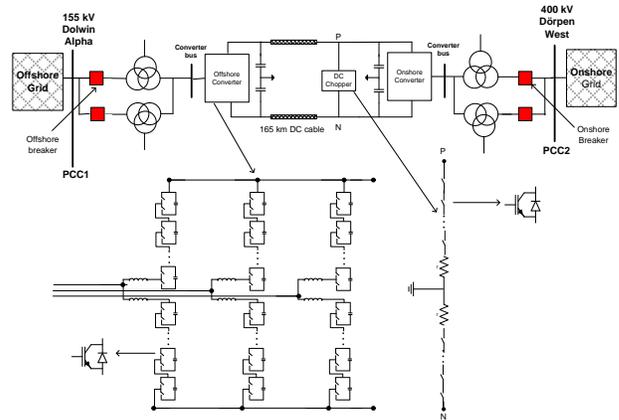


Fig. 1: DolWin1 transmission system.

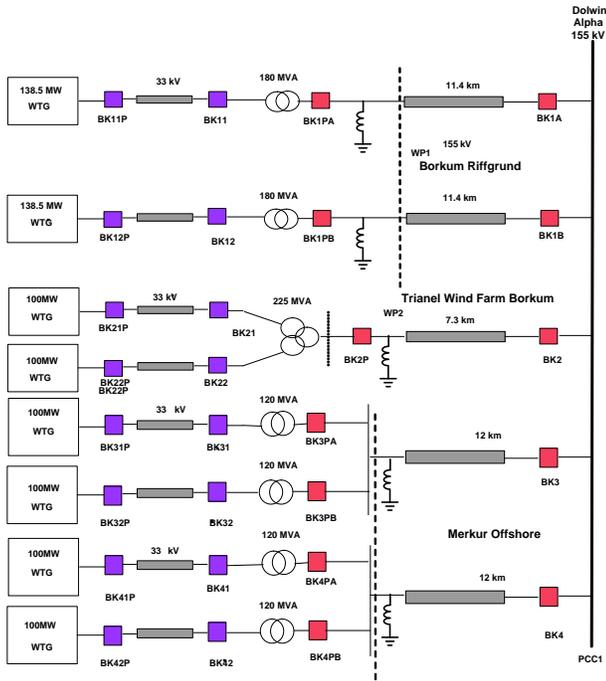


Fig. 2: Offshore grid with the layout of Borkum Riffgrund 1 and Trianel wind farm Borkum and Merkur Offshore, with aggregated modelling of WTGs.

### III. CONTROL MODES OF ONSHORE AND OFFSHORE CONVERTERS

During normal operation, the HVDC-Light converter station connected to the main onshore AC grid (inverter) is controlling the DC voltage and reactive power/AC voltage; the converter station connected to the wind farm (rectifier) is controlling the frequency and AC voltage in this islanded offshore AC grid. The wind farm sees the rectifier as a stiff AC voltage source. With this system arrangement, the HVDC-Light will automatically transmit as much active power as wind farms produce to the onshore AC system, while keeping a stable AC voltage and frequency in offshore AC grid.

### IV. CHALLENGES OF CONNECTING OFFSHORE WIND FARMS

For a remote large scale offshore wind farm and a transmission by VSC-HVDC, the major challenges are:

- The offshore AC system has low inertia.
- Large active power surplus in the offshore at load rejection.
- Sympathetic interaction at transformer energization.
- Possible control interaction between HVDC and WTGs.
- The offshore AC grid has low damping due to the low resistance in cables and transformers. Thus, resonances formed by the capacitance of cables and

the inductance of cables and transformers are poorly damped, especially during the early stage of AC system energization when there is low or no wind generation.

- Supplying enough short-circuit current for detection of phase-phase fault in the offshore grid at low power or disconnected WTGs.

In the following sections detailed discussion will be given for each challenge.

#### A. Offshore AC system has Low Inertia

An offshore AC system with WTGs is normally very weak in a sense that it has low inertia. A large frequency and phase angle excursion can take place in such AC system in case of load rejection, caused by onshore or offshore AC fault. This makes it challenging for the phase locked loop (PLL) of the WTG controllers to track the grid voltage accurately. Such difficulty with tracking may lead to instability in the offshore grid or trip of the WTGs by over-frequency or over-current protection; unless the power is reduced by the WTG controllers e.g. pitch control to mechanically reduce active power production. However, the WTG controllers can be relatively slow and may not be able to evacuate the power surplus before the frequency increases to the trip level. If there is high frequency voltage harmonics in the grid, the WTG PLL may not be able to track the voltage properly, resulting in misfiring of the converter and trip from over-current.

