Diode-Rectifier HVDC link to onshore power systems:
Dynamic performance of wind turbine generators and
Reliability of liquid immersed HVDC Diode Rectifier Units

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SUMMARY

The high potential of wind power far offshore calls for cost-effective solutions for grid connection. HVDC is the preferred grid access technology when large scale offshore wind power generation has to be connected to the energy system. The study investigates in the first part the interoperability of the offshore wind turbines with HVDC systems using diode rectifiers (DR) and voltage source converters (VSC). The wind turbines are assumed to be of type 4, which is the most commonly used wind turbine type in offshore wind power plants. Stable operation in AC and DC mode as well as a smooth transition between operational modes is achieved by implementation of the newly developed wind turbine grid side converter controller functions. In addition the dynamic behaviour including successful FRT test of entire DRU based DC grid access solution is demonstrated by comprehensive simulations.

In the second part of this study aspects of product requirements, design elements, operation behaviour and reliability of the HVDC Diode-Rectifier Unit are discussed. State of the art HVDC converters are configured as air insulated systems with related limitations in optimization of required space. The approach of the newly arranged offshore rectifier solution called “HVDC Diode-Rectifier Unit” is to combine on the one hand side transformer, rectifier and smoothing reactor functionalities and on the other hand to be handled practically comparable to a conventional power transformer in an offshore substation. Selected novelties and challenges in product design, usage of materials and components, production and test to meet the high requirements in installation, reliable operation and defined appropriate maintenance activities during the whole lifetime are presented in more detail.

KEYWORDS
Advanced Control, Type 4 WTG, Offshore, HVDC, Grid Access, Diode Rectifier Unit
I. INTRODUCTION

One of the main challenges today is to transmit off-shore wind power to the mainland grid as efficiently as possible. Efficiency strongly depends on the type of grid access, which becomes more demanding with the wind power plants moving further and further into the open sea. The VSC converter solution has already been applied in the first HVDC connected offshore wind power plant projects based on the conventional wind turbine (WT) and wind power plant (WPP) controls developed for connection to AC power systems. As alternative to conventional offshore DC grid access solution Siemens has developed a new technology that enables the efficient transmission of 1.2 Gigawatts of power from far-shore wind power plants that are located more than 160 kilometres away from the mainland [1]. The innovative New Grid Access (NGA) approach utilizes offshore AC to high voltage DC (HVDC) conversion by diode rectifiers [2], [3] and a high performance voltage source converter (VSC) located on-shore.

The Diode Rectifier (DR) HVDC solution has a potential for significant cost reductions and reliability improvements, but this solution requires changes to the WTGs and WPP controls in order to control the voltage and system frequency in the AC power collection system of the wind power plants.

The innovative “Siemens Grid Access - Diode-Rectifier Unit” approach utilizes offshore AC to HVDC conversion by diode rectifiers and a high performance voltage source converter (VSC) located on-shore.

The work presented in this paper evaluates WTG control and the main objective is to investigate and demonstrate the interoperability of the offshore wind turbines and wind power plant controls with HVDC systems using diode rectifiers (DR) and VSC converters. The type 4 wind turbines are characterized by a full scale converter utilizing advanced control of network side converter. The new developed network bridge controller described in detail in [4] allows connection of WTGs to HVDC system with diode rectifiers or extremely weak AC grid and thus allows flexibility to switch between AC and DC connection (hybrid operation) to onshore power system.

In order to test the functionality of the new technology, the demonstrator model has been set in the PSCAD simulation program. The simulation results are showing ability of the new concept to operate in DC transmission mode as well as switch back to the AC link operation and reliably transmit energy produced by WTGs when connected to very week system with SCR = 2. In addition the detailed study results showing dynamic behaviour of offshore wind park connected via HVDC DRU solution to synchronous power system are presented.

Inside of the Offshore Diode Rectifier Unit in a common tank ester liquid insulated and cooled diodes are implemented together with a transformer and a smoothing reactor. The offshore AC/DC conversion for e.g. 1200 MW / +/- 320 kV DC cable connection to shore consists of six (6) 200 MW “Diode-Rectifier Units” which shape a 24 pulse AC / DC rectifier mode and which are connected in series. The Diode-Rectifier Units are physical identical equipped including a vector group reconnection system inside the tank to set vector group on the wind park side of the transformer in order to shape a 24 pulse rectifier mode out of a pair of “Diode-Rectifier Units”.

