The wind power converter for tomorrow is already here.

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Abstract

ABB has developed a flexible medium voltage converter platform called PCS 6000 Wind. It is designed for wind turbines with conversion of the full generator power thus decoupling the generator side from the grid side through an intermediate DC link which gives an independent control of the grid side to enable compliance with existing and expected grid codes. The converter consists of two identical three-level inverter units equipped with IGCTs (Integrated Gate-Commutated Thyristors). The selected topology and power semiconductors allow for a power rating of 9 MVA without the need of series and/or parallel connection of power semiconductor devices keeping the part count to a minimum. The low part count exhibits a lower estimated failure rate compared with other solutions to reach this power level. The development in the IGCT technology will in the coming years allow a further increase in the converter power rating beyond 10 MVA without the need for changed converter footprint. Increased IGCT voltage ratings will also allow an increase in the operating voltage without changes in the basic topology of the converter. The platform is since end of 2009 in operation in off-shore wind turbines of type Areva Multibrid M5000 and further wind turbines equipped with PCS 6000 Wind will be put into operation in 2011.

Keywords: Drivetrain, Converter, IGCT, Reliability

1 Introduction

Four major trends in the wind power industry have a significant impact on the converter development of the electrical power train, which are the ever increasing wind turbine power ratings, wide frequency ranges from gearless multipole to high speed generators, much stricter grid codes for grid stabilization and much more demanding reliability needs for offshore installations. To be ready rather then to react to the changing needs, it is advantageous to select components and sub-systems now that can cope with new requirements without the need of major changes to the design and footprint of the electrical drivetrain of future wind turbines. Already now it is possible to standardize the design of a frequency converter that will cope with the demands of today and is prepared to meet the requirements of tomorrow. This paper describes such an ABB converter platform for wind energy applications and presents the recent developments on the power semiconductor devices that will enable even higher power outputs to be reached on the same proven technology platform.

2 The chosen topology and its features

The ABB converter platform, named PCS 6000 Wind [1], is a three-level NPC (Neutral Point Clamped) voltage source converter, see figure 1, designed for operation at medium voltage. The voltage levels are 3.3 kV and 4.16 kV. With the available power semiconductor components of today a power level up to 9 MVA without any paralleling of devices can be reached, meaning that at least already the next generation of wind turbines can be realized with the same converter platform available today. As shown later in this paper, power semiconductors under development will allow even higher power levels without any changes to the basic topology, thus the converter platform is prepared for the next-next generation as well.

The basic principle of the converter is that two identical inverters stages for AC to DC and DC to AC are used, coupled by the DC link capacitors. Filter elements reduce harmonics towards machine- and grid-side to an acceptable level. The key benefits of such converter are explained below.

