TRANSFORMATIONAL TRENDS

HVDC technology for offshore wind is maturing

Offshore wind is the fastest-growing renewable-power segment. The connection of wind farms that are far from the shore of national grids requires high-voltage direct current (HVDC) technology, with which ABB has long experience. What challenges have been overcome in the last decade in this maturing area?

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With an average annual growth rate of 13 percent over the last five years and total installed capacity reaching 540 GW in 2017, wind power has seen rapid development →1-2. Offshore wind power, although still contributing only 3.5 percent of total installed wind power, is expanding at an even higher rate: 28 percent →3. Offshore wind power is concentrated in the North Sea but is spreading to North America, East Asia, India and elsewhere.

As well as growing in terms of rated power, offshore wind power plants are also being located farther from coasts and grid entry points.

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AC versus DC for offshore connection

When choosing between AC or DC for connecting offshore wind farms to the grid, the main parameters to be considered are rated power, distance to shore and the distance on shore to the nearest strong grid connection point, which can be up to 100 km away as landfall is often located in lightly populated areas where the transmission grid is weak.

A major advantage of AC is the low station cost. However, in AC transmission, losses rise with the voltage, the capacitance and the cable length. Beyond the so-called critical length (100 to 150 km depending on cable type) there will be no capacity left for active power transmission. The classical way to increase the transmission capacity is to increase the voltage level, but because reactive power increases with the square of the voltage, the voltage increase reduces the critical length.

A DC connection has the advantage of lower cable costs. And because the cables are only charged when energized, and the complete current-carrying capability can be used for power transmission, cable losses above a certain distance are lower than with the AC equivalent. These factors compensate for higher DC converter costs.

Further, HVDC cables with XLPE insulation are lighter than other cables, making their installation offshore easier and cheaper. Their lower weight per unit length allows the transport of longer sections, which translates into fewer cable joints, reduced installation time and lower risk of failure.

The DC alternative, therefore, becomes competitive - both from an investment and operational cost perspective - with increasing power rating and transmission distance.

HVDC offshore today

Currently, 40 of the over 90 offshore wind farms in Europe have a nameplate capacity (intended full-load sustained output) higher than 200 MW and roughly one-third of these are connected to the grid by HVDC transmission, individually or in groups. So far, there are seven HVDC offshore wind connection systems in operation and another three under construction. They are all located in the area of the North Sea known as the German Bight and are operated by the transmission system operator TenneT Offshore. With further projects proposed around the globe, the short- to mid-term outlook for offshore wind HVDC connection is bright.

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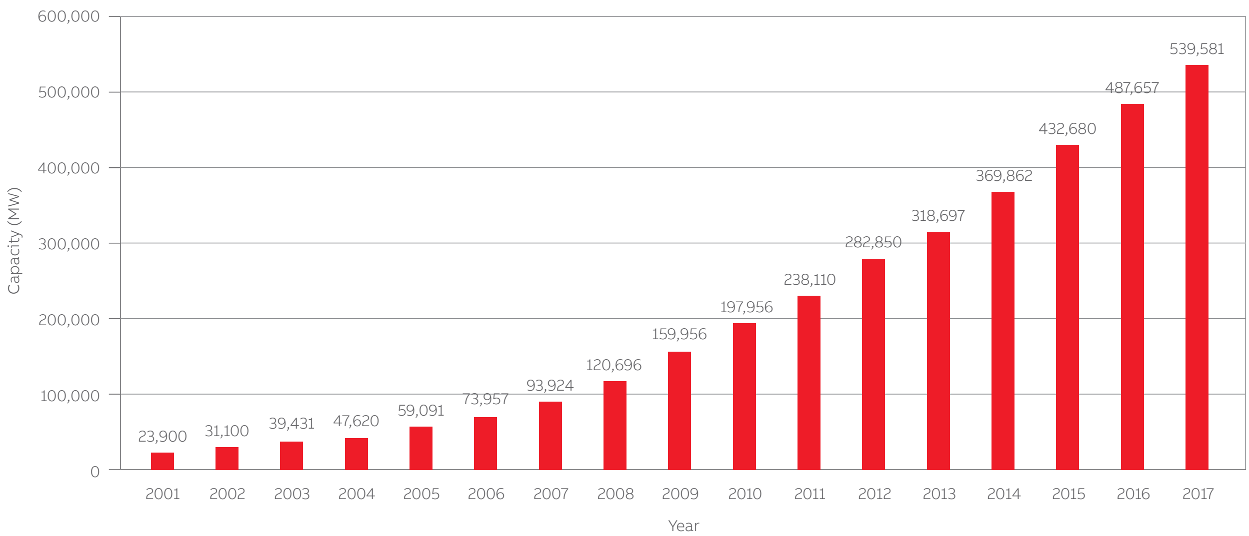
01 Offshore wind power generation grew by nearly 30 percent in 2017.