The HVDC DC chopper discussed in next section together with the frequency and AC voltage control in the HVDC offshore converter are the best measures to guarantee the stability of the offshore grid in case of onshore AC faults, as it isolates the offshore grid from the onshore disturbance. For faults in the offshore grid, proper control design for the HVDC and WTGs is required. The control shall ensure that the fault current supplied by the converter is below the valve capability on one hand and it is on the other hand enough for the grid protections to detect and isolate the fault. The most challenging aspect is the voltage tracking by different PLLs, also described in [7]. Once the offshore fault is cleared, the voltage and frequency of the offshore grid shall be controlled by the HVDC converter to their set points, as quickly as possible, so that the stability of the offshore grid is maintained and the power transfer is resumed.

#### B. Large Active Power Surplus in the Offshore Grid at HVDC Load Rejection.

HVDC load rejection can occur due to fault in the onshore AC system or control failure. In that case a situation of large active power surplus occurs in the offshore AC grid.

HVDC control failure is extremely rare as the control system is built up with a high degree of redundancy. If a control failure takes place in the offshore station, only the offshore converter will trip and the onshore converter will continue operating in STATCOM mode to support the onshore AC grid. Control failure in the onshore station will

lead to the trip of the HVDC link. If the offshore converter trips; WTGs will also trip. Depending on the WTG type, the WTG trip may be initiated by over-speed or over-voltage/under-voltage protection or chopper resistor over-temperature protection in full converter WTG.

For faults in the onshore AC system, the HVDC shall remain connected, with the onshore converter supporting the grid voltage by supplying a reactive current according to Fig. 3 below from the German Grid Code of 2010. The amount of active power transmitted to the onshore grid during such faults is reduced depending on how severe the fault is; e.g. zero power is transferred in case of solid three phase-to-ground fault at the point of common coupling (PCC) of the HVDC with the onshore grid. If the active power on the rectifier side is not reduced correspondingly, there will be an active power unbalance in the DC system as the power injected into the DC link is not fully transferred to the onshore grid. This leads to charging of the DC capacitance (comprised of DC pole capacitance, cable capacitance and capacitance of valve cells) and, as a result, the DC voltage will increase to a level that the HVDC link is tripped by overvoltage protection, unless other protective action are taken.

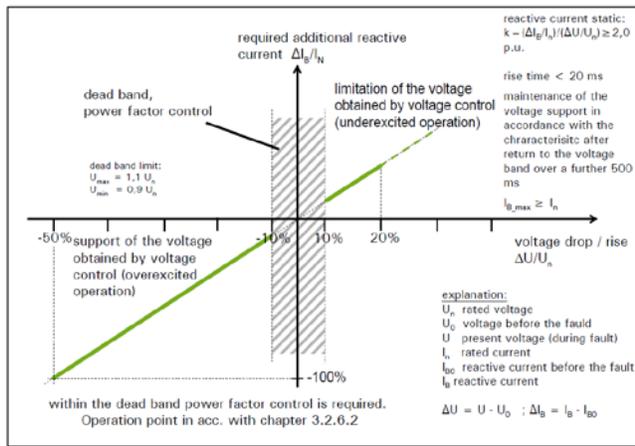


Fig. 3: Voltage support during grid disturbance [8].

There are many solutions proposed in literature for limiting the DC voltage during AC faults in onshore grid. Among them are [10]-[12]: fast reduction of the rectifier AC voltage magnitude as soon as the reduction in the inverter active power transfer is identified; slow (ramped) AC voltage magnitude reduction combined with a small DC chopper; increase in AC voltage frequency combined with a small DC chopper; and large DC chopper. The most robust and practical solution is the large DC chopper as the wind farms, regardless of the WTG type used, will not be affected by an AC fault in onshore grid. The chopper acts as a firewall buffering the disturbance in the onshore grid from entering into the offshore grid. It temporarily absorbs the excess energy from the wind farms which cannot be transmitted to the onshore grid during the disturbance. This solution is used

by ABB in BorWin1, DolWin1 and DolWin2 projects. The DC choppers consists of a resistor connected in series with an IGBT valve, see Fig. 1, which is turned on when the DC voltage exceeds a certain level, dissipating the excess power in the resistor, and is turned off when the DC voltage drops below a certain level. Results from PSCAD simulation of an AC fault with ~5% remaining voltage at the PCC onshore are presented in Fig. 4 and Fig. 5. In the plots, the active and reactive power convention is positive toward the AC grid. It can be seen from the offshore plots (Fig. 5) that offshore voltage and power are hardly affected by the onshore disturbance. Furthermore, the reactive current during the onshore fault is provided according to Fig. 3; see the last plot in Fig. 4. The chopper is turned on twice (once during the fault and once after the fault) to bring down the DC voltage, see the third plot in Fig. 4. After the fault clearance the DC voltage is brought back to the pre-fault value by the DC voltage controlling station and the active power transfer is resumed.