The selected approach offers on the one hand side to significantly reduce weight and size of rectifier technology by application of robust power electronics equipment and insulation liquids. On the other side the split into several identical units offers significant cost reduction potential for the complete offshore installation e.g. a distribution of the equipment on smaller platforms.

Taking into account the application of ester liquid furthermore environmental and fire
protection efforts can be reduced significantly.
The reduced number of primary electric components on the one hand and the limited number of auxiliary equipment e.g. necessary for rectifying function on the other hand leads to significantly decreased monitoring and maintenance efforts as well and meets the requirements for harsh offshore environment conditions in comparison to proven air insulated HVDC converter technology.

II. ADVANCED CONTROL WTG CONVERTER CONTROL

A. Introduction
As already stated above WTG concept considered for DR grid access solution is based on wind turbines with full power converter which interconnect WTG to AC collection system offshore. Due to new challenges related to ability to operate WTGs with diode rectifiers or being connected to very weak grids (e.g. SCR < 3) converter network bridge control strategy needs to be modified. The conventional control known also as current oriented would not satisfy operational requirements of the system as it is more suitable for strong connections. Therefore, voltage oriented control needs to be applied which include also grid forming capability. In general, when choosing appropriate controller for WTG converter two limiting cases of power systems have to be considered:

B. Basics of the advanced Network Bridge control
Fig. 1 shows the principal configuration including measured voltage $V_M$ and current $i_M$ as well as converter output voltage $V_O$. The dominant coupling reactance determines the steady-state conditions of converter output voltage.

![Figure 1: Equivalent circuit representing terminals of LSC with coupling reactance](image)

Wind turbine Line Side Converter (LSC) output voltage $V_{Out}$ is composed of three components fulfilling individually the required power balance regarding steady-state conditions with reference to the measured voltage $V_M$ represented in synchronized rotating frame at given frequency $f_1$ (see Figure 2):

\[
V_{Out} = V_M + V_|| + V_\perp \quad (1)
\]
\[
V_|| = c_|| V_M; \quad (2)
\]
\[
V_\perp \cdot V_|| = 0, \text{ i.e. } V_\perp \perp V_M \quad (3)
\]
Following relationships hold at different power system conditions:

- **No-load condition**, where $V_{Out} = V_M$, i.e. $P_M = Q_M = 0$
- **Active power export** $V_{Out} = V_M + V_\perp$
  \[ P_M = -V_\perp |V_M| / X_C \text{ and } Q_M = 0 \]
- **Reactive power control (SVC)** $V_{Out} = V_M + V_{\|}(f)$,
  \[ P_M = 0 \text{ and } Q_M = -V_{\|}(f) |V_M| / X_C \]

In case of a strong network it can be assumed
\[ \vartheta(f) = 0; V_{\|}(f) = 0 \] (4)
since the current-dependent change in network voltage can be then disregarded.

When the network connection feedback becomes measurable the additional terms are applied via Q/f-droop [5] namely:

- $\vartheta(f)$ contribution of frequency controller to total angle of converter output voltage
- $V_{\|}(f)$ contribution of frequency controller to total magnitude of converter output voltage

The fundamental parts of the converter output voltage represented in the rotating frame are described below:

- $V_M$ contribution of measured voltage at network terminals of coupling reactor as feed forward to converter output voltage
- $V_\perp(P)$ contribution of active power controller to total magnitude of converter output voltage via orthogonal component
- $\vartheta(P)$ contribution of active power controller operating point to total angle
The relationship between all relevant constituents is visualized in Figure 3. The physical converter voltage is aligned with a static coordinate system using $\alpha$, $\beta$-components according to space-vector representation.

A rotating frame is used for the converter control as indicated by brownish d-, q-axes. The brown vectors illustrate the essential “strong” network relationship. The additional red vectors represent the feedback of “weak” network conditions in the converter output voltage to achieve control task.

### III. DEMONSTRATOR OF DR DC GRID ACCESS

In order to test the functionality of the new technology, a demonstrator model shown in Figure 4 has been developed in the PSCAD simulation program. The main electrical parameters of the synchronous AC power system and the DC line are presented in TABLE I and basic parameters of the wind power plant are summarized in TABLE II. The purpose of the Demonstrator is to investigate the connection and operation of an existing windfarm via the new technology. In a real-life implementation it is important to ensure that if any problems occur during the DC link testing and operation it can be possible to switch back to the AC link operation in order to transmit the WTG energy. Therefore the PSCAD model has been designed for two modes of operations:

- **DC mode** where the power produced by the wind farm is transmitted via the DC link
- **AC mode** where the DR and DC line is effectively bypassed.
IV. SIMULATION RESULTS

A. Demonstrator setup DC to AC transition test
This test case was performed following DC transmission operation mode was established and operated at nominal power reference. A set point change is initiated at 1sec and the DC
The power transmission system is rapidly ramped down to zero and then the DC transmission system is disconnected. After a short period in which the WT remains in island mode the AC cable is connected at 3.2 sec and the two systems get synchronized. The reference active power is then set to 1 p.u. at time instant of 4 sec and the total power reaches the nominal power following a ramp. The results shown in Figure 5 illustrate the flexibility of the WTG controller to perform under different operating modes. In addition to the points analyzed above, Fig. 5 shows that the WTG controller is able to maintain the frequency and the voltage of the WPP 33 kV bus when the DC transmission system is disconnected. WPP also successfully synchronizes with the weak AC network after the AC cable is reconnected that makes system ready for power export in AC mode.

![Figure 5: Transition from DC mode with nominal active power export to AC mode with nominal active power export](https://example.com/figure5.png)

**B. Dynamic simulation of Offshore Wind Park connected via HVDC DRU**

The most comprehensive simulations were performed in PSS Netomac featuring 200 km cables to shore, 201 independent WTG including detailed controllers models and onshore HVDC converter control. The simulation setup is depicted in Fig. 6.
As an example the Figure 7 shows the simulation of an energization sequence of one out of the 18 wind turbine strings with 12 WTGs.

Figure 7 shows the following sequence of events:
1. Energization of string cable
2. WTG transformer energized. WTGs provide reactive power
3. DRU unit energized and connected
4. First WTG starts power production
5. Energization of Filter, WTG ramp to 20% of rated power
6. WTGs ramped to full power
7. Umbilical Cable disconnected
8. Frequency operation point adjusted

In this simulation active power ramp-up is accelerated and umbilical cable disconnection is delayed to represent a worst case scenario for system stability. UK grid codes requires that the wind farm and the HVDC converter shall remain transiently stable and connected to the system without tripping for a close-up solid three-phase short
circuit fault or any unbalanced short circuit fault on the transmission system for a total fault clearance time of up to 140 ms. The wind farm and the HVDC converter shall be de-signed such that upon both clearance of the fault on the transmission system within 140ms and within 0.5 seconds after the restoration of the voltage at the Interface Point to within 90 % of nominal, the active power output shall be restored to at least 90% of the level available immediately before the fault. Figure 8 and 9 show the onshore FRT behaviour of the simulated system.

Figure 8. Offshore and onshore AC voltage during and after an onshore grid fault event

Figure 9. Power export during and after an onshore grid fault event

From figure 9 you can see, that active power post-fault recovery is achieved within 0.35s, which is well within the defined limit of 0.5s.

V. RELIABILITY OF LIQUID IMMERSED HVDC DIODE RECTIFIER UNITS

A. Requirements

The HVDC Diode Rectifier Unit requirements are driven by implementation of features to reduce weight, size and connected efforts for safe and reliable operation of the system to overall improve significantly economic efficiency of the HVDC Offshore Grid Access solution.

Main levers to support this are replacement of air insulated and water cooled rectifying technology with oil/ester to optimize insulation and cooling, implementation of ester liquids to optimize fire safety, environmental pollution and connected efforts inside of the offshore platform (e.g. safety, aux requirements), changed maintenance strategy towards no maintenance activities inside the tank during estimated life time and finally more easy transportation through encapsulation in a common tank.

Addressed main HVDC Diode Rectifier Unit requirements:
• Power conversion AC / DC, overall 24 pulse rectifying mode, offshore AC Grid \( U_{\text{in}} \) 36 kV or 72,5 kV, export cables 320 kV DC (or higher)
• Encapsulated unit comprising transformer active part, rectifier and smoothing reactors
• Safe and reliable operation up to 30 years w/o maintenance inside the tank
• Spare unit to fit into every place of the rectifier scheme
• Ester liquid insulation

B. State-of-the-art, novelties, challenges
State-of-the-art VSC and Classic HVDC converter industry and power transformer industry on global scale recently implements a lot of proven technological features into power transmission systems:
• Power transformers usually come along with mineral oil insulation/cooling systems up to voltage levels 1200 kV AC and 800 kV HVDC. In the field of HVDC even higher operating voltage levels up to 1100 kV HVDC are reported to be technically feasible
• Different kinds of natural or synthetic based ester liquids are utilized successfully over a long time period in distribution and power transformers. Also reference units up to voltage level 420 kV AC are installed.
• VSC and Classic HVDC technology is utilized up to +/- 800 kV HVDC and appr. 8000 MVA capacity. Very rare also mineral oil converter technology can be found, mainly installed up to 50 years ago.
• Also liquid immersed reactor technology is well developed and can be found in AC and HVDC transmission applications.