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Possible configurations for HVDC connection
The most straightforward HVDC offshore wind farm configuration is a point-to-point connection of an offshore converter, installed on a platform, and an onshore converter →4a. So far, all offshore wind HVDC connections in operation are of this type.

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An offshore "hub" located on a platform is connected via "spokes" to several onshore grids in the same or different synchronous areas.

A concept of increasing interest is the hybrid system, ie, a combination of subsea interconnectors between offshore grids and connection of these to shore →4b-4d. Such concepts have been recently proposed for the North Sea and are referred to as "hub-and-spoke" arrangements: An offshore "hub" located on a platform, or even on an artificial island, is connected via "spokes" to several onshore grids in the same or different synchronous areas. This concept can be utilized both for AC connections and DC connection to shore, although the distances to shore in the North Sea are prohibitive for the AC option. For the DC option, the hub may either be interconnected with multiple, parallel point-to-point HVDC links or with a multiterminal HVDC system.

Advantage of hub-and-spoke
Interconnection with other grids greatly increases link utilization as the link utilization of a single-purpose offshore wind connection depends solely on the intermittent character of the local wind.

Further, if an internationally coordinated approach to the installation of the transmission infrastructure can be adopted, costs can be reduced. Additional benefits may accrue from the facilitation of energy exchange between international markets.

Finally, the hub-and-spoke concept enables stepwise expansion, with transmission capacity added in stages, thus allowing higher energy availability sooner. The stepwise approach also means changes can be carried out and new technology incorporated as the wind farm develops, and investment can be made incrementally.

The first project of this kind is currently under construction in the Baltic Sea. In the Kriegers Flak Combined Grid Solution project, an AC interconnector has been established between Denmark and Germany via the offshore wind farms Kriegers Flak A and B, and Baltic 1 and 2. To provide frequency decoupling between the Nordic and continental Europe synchronous areas, ABB is supplying a back-to-back HVDC converter at the landing point in Germany (Bentwisch) and a master controller that best utilizes the hybrid interconnector assets. Operational experience from this project is expected to play an important role in the further deployment of the hub-and-spoke concept.

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02 Global cumulative installed wind capacity 2001 to 2017.

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03 Installed offshore wind capacity worldwide.

03a Cumulative offshore wind capacity by country 2016 versus 2017.

03b Annual cumulative capacity 2011 to 2017.

ABB HVDC offshore wind connections
ABB has successfully delivered three HVDC links for offshore wind connection →5-7. These projects would not have been possible without significant development steps in platform design by ABB's partners and in HVDC technology by ABB.

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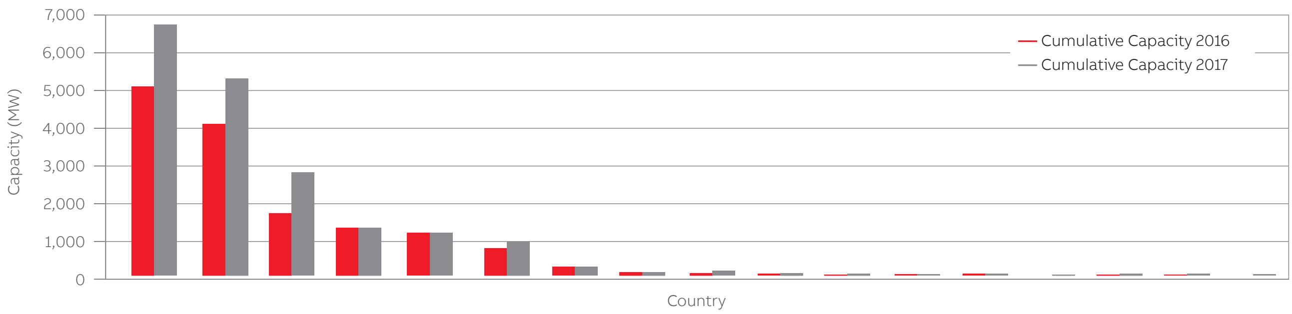
The compact design of the HVDC Light equipment allows for cost-effective implementation on an offshore platform.