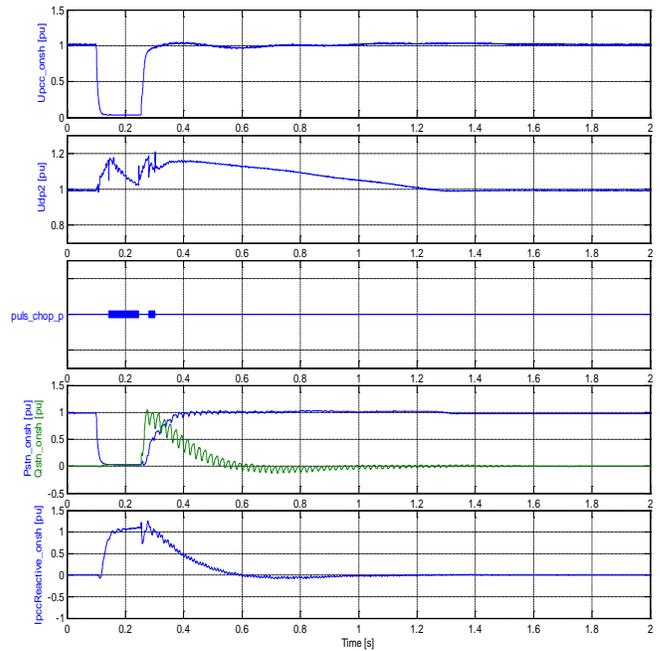


Fig. 4: 3ph-to-ground fault, PCC onshore, remaining voltage ~5 %, duration 150 ms, onshore station (U<sub>pcc\_onsh</sub>: PCC voltage, U<sub>dp\_onsh</sub>: positive pole-to-ground voltage, puls\_chop\_p: positive pole-to-ground chopper switch pulse, P<sub>stn\_onsh</sub>: active power measured at the PCC, Q<sub>stn\_onsh</sub>: reactive power measured at the PCC, I<sub>pccReactive\_onsh</sub>: reactive current at the PCC).

The oscillation seen post-fault in the reactive power in Fig. 4 is related to the saturation of the converter transformer that occurs due to the voltage recovery following voltage sag caused by the AC fault. This phenomenon is known as “Pseudo-inrush” and is described in [14].

No overvoltage in the offshore grid is seen during the load rejection caused by AC fault on the onshore grid thanks to the DC chopper and AC voltage control function in the offshore station.

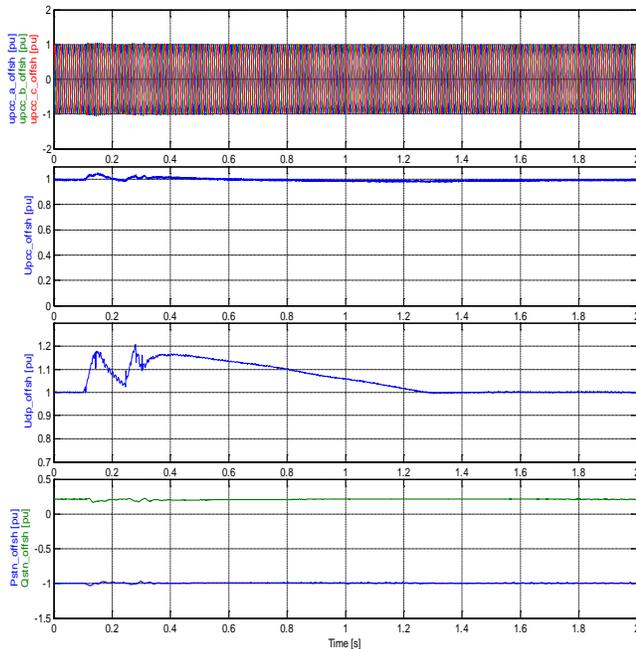


Fig. 5: 3ph-to-ground fault, PCC onshore, remaining voltage  $\sim 5\%$ , duration 150 ms, offshore station (U<sub>pcc\_offsh</sub>: PCC voltage, U<sub>dp\_offsh</sub>: positive pole-to-ground voltage, P<sub>stn\_offsh</sub>: active power measured at the PCC, Q<sub>stn\_offsh</sub>: reactive power measured at the PCC).

### C. Sympathetic Interaction During Transformer Energization

Transformers are normally energized by closing arbitrarily the circuit breaker contacts, with the system voltage being applied on the transformer windings at random instants. This switching introduces an asymmetrical magnetic flux in the windings which drives the transformer into saturation, generating high magnetizing transient inrush current. If there is enough damping in the network, in the form of loads or resistance in the energization path (such as circuit breaker pre-insertion resistor), the inrush current decays usually in few cycles when a transformer is energized in presence of no other transformers.