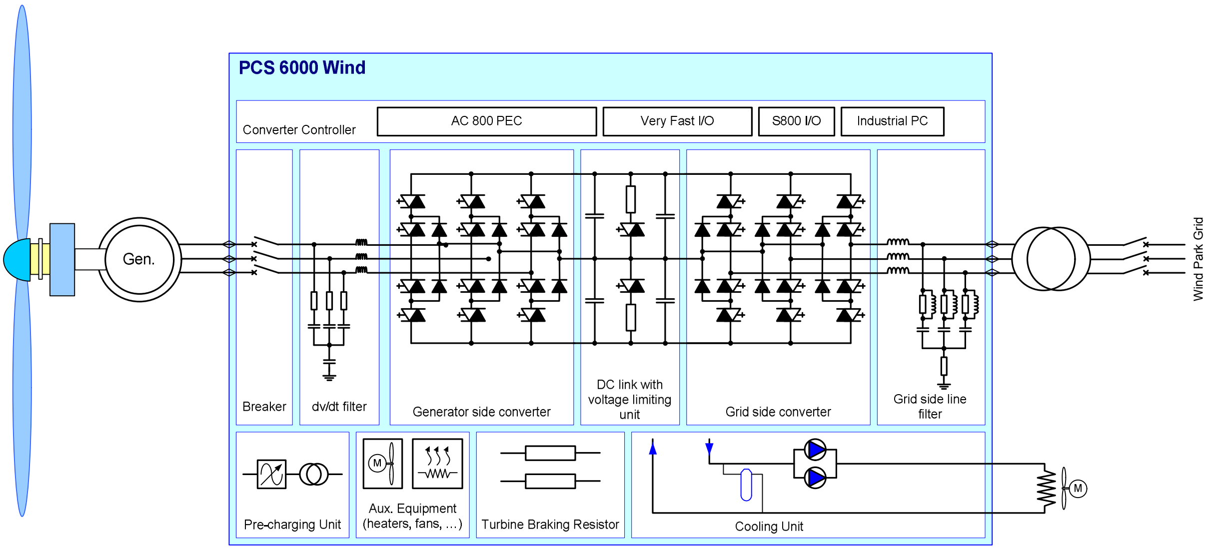


Figure 1: The modular concept of the PCS 6000 Wind.

The chosen three-level topology has an improved output voltage wave form compared to a two-level topology which reduces the needed output filter and simplifies strategies for harmonic mitigation elimination. Overall system improvement is furthermore possible by adapting the semiconductor switching frequency and the modulation strategy matching the machine- and grid-side criteria. Using a harmonic elimination algorithm in the converter control the harmonic content in the current is even further reduced without the need for bigger filter components to a total harmonic content well below the requirements in IEEE519 as can be seen in figure 2.