So the main novelties and challenges in successful development of a HVDC Diode-Rectifier Unit were:
• Application investigation of natural or synthetic based ester liquids for utilization in HVDC apparatus like power transformers, converter technology and reactor technology
• Material compatibility tests and release, mainly the interaction between the different liquids and the different materials and components implemented in the HVDC Diode-Rectifier Unit
• Development and application of reliability assessment methodology to verify and implement life time expectations either in utilized components or its arrangement in the HVDC Diode-Rectifier Unit
• Also liquid immersed reactor technology is well developed and can be found in AC and HVDC transmission applications
• Development and application of appropriate type and series tests to verify successful operation
• The product development itself including a series of simulation activities to verify several operating conditions and impact on consumed lifetime

C. Solution
Figure 10 illustrates the arrangement of a pair of two HVDC Diode-rectifier units in an offshore environment.
The AC sides of the HVDC Diode-Rectifier Units on the left are connected to the AC GIS, each of the units in parallel. Both of them are also consist of a 12 pulse diode rectifier. The primary windings are connected in Zig Zag vector group and are adjusted individually for Rectifier Unit 1 or 2. So the primary winding vector group connection ensures that the vector groups of the Y respective D windings of each rectifier unit show a phase shift of 15°
compared to the “sister” rectifier unit. Sides on the right are connected in series to feed the DC export cable.

Figure 10. Connection scheme HVDC Diode-Rectifier Units

Figure 11 illustrates the physical arrangement of a HVDC Diode-rectifier unit. The Diode Rectifier unit combines the active component of a transformer together with a 12-pulse diode rectifier and DC smoothing-reactors in a common tank filled with ester liquid. Cooling mode is KDAN, consequently a number of oil pumps is arranged to ensure proper ester liquid flow in all areas inside the tank. Compared to thyristors diodes do neither need protection against steep rise of current when fired and are not susceptible for failure events within the recovery time nor do they require for firing and monitoring electronics. The insulation liquid allows the reduction of the size of the complete unit and is also used for cooling of the diodes and their individual snubber RC circuits. That can be done with a single cooling system for both, transformer and rectifier. The electrical circuit of the diode rectifier itself consists of four simple components per diode-level: A snubber RC-circuit, a grading resistor and of course the diode with its heat sink itself. That decreased number of components and a number of redundant levels increase MTTF values significantly.

Figure 11. HVDC Diode-Rectifier Units

D. Results, reliability

The design of the high voltage diodes in disc housings guarantees reliable conduct on fail so that in the unlikely event of a level-malfunction uninterrupted operation is possible. By providing enough redundant diode-levels continuous operation can be achieved for up to 30
years without diode replacement and a minimum of maintenance. Regularly checks can be reduced from monitoring every single semiconductor to a simple pass/fail decision.

No offshore repair is foreseen for internal components. In case of need the whole unit is subject to replacement. As insulation liquid a ester is used. Due to its higher flash point and the fact that it is recognized as biodegradable, it is an appropriate choice for an environmentally sensitive maritime environment.

VI. CONCLUSION

The study successfully demonstrates the interoperability of the offshore wind turbines of type 4 with HVDC systems based on diode rectifiers (DR) and voltage source converters (VSC). The key performance requirement for a stable operation in AC and DC mode and a smooth transition between them is achieved by the advanced wind turbine grid side controller functions. In DC mode, the controller complies with the steady-state diode bridge characteristic and coupling characteristic of WTG (correlation of the key values active and reactive power, frequency, voltage magnitude). In AC mode the controller shows robust behaviour. The dynamic behaviour including successful FRT test of entire DRU based DC grid access solution were demonstrated by comprehensive simulations.

The integrated approach as shown in the HVDC Diode-rectifier unit simplifies the interconnection between transformer, rectifier and reactor. The assembly and interconnection is done in the factory. The integrated unit can be fully tested there providing highest quality and reliability.

All 6 units used are identical. The voltage withstand capability vs. ground is always designed for the full DC voltage of ±320kV, although not really needed for the middle units. By doing so only a single spare unit has to be kept ready for replacement purposes.

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BIBLIOGRAPHY