Sympathetic interaction occurs when a transformer is energized onto a system in presence of other electrically close and energized transformers. The inrush current drawn by transformer being energized produces a DC voltage drop across the series impedance connecting the other transformers and, therefore, drives the already energized transformers into saturation, resulting in an apparent inrush current. This phenomenon is called sympathetic inrush current and its physical description is provided in detail in [14]. In practice, transformers are energized in parallel or series with other transformers that are in operation. Sympathetic interaction may occur, whether the transformer being energized is in parallel or series with other transformers that are in operation [14]. Sympathetic interaction can significantly change the magnitude and prolongs the duration of the transient inrush current. The phenomenon was first reported in [13] following field tests trying to find the reason for malfunction of transformer differential relays. It is reported that a transient

magnetizing current of higher magnitude can flow, not only in the transformer being switched on but also in other parallel transformers already in operation, with current decaying at a much slower rate than would occur if the transformer had been switched onto a system having no other connected transformers. The inrush current may cause serious disturbances in the power systems. Examples of these disturbances are malfunction of transformer differential and overcurrent protection, temporary harmonic over-voltages that can impose excessive stress on the equipment, RMS voltage dip [14] that can be disruptive to power quality sensitive load, interference with telecommunication, and electromagnetic stress on the transformer windings which reduces the transformer life time.

Sympathetic interaction can be very common in offshore AC grids, where several WTG transformers may be energized within few minutes. Thus, proper protection settings that on one hand guarantees protection of equipment against overcurrent or overvoltage and on the other hand do not lead to false trips, are necessary. In the DolWin1 project, the onshore and offshore converter stations have two converter transformers are connected in parallel for purpose of redundancy, see Fig. 1. Each transformer is rated to carry the full power of the link which is 800 MW. It can happen that one of the offshore converter transformers is taken out of operation, e.g. for maintenance or unplanned outage. If the transformer is to be energized again while the other transformer is in operation, it has to be ensured that the inrush current due to sympathetic interaction between the two transformers does not lead to a severe disturbance that trips the transformer that is in operation, and consequently the offshore converter; this has to be ensured even under low wind or no generation conditions where the grid damping is at its minimum. Thus, to guarantee stable operation of the system when a parallel converter transformer with such high power rating is energized, measures for minimizing the inrush current (see the mitigation methods described below) complemented by proper protection settings are indispensable.

Energizing of a parallel onshore converter transformer while the HVDC link is in operation with the other transformer will not create a problem as the onshore grid is quite strong and have high damping.

#### 1) Mitigation of Sympathetic Interaction

There are several techniques summarized in [14] to minimize the inrush current magnitude and duration. Among them are the techniques discussed in sections a, b and c below; the first two are quite common. The method discussed in section d is presented in [16].

##### a) Installation of Pre-insertion Resistor (PIR) in Series to the Circuit Breaker Energizing the Transformer

Pre-insertion resistor is a relatively large resistor that is installed in series with circuit breaker. The voltage drop across the resistor produced by the inrush current decreases the voltage in the transformer windings, which in turn decreases the magnetic flux in the core. As a result, the magnitude of the transient magnetizing current will also be reduced.

However, the pre-insertion resistor will probably occupy significant space, which is not desired for offshore applications. Furthermore, circuit breakers equipped with pre-insertion resistors are no longer available off-the-shelf for voltage less than 500 kV since modern breakers in those voltages ranges are designed for use with point-on-wave (POW) closing [14], while PIRs are available off-the-shelf for Extra High Voltage GIS breakers above 500 kV.

*b) Controlling the Switching Time of the Energizing Circuit Breaker*

The magnitude of the inrush current, and hence the transients associated with transformer energization, depend on the voltage phase position at which the switching takes place and the magnitude of the residual flux from the previous de-energization. Transformer energization by segregated-pole breakers equipped with a special purpose point-on-wave (POW) controller can minimize the inrush current. If the residual flux is ignored, the most common controlled closing strategy is to close the first phase at its voltage peak and to delay the energization of the other two phases by a quarter of cycle ( $T/4$ ) [14]. Fig. 6 and Fig. 7 show the PSCAD simulation results of inrush currents following the energization of one of the DolWin1 parallel offshore converter transformer from DolWin Alpha 155 kV busbar (with converter side breaker opened) where all breaker phases closed at once (at zero crossing of phase a) and using the aforementioned strategy respectively, zero residual flux is assumed. It can be seen from Fig. 6 that significant inrush currents are flowing through the transformer being energized, due to the asymmetrical flux which drives the transformer into saturation. The inrush currents in the transformer in operation, caused by the sympathetic interaction, are also significant, in the same size as currents in the transformer being energized. The inrush currents are eliminated when the transformer is energized by closing the phase A at its voltage peak and phase B and C  $T/4$  later, as seen in Fig. 7. However, in many cases the residual flux can be considerable and closing according to the aforementioned principle gives unsatisfactory results i.e. with regard to the magnitude and duration of the inrush currents, an example of that is given [9]. Therefore, it is important to take the residual flux into account when the breaker switching instants are decided. Reference [9] gives an example of circuit breaker with a POW controller that measures the residual flux in each phase based on the integral over time of the decaying voltage measured at the transformer terminal during the transformer de-energization. When the transformer is to be energized again, the controller adjusts the circuit breaker closing points on the voltage wave in a way that the residual flux is compensated and hence the flux is made symmetrical, resulting in the inrush current being eliminated or limited as far as possible. Field test results for energizing of a 100 MVA parallel transformer using similar algorithm are presented in [9]. There it is shown that the inrush current is almost eliminated.