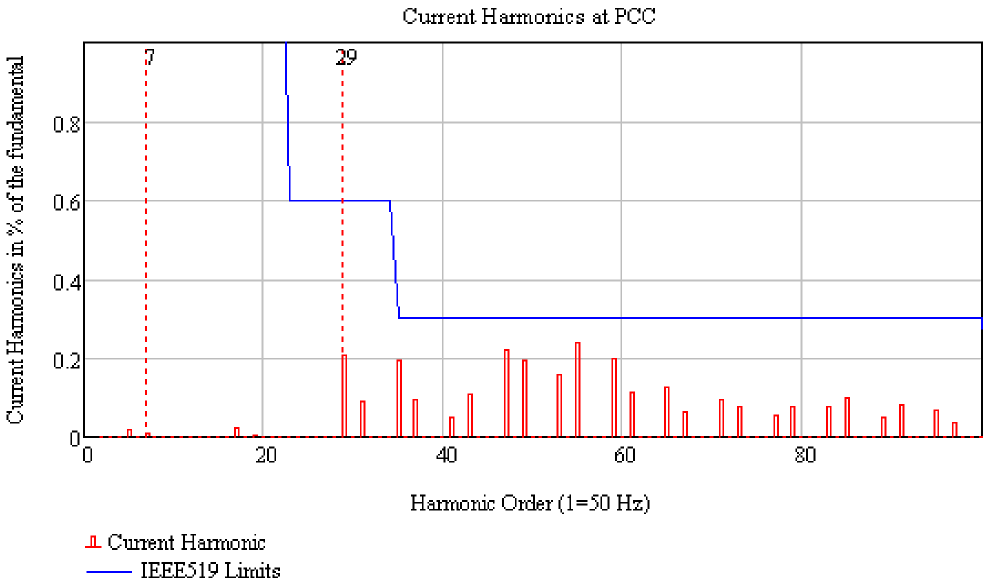


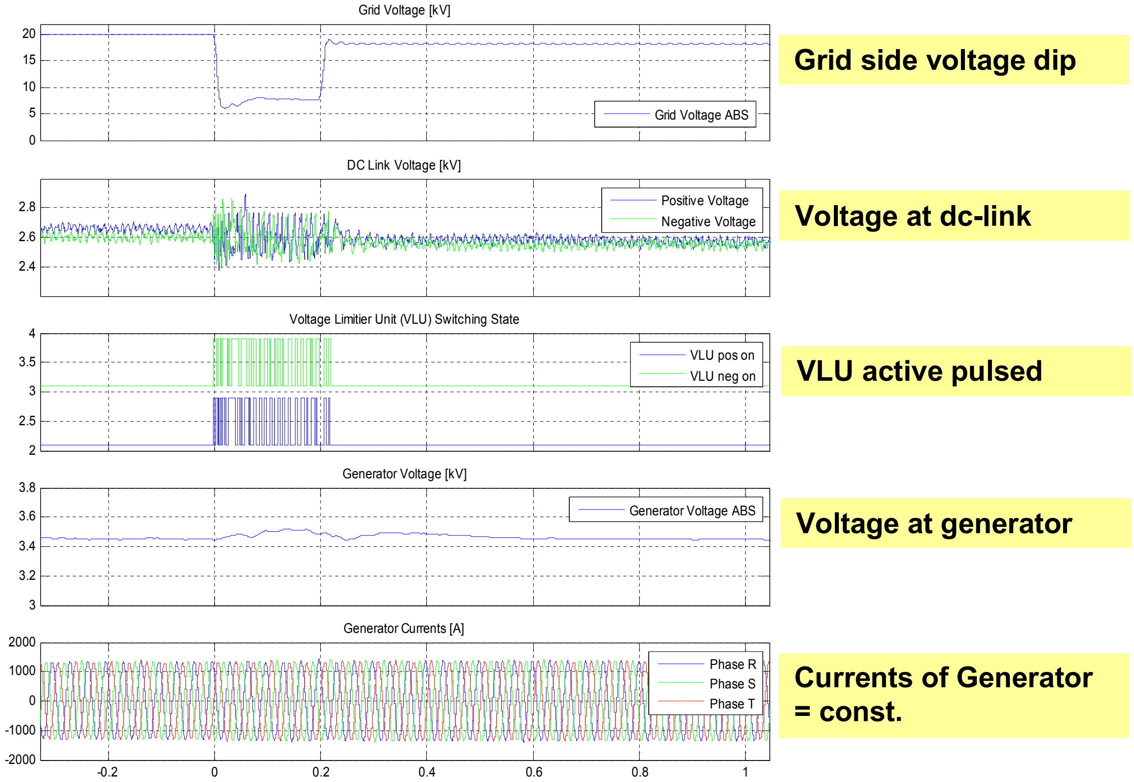
Figure 2: Content of current harmonics compared to the IEEE519 limits.

A different method of wave form and the harmonic content improvement could be achieved through the use of a multi-level topology [2] [3], but due to the increased complexity and part count, this solution has not been favored for use in the wind industry so far due to the high number of required devices for multilevel systems which is assumed to have a negative effect on the reliability as will be shown later.

Other reasons for choosing the presented topology are:

Through the use of a full converter the ability to control current and voltage independently the wind turbine can not only provide active power but can also be used to provide or consume reactive power - to or from the grid - which means that the transmission of the power can be optimized to the characteristics of the cables from the wind turbine to the central connection point in a wind farm.

A voltage source inverter decouples the generator from the grid and enables an optimized control of the power output to comply with grid codes without having a negative impact on the generator design and control functions. In figure 3 the behavior of the main voltages and currents in the electrical drivetrain are shown at a voltage dip on the grid of about 70 % during 0.2 s.



Grid side voltage dip

Voltage at dc-link

VLU active pulsed

Voltage at generator

Currents of Generator = const.

Figure 3: Recordings from a low voltage ride through test.

A medium voltage drivetrain can operate at high power levels without the need for extensive cabling thus simplifying the installation and offers lower copper losses than an equally rated low voltage power train. As a rule-of-thumb the required copper area and losses for an equal power rating, are reduced linearly to the voltage increase. By going from low to medium voltage a large reduction in required copper area and losses can be achieved. If we assume that 4 MW power with power factor 1.0 is transmitted at voltage levels 690 V and 3.3 kV we get for the 690 V case a phase current of 3350 A whereas the phase current at 3.3 kV is only 700 A. In turbine designs where this power has to be transmitted from the nacelle to the tower foot, a large bunch of cables are needed. For ease of calculation we assume that the maximum allowed current load on a copper cable is 2 A/mm^2. For the 690 V case we then need three phases each having a copper area of 1675 mm^2 whereas the 3.3 kV case only needs 350 mm^2 which is 4.8 times less. Considering that thicker and/or parallel cables normally can have a lower load per mm^2 then thinner ones, the real difference would in our case probably be well above a factor 5. If we consider a cable length of 120 m from the generator to the transformer the medium voltage solution saves about 4300 kg of copper.