Voltage source converter technology, first launched by ABB as HVDC Light®, has been the key enabler for offshore HVDC links. By controlling voltage and frequency in the islanded offshore AC grid, the offshore converter station automatically transmits as much active power as wind farms produce to the onshore AC grid while maintaining a stable AC voltage and frequency in the offshore AC grid. At the same time, the compact design of the HVDC Light equipment allows for cost-effective implementation on an offshore platform.

Pioneering HVDC work for offshore wind connection
Compared to other HVDC scenarios, offshore implementation presents some unique design requirements. Some of the main challenges arise from environmental conditions offshore, the lack of widely used standards for offshore HVDC systems and components, accessibility and marine operation limitations, and challenging interface management. At the same time, the system behavior of an islanded offshore AC grid differs significantly from typical transmission grids.



	UK	Germany	PR China	Denmark	Netherlands	Belgium	Sweden	Vietnam	Finland	Japan	S Korea	US	Ireland	Taiwan	Spain	Norway	France	Total
Total 2016	5,156	4,108	1,627	1,271	1,118	712	202	99	32	60	35	30	25	0	5	2	0	**14,483**
New 2017	1,680	1,247	1,161	0	0	165	0	0	60	5	3	0	0	8	0	0	2	**4,331**
Total 2017	6,836	5,355	2,788	1,271	1,118	877	202	99	92	65	38	30	25	8	5	2	2	**18,814**

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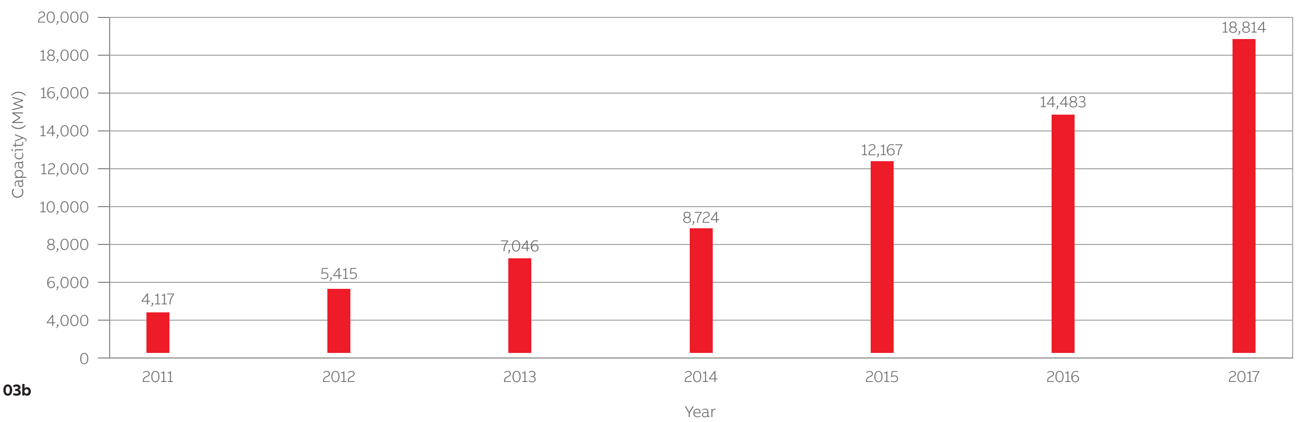

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Environmental conditions offshore
Offshore HVDC transmission systems will typically face harsh environmental conditions such as mechanical loading from vibration, temperature extremes, excessive humidity and salt pollution. Also, weather and sea conditions, and marine handling impact equipment storage and transportation. However, experience shows that, with careful design, these challenges can be overcome.