An AC breaker equipped with POW controller which takes residual flux into account, when deciding the closing

instants, is an ideal solution for offshore applications as the POW controller is integrated in the breaker and no extra space is required, as in the pre-insertion resistor. The breaker is used by ABB in the DolWin1 project for energizing the parallel offshore converter transformer when the HVDC link is in operation with the other transformer. However, as stated in [14], the commissioning of any practical POW system for transformer switching involves a number of tests including some online uncontrolled or pseudo-random closings in order to determine the parameters required for the POW controller. Among the tests are: off-line breaker tests to measure the mechanical operating speed of the breaker; energization test to determine the Rate of Decrease of Dielectric Strength (RDDS) based on mechanical operating time and current conduction time of the arc; energization test without taking into account the residual flux; and energization tests with optimal POW closing to verify the performance the POW breaker, including the flux calculation.

*c) Pre-insertion Neutral Resistor*

An inrush current mitigation strategy based on a pre-insertion neutral point resistor is presented in [15]. This method is however restricted to star grounded transformers.

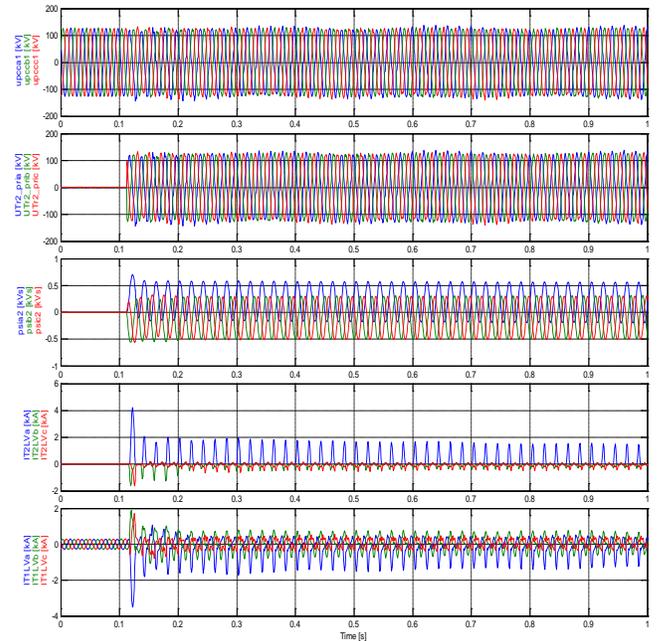


Fig. 6: Energization of parallel converter transformer from DolWin Alpha 155 kV busbar with all breaker phases closed at once and zero residual flux. **Preconditions:** HVDC link is transferring 50 MW with one transformer in operation. **Plotted signals:** upcca,b,c: PCC voltages measured at DolWin Alpha 155 kV, UTr2,a, b, c: voltages on the 155 kV side of the transformer being, psia2, b2, c2: flux of the transformer being energized, IT2LVa, b, c: inrush current measured on the primary side (155 kV side) for the transformer being energized, IT1LVa, b, c: sympathetic inrush current measured on the primary side (155 kV side) of the transformer in operation.

*d) Energizing from auxiliary diesel generator*

An alternative method to reduce transformer inrush current is to energize the transformer from an auxiliary generator, such

as a diesel generator, and then connect it to the medium or high voltage grid [16]. This method requires the auxiliary generator to be dimensioned and its control optimized for the purpose, and a synchronization unit is used when the transformer is connected to the medium or high voltage grid.