3 Reliability estimations of the converter

When looking at the reliability of a wind turbine, the converter and the power semiconductor devices are often in focus and worth to have a closer look into it.

Reliability comparisons are notoriously unreliable since it is very difficult to compare components and systems at equal conditions and for equal performance. There is therefore always a risk of a certain bias in comparisons since certain factors are forgotten or wrongly estimated. So any comparison must be carefully checked to ensure that the data is appropriate for its intended use.

When comparing power semiconductor devices as IGCTs and IGBTs (Insulated Gate Bipolar Transistor) it must be considered that the IGCT has an integrated gate unit compared with high power IGBT-modules that work with a separate gate unit. On the other hand certain IGCTs need a separate free-wheel diode that most IGBT-modules have integrated within the same package. Consequently, to make a good comparison the IGCT with a free-wheel diode must be compared with an IGBT-module with its gate drive.

In the ideal world you have a lot of field data that you can base models on to predict the reliability of each sub-system, but although a number of studies have been made, the methodology and results from them are difficult to compare [4] [5]. They also often lack the depth of failure analysis that for instance a power semiconductor manufacturer would need to see what kind of failures did occur, for example at what frequency and under what conditions. As well power semiconductor devices might be the component that fails when as a root cause other parts of the system have a temporary or stationary malfunction. Until a standard reporting method is settled and a number of large manufacturers and operators are feeding a common data base with field data we have to live with the situation that it will be hard to calibrate any reliability calculation methods with field data. This will in turn lead to a situation where the reliability estimations will have a quite large uncertainty since the used methods will be based on experience in other applications fields without taking enough consideration to the peculiarities of the wind turbine, especially for offshore conditions. It must be stated though that it is not easy either to get reliable and useful field data from other applications as industrially drives and rolling stock in traction either so the models taken from there also have an uncertainty.

The reliability of a power semiconductor device is to a large degree determined during the design phase both of the device as well as of the equipment where it is used. Three of the major failure causes are quite well characterized and are considered in the converter design. It concerns the selection of the device voltage rating for a given output voltage [6] and the connected stray inductance to ensure that the over voltage peak during turn-off is within the device capability. Also the failure rates due to cosmic rays are documented and considered [7] [8]. Most crucial is the thermal design since both the maximum allowed junction temperature of the device must be considered as well as the thermal fatigue through load cycling that can lead to a low life time if not considered in the design [9]. Other failures result from field operation, mainly of transient character, and therefore the estimated field failure rate will be the sum of the probability of the different failure effects at the expected operation conditions.

Despite all the uncertainty spread over the earlier paragraph we have made an estimation of the reliability of a well-designed 8 MVA inverter unit according to the knowledge for the different power semiconductor devices that come into question for a wind turbine converter. The result is presented in table 1. For the comparison we have used the three-level inverter topology like PCS 6000 Wind and have compared it with a GTO as well as an IGBT solution using standard high power modules with baseplate 190*140 mm by ABB referred to as HiPak. The estimation is based on the experience that ABB as manufacturer of all three device types have, although as earlier stated, much of this experience is from other applications then wind turbines. In the calculation we have used the common reliability term FIT = Failure In Time where one FIT corresponds to one failure in 10^9 hours of operation. This term is only usable for the steady state failure rate excluding early failures, often referred to as infant mortality failures. To really consider the fatigue failures due to load cycling, a detailed knowledge about the load profiles is needed. Since we do not have so much data about the load profiles for wind turbines we have considered experience from applications as rolling stock for traction and large steel mill drives since they often have more severe load cycling stress.