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ABB has developed and successfully implemented innovative concepts for the control of islanded offshore grids during normal conditions and disturbances.

Platform design and design codes
The first two platforms built for offshore wind HVDC converter stations were based on a conventional topside jacket solution. For the DolWin2 project, ABB developed, in close cooperation with a Norwegian yard, a flexible, highly innovative, robust and scalable platform for greater production efficiency and ease of installation (no heavy-lift vessels or jack-up operations are required) →7-8.

This platform is based on a combination of semisubmersible and gravity-based designs – ie, it acts as a semisubmersible platform during transport and installation, after which it is ballasted to sit solidly on the seabed.

The offshore industry has strict requirements and designs must be approved by a certifying authority. A strong partnership with a knowledgeable platform designer is crucial in this respect to ensure short project lead times and reduce risk.

Modes of operation
ABB has developed and successfully implemented innovative concepts for the control of islanded offshore grids during normal conditions and disturbances. One such innovation is the installation of a large, electronically controlled brake resistor (chopper) to enhance the stability of the offshore grid in case of disturbances in the onshore grid.

Lessons learned from early offshore wind connections motivated TenneT to adjust the offshore grid connection codes. The flexible, modular control software design used by ABB for HVDC and ABB's FACTS (Flexible Alternating Current Transmission Systems) allowed for the easy implementation of the new grid codes in already operational links.

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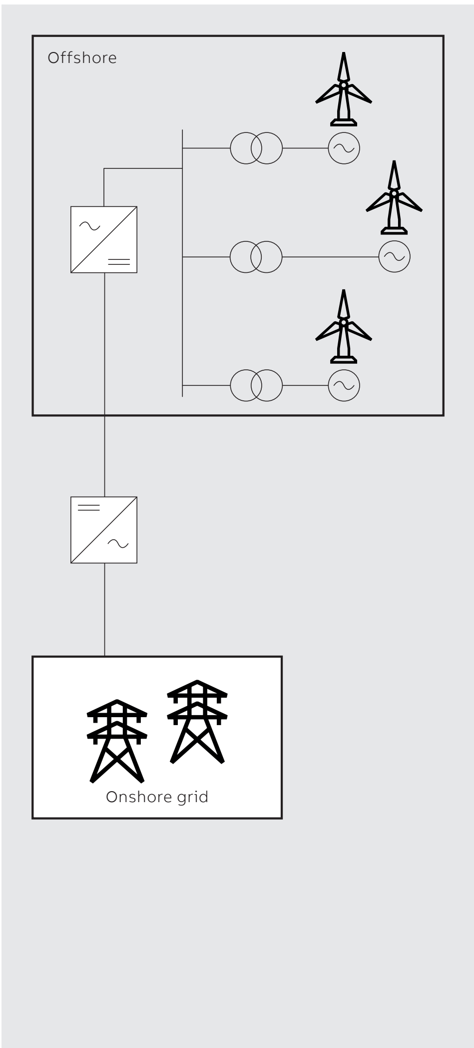

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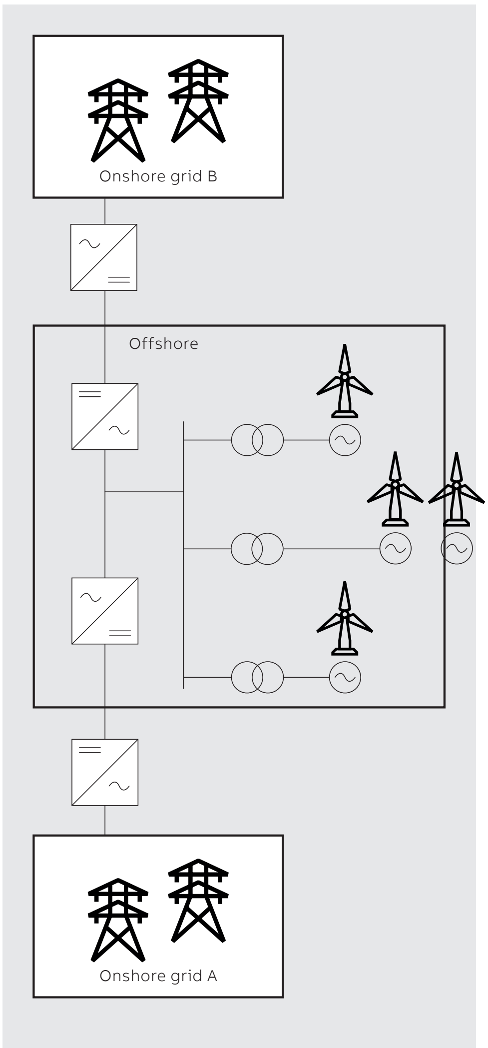