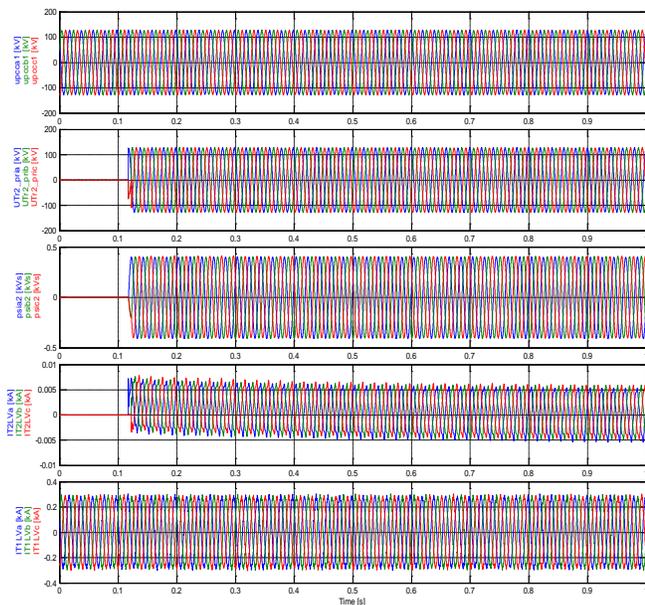


Fig. 7: Energization of parallel converter transformer from 155 kV side with phase A closed on the peak and phase b and c close quarter of cycle ( $T/4$ ) later, zero residual flux. **Preconditions and Plotted signals:** As in Fig. 6.

#### D. Possible Control Interaction Between HVDC and WTGs

The behavior of the controllers for the WTGs to be delivered is in most cases not known for the HVDC suppliers during the design phase of the project. Likewise, the WTGs developers are not fully aware of the HVDC control behavior. The interaction between the HVDC suppliers and WTG developers during the design phase of the project is limited due to protection by intellectual property (IP) or that the WTG manufacturer is not yet selected. The HVDC suppliers normally perform the system studies based on generic models which may not always reflect the behavior of the actual WTGs. All the previously mentioned factors make it hard to accurately know from the system studies (during design phase of the project) if there will be an adverse interaction between HVDC and WTG controllers, adverse interaction can be discovered during the commissioning. The interaction may appear in a form of harmonics, oscillations resulting in e.g. voltage instability, or trips from over-current. The nature of harmonics and the time they appear vary depending on the amount of generation from the WTGs and the AC network topology that connects the available WTGs to HVDC. Adjusting the HVDC controller to damp such harmonics in the field can be a challenging and daunting task.

#### E. The Offshore AC grid has Low Damping for Resonances, especially during Low Wind Conditions and Early Stage of AC system Energization

Offshore grids are characterized by low damping due to the small active power loss in the resistance of the AC cables and transformers connecting the WTGs to HVDC. The high capacitance of the AC cables together with the inductance of cables and transformers forms resonance circuits with arbitrary resonance frequencies ranging from some 100 Hz for systems with long cables and large transformers, to above 1000 Hz for shorter cables and smaller transformers. As the resonance circuits are formed by the cable and transformer electrical parameters, the resonance frequencies are not limited to integer multiples of the fundamental frequency. The inrush current associated with transformer contains, in addition to DC components and fundamental frequency, 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup>, 5<sup>th</sup> harmonics [14], and possibly harmonics with order higher than 5<sup>th</sup>. This implies that resonance can be excited by inrush current if the natural resonance frequency of the resonance circuit coincides with the frequency of one of inrush current harmonic components. If a resonance occurs, offshore equipment may experience harmonic over-voltage which, depending on its magnitude and duration, can damage the equipment unless it is tripped by the protection. The worst case with lowest damping is when WTGs are disconnected. Energization of a large transformer (i.e. converter transformer or 155/33 kV transformer) under such conditions may excite resonance. The resonance can also be excited when an AC cable is energized (155 kV AC cable) under the aforementioned conditions.

Studies are normally done during the design phase of the project to identify if there is a potential of resonance in the offshore grid, and to take the appropriate measure accordingly. Measures can be in a form of installation of breakers with POW controllers, e.g. for energizing converter parallel transformer as discussed previously or for energizing AC cables, or installation of harmonic filters although that is not desired as they require extra space offshore, increasing the platform size and the total project cost. Furthermore, it is extremely important that the HVDC and WTG converter control is tuned in such a way that it does not amplify oscillations caused by resonance, but should rather damp them or not interfere with them and let them damp naturally.

#### F. Supplying Enough Short-circuit Current for Detection of Phase-phase Fault in the Offshore Grid at Low Power or Disconnected WTGs.

The control of VSC converter connected to AC network is normally designed such that the converter does not inject negative sequence current into the AC network. The reason is that converter shall not contribute to the unbalance in the network caused by asymmetrical faults. This can be realized by controlling the negative sequence voltage drop across the converter, the phase reactor, and transformer to zero, e.g. using a negative sequence current controller where the reference active and reactive currents are set zero. This implies that the converter will generate the same negative

sequence voltage as the one measured at the point of connection with the grid.