Estimated long term reliability of an 8MVA, three-level inverter with water cooling

8 MVA Inverter Type	Switch	FW Diode	Gate Driver	N° of Parallel Devices	Equivalent NPC Diode per position	Equivalent Clamp per position	Inverter Total (12 positions)	FIT Ratio to IGCT
	FIT	FIT	FIT		FIT	FIT	FIT	
IGCT	100	20	200	1	10	50	4'560	1
GTO	100	20	200	1	10	200	6'360	1.4
IGBT	250		150	2	50	0	10'800	2.4

Table 1: Estimation of the reliability for the main converter components.

The difference between the IGCT and IGBT mainly comes from the power levels of available power semiconductors. To reach the same power levels as possible with IGCTs, the IGBT-modules needs to be parallel connected thus increasing the number of devices with a factor of two. For the same topology with the same number of devices the difference in expected long term reliability is within the accuracy of the estimation neglectable. With no need for parallel nor series connected semiconductors as required in some multilevel topologies the part count of an IGCT converter is very low. The converter power can increase by using bigger IGCT-modules, bigger reactors and capacitors, with the very positive effect that the overall number of converter components and its FIT rates remains at the same low level.

4 High power semiconductor technology

The IGCT, see figure 4, has since its introduction in 1997 established itself at several suppliers and converter brands as the device of choice for medium voltage industrial drives, but has also found its place in conversion of energy from renewable energy sources [10], [11]. Due to the integration with a low inductive gate unit this GTO-based device conducts like a thyristor and switches like a transistor. This means that it can, as an IGBT, operate without a snubber and making the circuitry very simple. The IGCT is available with turn-off current ratings between 520 and 5000 A and with blocking voltage capabilities of 4500, 5500 and 6500 V, all as asymmetric and reverse conducting devices where the latter has a free-wheel diode already integrated on the silicon wafer. The presspack design of the IGCT, where the wafer is pressed between Molybdenum plates, has an advantage in load cycling compared with devices with internal bonding and soldering, which also has an impact of the overall reliability of the converter. The field experience we have gathered shows due to its presspack design that the IGCT at a device failure fairly quietly goes into a short circuit without causing much harm to the environment which cannot always be said for failing bonded IGBT-modules.

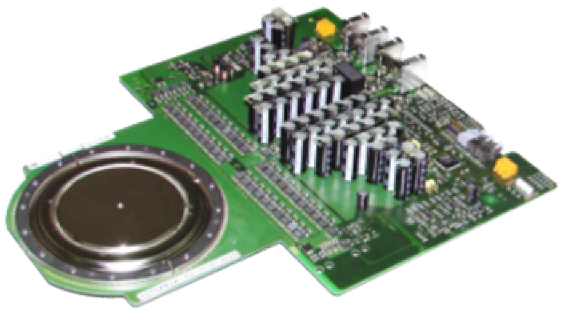


Figure 4: An IGCT rated 4000 A, 4500 V used in PCS 6000 Wind.

A concern when comparing ICGT with IGBT is the reliability of the fairly large looking IGCT gate unit. Actually the circuit is simple but in need for a certain amount of capacitor energy to clear the gate. Especially the electrolytic capacitors on the IGCT gate unit has been designed for reliability with considerations taken towards ageing and has been selected carefully. Our experience shows that the gate unit reliability is well within an acceptable range. How competitive this reliability is towards the IGBT gate units is though quite difficult to say due to the absence of published field data for gate units for devices in a power range close to the IGCT.

Development programs are on-going to improve the performance of the IGCT to enable higher voltages for the common three-level topology as well as to increase the power rating of existing voltage ratings. Through the newly released HPT-IGCT a 30 % increase of the turn-off current without any mechanical changes to the power semiconductor housing has been made possible. Developments are on-going to further improve these new devices in terms of lowered losses and the possibility to allow a higher junction temperature is also investigated. Both these activities aim towards an increased output power of the converter still without having to make any other changes to the converter design. The verification and qualification of these improvements are still outstanding but the first results give confidence that the rating of the converter design can be increased above 10 MVA with these new components not touching the converter footprint.

For future converters rated 6 kV using the basic three-level topology and also without any series connection a further IGCT is being developed. It uses the same platform as the HPT-IGCT and will only differ in the height of the ceramic needed to be higher than for the 4500 V version due to creepage and clearance distances. The full qualification is not done completely and therefore the final ratings have not been determined yet. The available turn-off switching results show a robust device that can handle turn-off power peaks above 20 MW, see figure 5.