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04 HVDC connection schemes for offshore wind.

04a Point-to-point connection.

04b Hub-and-spoke with multiple HVDC links.

04c Hub-and-spoke with multi-terminal HVDC system.

04d Hub-and-spoke with AC links and HVDC back-to-back station as is implemented in, for example, the Kriegers Flak Combined Grid Solution project.

Special features of offshore AC grids
Unlike typical transmission grids with transmission lines, loads and large generating units based on synchronous machines, an offshore AC grid comprises nonsynchronous generating units, submarine cables as well as many transformers in the step-up AC substations

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The flexible, modular control software design used for HVDC and FACTS allowed for the easy implementation of the new grid codes in already operational links.

and the wind turbine generators (WTGs) that are close to each other. Due to the lack of synchronous machines, an offshore AC system has low, or even no, inertia. A large frequency and phase-angle excursion can take place in such a system in the case of load rejection caused by an 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. For faults in the onshore grid, the DC chopper mentioned above acts as a firewall, absorbing the excess energy from the wind farms that cannot be transmitted to the onshore grid and, thus, preventing the disturbance in the onshore grid from entering the offshore grid. Together with the frequency and voltage control in the offshore HVDC converter, the chopper guarantees the stability of the offshore grid. For faults in the offshore grid, proper control design for the HVDC and WTGs is required. Further, resonances created 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 little, or no, wind generation.

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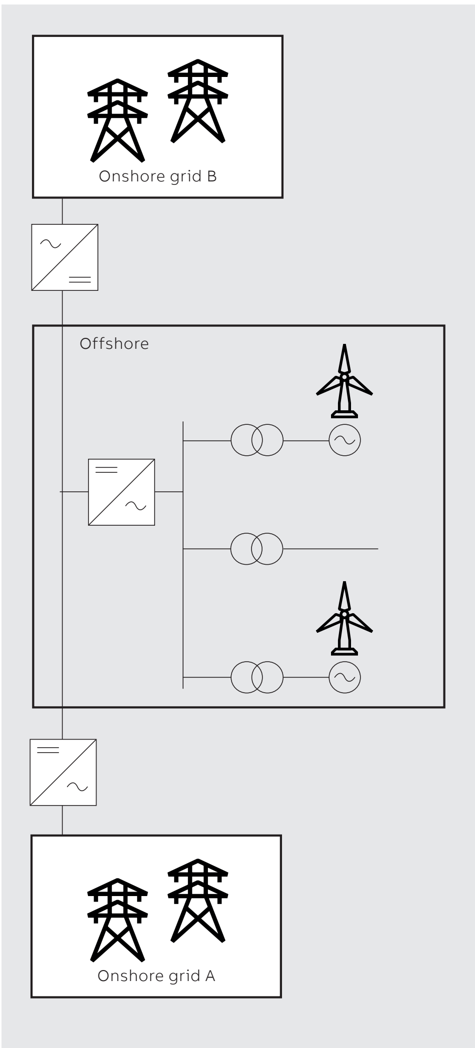