Complete suppression of the negative sequence current by converter control would reduce the fault current during phase-to-phase short-circuit fault to a level which could hardly be detected by the protection, if converters are the only source for supplying the short-circuit current as in DolWin1 offshore grid. The worst case is if a phase-phase fault occurs during the energization phase where the HVDC converter is the only supply of the fault current. As an example, consider that a phase-phase short-circuit fault occurs at DolWin Alpha 155 kV bus soon after energizing the 155 kV AC cable of Trianel wind farm Borkum, see Fig. 8.

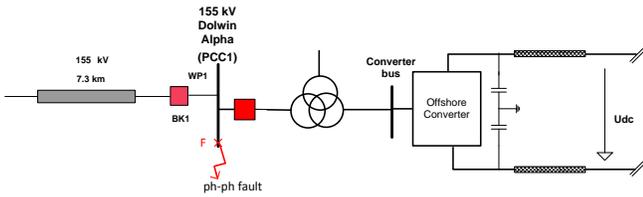


Fig. 8: Phase-phase short-circuit fault at DolWin Alpha 155 kV bus. The offshore converter is deblocked with transformer in operation.

The sequence networks for the above mentioned fault, where the converter is represented by AC voltage source, are presented in Fig. 9. The shunt capacitive impedance of the cable is much higher than the transformer and reactor impedance. Thus, it is obvious from Fig. 9 if the negative sequence is completely suppressed i.e.  $I_{conv\_neg}=0$ , the short-circuit current will be limited to the capacitive current through the cable, posing challenges for conventional protection devices to detect the fault and isolate it.

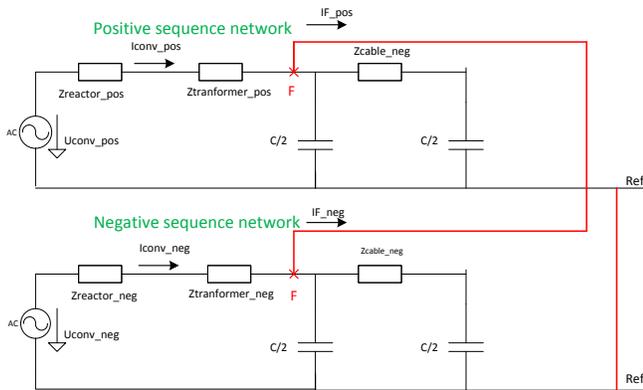


Fig. 9: Sequence networks for the phase-phase short-circuit fault in Fig. 8.

Simulation results for the fault case are shown in Fig. 10 and Fig. 11. In the case presented in Fig. 10, the negative sequence current injected by the converter is not sufficient to bring the fault current above the nominal value which would make it difficult for the protection to sense and clear the fault. As stated earlier, if no negative sequence current is injected, the fault current will be too low and limited to the capacitive current through the cable. In the second case, presented in

Fig. 11, the converter was allowed to inject more negative sequence current so that a fault current above the nominal current is obtained.

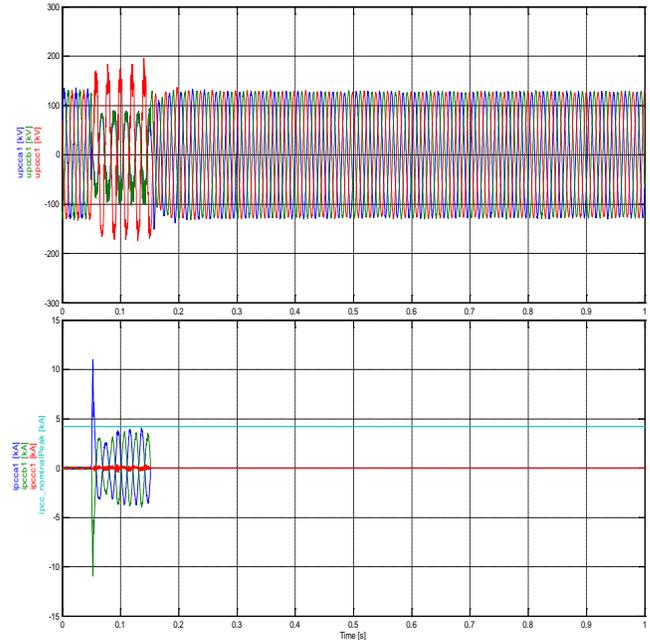


Fig. 10: Phase-phase short-circuit fault at DolWin Alpha 155 kV bus, fault current is below the nominal current. Top plots: voltage at DolWin Alpha; bottom plots: fault current supplied by the converter (measured at the PCC) compared with the nominal current.