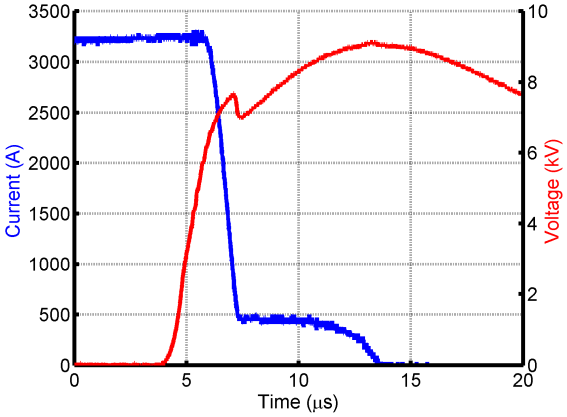


Figure 5: Turn-off waveform for a 91 mm 10 kV HPT IGCT at V_{DC} = 6 kV, I_T = 3.2 kA resulting in a peak power of 20.7 MW.

The development of the switching element is of little avail if there are no accompanying diodes that enable the utilization of the increased switch performance in the converter. Therefore the improvements in the IGCT technology need a similar improvement in the diode technology. This has in recent years sometimes proven to be a more difficult task then increasing the capability of the switching element itself. Since a number of requirements, whose standard solution would require contradicting silicon design requirements, are set on the performance on the diode, as low losses and soft switching without snappiness. New possibilities to solve some of these issues without compromising other features have recently been developed [12] and they are being implemented in the new designs. This development is well done in connection to the development of the IGCT switch to ensure that they operate well together. For the earlier mentioned 10 kV IGCT a corresponding 10 kV FRD (Fast Recovery Diode) for dual use as Free-wheel Diode as well as NPC-Diode (Neutral Point Clamped) in the three-level connection is developed. A typical switching waveform for this diode is seen in figure 6.

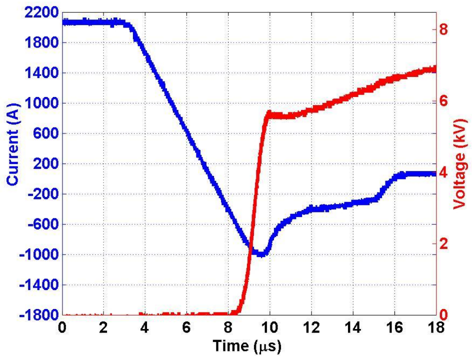


Figure 6: Soft reverse recovery waveforms for 91 mm FCE 10 kV diode in nominal conditions: V_{DC} = 5.5kV, di/dt = 500A/μs, T_j = 125°C.

5 Field experience

The PCS 6000 Wind has been designed to match the demanding needs for large-scale wind turbines and has already shown its capability as a key component of Areva's Multibrid M5000 5MW offshore wind turbine, see figure 7. Along with the M5000 prototype turbines PCS 6000 has been extensively and successfully tested, as well the e.on grid code compliance was approved in a dedicated test setup. Since 3Q2009 all M5000 wind turbine in the offshore test field Alpha-Ventus equipped with ABB's PCS 6000 Wind have been commissioned and are successfully in operation. Several further PCS 6000 converters are on its way to different wind turbine manufactures into their new large-scale turbine designs and will be commissioned in 2011.