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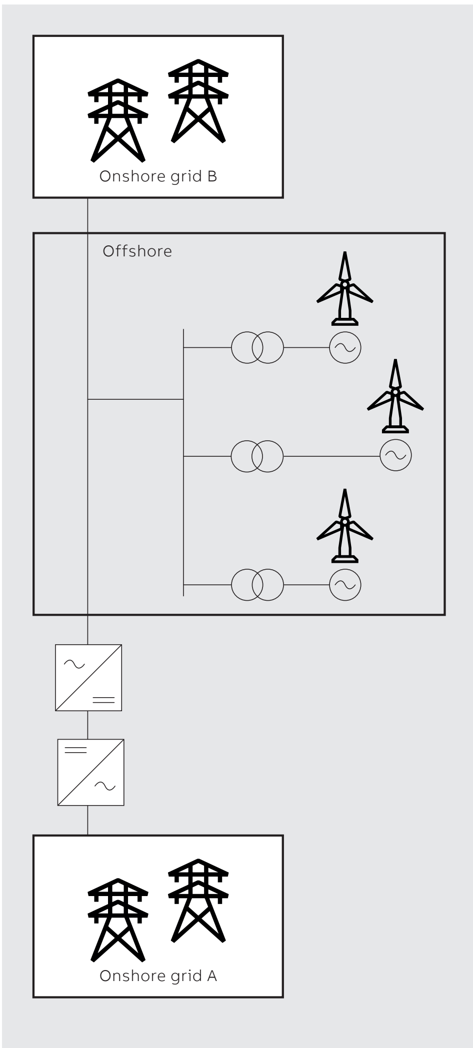

	BorWin1	DolWin1	DolWin2
Customer (location)	TenneT (Germany)	TenneT (Germany)	TenneT (Germany)
Operating since	2009	2013	2014
Power rating (MW)	400	800	916
AC voltage (offshore) (kV)	155	155	155
DC voltage (kV)	±150	±320	±320
AC voltage (onshore) (kV)	380	380	380
Land cable length (km)	2 x 75	2 x 90	2 x 90
Sea cable length (km)	2 x 125	2 x 75	2 x 45
Platform supplier	Heerema Fabrication Group	Heerema Fabrication Group	Aibel AS
Platform design	Jacket topside	Jacket topside	Gravity-based
Connected offshore wind farms	Bard Offshore 1	Borkum West II MEG Offshore 1 Borkum Riffgrund 1	Merkur Offshore Trianel Borkum Borkum Riffgrund 1

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Also, due to the close electric proximity of transformers, sympathetic interaction during transformer energization at the start-up of an offshore wind farm can be expected, causing temporary harmonic overvoltages, increased stress on transformer windings and potential malfunction of transformer differential and overcurrent protection. Start-up of an offshore AC grid is by no means a trivial task. Possible measures to avoid exciting resonances or sympathetic interaction of transformers include controlled switching (point-on-wave switching), enhanced harmonic filtering with the offshore HVDC converter or installation of harmonic filters. Together with TenneT, ABB has developed solutions to tackle such instabilities.

The DC chopper absorbs excess energy to prevent onshore grid disturbances from entering the offshore grid.

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05 HVDC systems for offshore wind connection delivered by ABB.

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06 The DolWin2 platform en route to its installation site.

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07 DolWin2 Beta HVDC platform.

The value of standardization

Over the last decade, the industry has collected valuable experience in the design and operation of offshore HVDC wind connections. Lessons learned and best practices are collected in industry recommendations and grid codes. Standardization of system design is a powerful way to exploit best practices and enhance harmonization between vendors.

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A robust design that is proven in practice and openness toward technical innovations are important factors in further reducing the cost of offshore wind generation.

Nevertheless, standardization should not hinder technical innovations, such as the currently discussed concept of direct connection of wind turbines to the HVDC offshore converter without intermediate step-up AC substations on separate platforms.

Maintaining the right balance between keeping a robust design proven in practice and opening up for technical innovations with potential advantages is important in order to further reduce the cost of offshore wind generation.

Market tailwinds

The offshore wind industry has expanded rapidly over the last decade and will continue to grow, supported by economy of scale throughout a supply chain devoted to the supply of generating units with ever-higher rated powers and wind farms with ever-higher nominal powers. This development will create further demand for HVDC connections. Technology maturity, together with increasing positive experience from already-operating systems, helps to lower risk and secure timely and efficient implementation of grid connections. At the same time, ABB, with its long-term commitment to offshore wind connections, will continue to introduce innovations in HVDC technology in order to enable stronger, greener and smarter offshore grids. ●

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