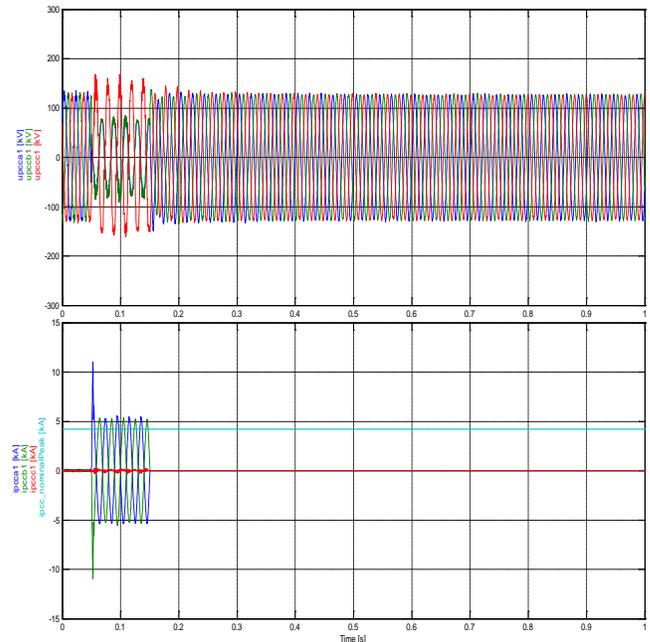


Fig. 11: Phase-phase short-circuit fault at DolWin Alpha 155 kV bus, fault current is higher than the nominal current.

## V. CONSTRUCTIONAL CONSIDERATIONS WHEN SIMULATING FAULTS IN AN OFFSHORE CABLE SYSTEM

Offshore cable systems of 33 kV and higher voltages are generally constructed with a metallic screen / sheath around each conductor [18]-[25] independently of whether the cables are so called “three-core cables” as in Fig. 12 or “single-core cables”. This is especially valid for high voltage cables. At those voltages, constructions of three-core cables without individual metallic sheath are rare; only one manufacturer is found [26]. This sheath is commonly made of lead or copper tape and has longitudinal water sealing function. If water penetrates the cable outer layers to the lead sheath, then the sheath can be considered grounded along the length of the cable, with lower ground resistivity when the water salt content is higher. With metallic layers around each conductor, any short circuit from a phase conductor to a metallic part must go involve earth; hence a phase-phase fault cannot occur in such a cable system, and simulating such faults on certain locations is unrealistic.

For a phase-phase fault to be able to occur in a cable system, the cables must be constructed without metallic sheaths around each core, such as [26]. This construction is more commonly occurring in land cables of lower voltages, such as 10 kV and lower.

Transformers however are most often constructed with all three-phases in one grounded encapsulation. Depending on the winding construction [17], a short circuit that does not involve earth could occur in a three-phase transformer. This includes both short circuits between phases and from the high voltage winding of a phase, to the low voltage winding of the same phase, depending on where the insulation would deteriorate and break down.

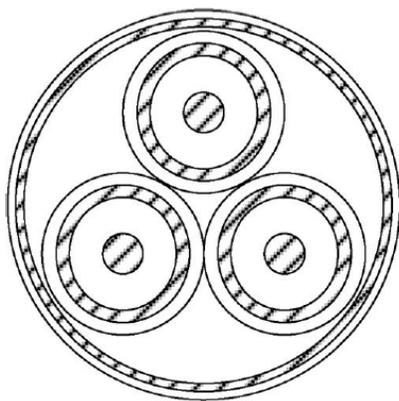


Fig. 12: Construction sketch of a typical offshore three-core cable. Each core is commonly surrounded by an individual metallic screen/sheath, forming a phase cable. Outside the three phase cables is a common metallic armor with the purpose of increasing mechanical strength.

## VI. CONCLUSION

The DolWin1 project shows the importance of control coordination between the HVDC and the WTGs to obtain a

system that is stable both during steady state and transient conditions. Considering the challenges with resonance circuits and sympathetic inrush, the latest technology in mitigation methods is used to mitigate the issues that arise in the unconventional offshore network. Thanks to the chopper installed, the offshore network is made immune to onshore faults. The lack of inertia offshore increases the demand on the control systems to ensure frequency stability, and the detection of phase-phase faults could be difficult depending on the control system design, setting a requirement on the HVDC control to ensure sufficient short circuit current during such faults. While ensuring sufficient short circuit current and preventing harmonic oscillations, the control must be prevented from interacting with the WTG controllers during all conditions to ensure stable operation. All these challenges have been faced and overcome during the project.

In both the onshore and offshore networks, the grid codes are fulfilled, ensuring stable operation as proven in the studies prior to commissioning.

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