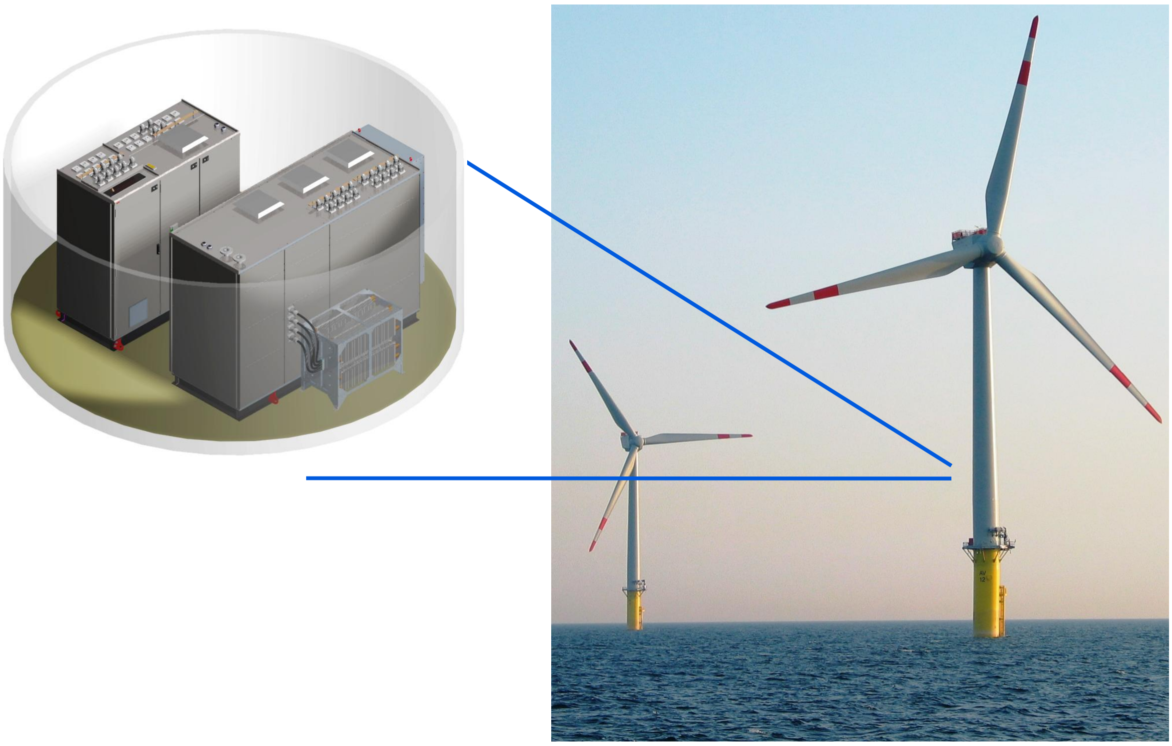


Figure 7: PCS 6000 Wind tower installation at Alpha-Ventus.

References

[1] T Kärnä, S Ebner; Challenges and solutions for the electrical drive train of large offshore wind turbines. Choosing the right technology and supply-chain partner. Husum WindEnergy, Husum, Germany 2010

[2] A. Lesnicar and R. Marquardt, An innovative modular multilevel converter topology suitable for a wide power range, IEEE 2003 PowerTech Conference, Bologna, Italy, 2003.

[3] T. Meynard; Review of the ECPE Workshop on advanced multilevel converter system, Västerås, Sweden, 2010, reported in Bodospower issue November 2010.

[4] S.Faulstich, P-Lyding, B. Hanh, K. Rafik; Optimising maintenance data management to boost turbine efficiency, DEWEK, Bremen, Germany, 2010

[5] M.Lange, M.Wilkinson; Wind turbine reliability analysis, DEWEK, Bremen, Germany, 2010

[6] 5SYA2051 Voltage dimensioning of high power semiconductors, ABB application note

[7] 5SYA2042 Failure rates on HiPak modules due to cosmic rays, ABB application note

[8] 5SYA2046 Cosmic ray on IGCT, ABB application note

[9] 5SYA2043 Load cycling capability of HiPak modules, ABB application note

[10] B. Backlund, M Rahimo, S Klaka ,John Siefken; Topologies, voltage ratings and state of the art high power semiconductor devices for medium voltage wind energy conversion, PEMWA, Lincoln Nebraska, the US, 2009

[11] B. Backlund, M Rahimo; Comparison of High Power Semiconductor Technologies for Renewable Energy Sources, PCIM, Nürnberg, Germany, 2010

[12] A. Kopta, M Rahimo; The Field Charge Extraction (FCE) Diode. A novel technology for soft recovery high voltage diodes, ISPSD, Santa Barbara, the US, 2005