Enabling the power of wind

HVDC Light® for large-scale offshore wind integration

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Wind power is one of the most important renewable energy sources today. At the end of 2007, a total of 94 GW of wind power had been installed globally, of which only 1 GW was attributed to offshore installations. However, an increase of more than 1 GW per year is anticipated over the next five years, with a majority of that coming from about 100 planned offshore wind farms in Europe. Because many of these offshore power plants will be located quite a distance from the coast in an extremely hostile environment, their design, construction and operation requires specialized skills.

With over 20 years experience in the wind power industry, ABB has acquired a thorough understanding of both wind turbine applications and power systems. With this knowledge, it has developed a detailed design concept to connect the world's largest and most remote offshore wind farm to the German grid using, for the first time in such an application, its innovative and environmentally friendly HVDC Light® transmission technology.

By the end of 2007, Europe had more than 56 GW of installed wind power capacity out of a global cumulative total of 94 GW 2. In recent years, however, the US and China have become the largest markets for installed wind power: in 2006, the US alone installed around 2.5 GW, while in 2007 this figure increased to more than 5 GW. From having very little or no wind power, China became the second largest market in 2007, with more than 3 GW. According to some forecasts [1], the installed capacity in the US and Asia in 2012 will be three times that of today 3. In Europe, the amount of installed power will still more than double by 2012, in part because older wind turbines will be replaced with larger and more efficient ones.

With an accumulated total of slightly more than one GW at the end of 2007 – most of which is exclusively concentrated in a few European countries 1 – the offshore market is definitely a minor part of the overall wind market. An increase of more than one GW per year over the next 5 years has been predicted. However, the market is expected to really take off in 2011/2012 due to the anticipated development of large wind farms off the northern coast of Germany.

Offshore and land-based installations

In general, an offshore installation requires more new electrical infrastructure per MW than a land-based wind park. In addition, the electrical system design and installation are much more challenging because of the harsh environment and high availability requirements, as repair and replacement are generally quite expensive and weather-dependent.

> High cable capacitance makes AC transmission less actractive than DC transmission over long distances.

The turbines used in offshore installations are normally larger than those on land, and they need to be separated by distances that often exceed 500 meters. An underwater medium-voltage cable grid (often 24 or 36 kV AC) connects the turbines to each other and collects the power, which is then transmitted to a suitable connection point in the transmission grid on land. Depending on the size of the park and its distance from the shore, this connection can be made at a medium- or high-voltage level (eg, 130 kV AC). However, AC transmission is not suitable for the transmission of power from large parks located a significant distance from the shore because of high cable capacitance. In other words, the entire transmission capacity of the connection would be needed just to charge the cable itself, making the transport of any power impossible. A high-voltage direct current (HVDC) solution overcomes this problem, and for large wind parks located somewhere between 50 and 100 km from the transmission grid, ABB's HVDC Light system is more than up to the task.

HVDC Light generalities

HVDC Light is based on voltage source converter (VSC) technology, in which power transistors connected in series allow VSCs to connect to networks at voltage levels that were previously beyond reach. This setup can be used for power transmission, reactive power compensation and for harmonic/flicker compensation.

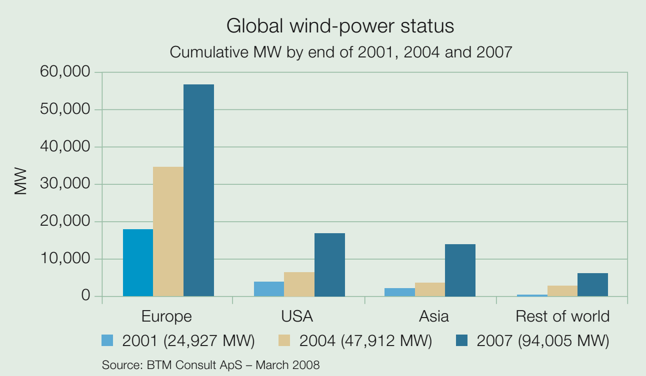
An HVDC Light station comprises the converter, AC and DC switchyards, fil-

1 Installed offshore wind power in the world (2006 and 2007) [1]

Country	Installed MW 2006	Accu. MW 2006	Installed MW 2007	Accu. MW 2007
Denmark	0	397.9	0	397.9
Ireland	0	25	0	25
The Netherlands	108	126.8	0	126.8
Sweden	0	23.3	110	133.3
UK	90	304	90	394
Total capacity – world	198	877	200	1077

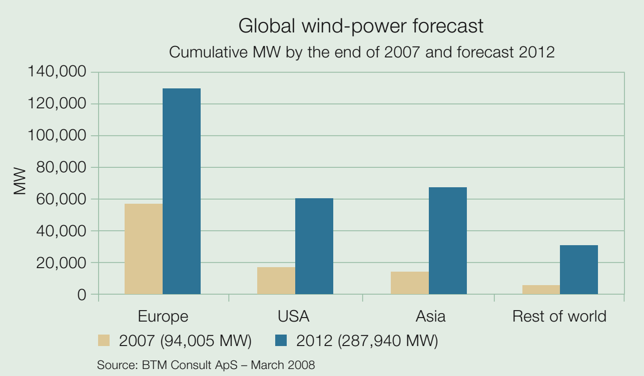
Source: BTM Consult ApS – March 2008

2 Total installed wind-power capacity at the end of 2001, 2004 and 2007 [1]



Source: BTM Consult ApS – March 2008

3 Cumulative installed capacity by region at the end of 2007 and by 2012 [1]



Source: BTM Consult ApS – March 2008

ters and a cooling system 4 5. ABB's HVDC Light converter design is based on a two-level bridge, grounded via a midpoint capacitor, which ensures both steady-state and dynamic operation with extremely low levels of induced ground currents. This feature is very important if an HVDC system is to be implemented in an offshore environment. There is no need for any cathode protection in conjunction with the installation.

In VSC-based HVDC, pulse width modulation (PWM) is used to generate the fundamental voltage 6. With it, the magnitude and phase of the voltage can be freely and almost instantaneously controlled within the system design limits. This allows independent and fast control of the active and reactive power while imposing low harmonic levels, even in weak grids. Normally, each station controls its reactive power contribution – both inductive and capacitive – independently of the other station. The active power can continuously and almost instantaneously be controlled from "full power export" to "full power import". However, the active power flow through the HVDC system must be balanced.[1)] The DC voltage will rapidly increase or decrease if a difference between input and output power exists. Power balance is attained not through telecommunications but by simply using DC voltage measurements: one station is used to control the DC voltage, by adjusting its power, while the other arbitrarily adjusts the transmitted power within the power capability limit of the HVDC Light design.

From a system point of view, the VSC acts as a zero-inertia motor or generator that can control active and reactive power almost instantaneously. Furthermore, it does not contribute to the short-circuit power as the AC current can be controlled.

Offshore wind integration

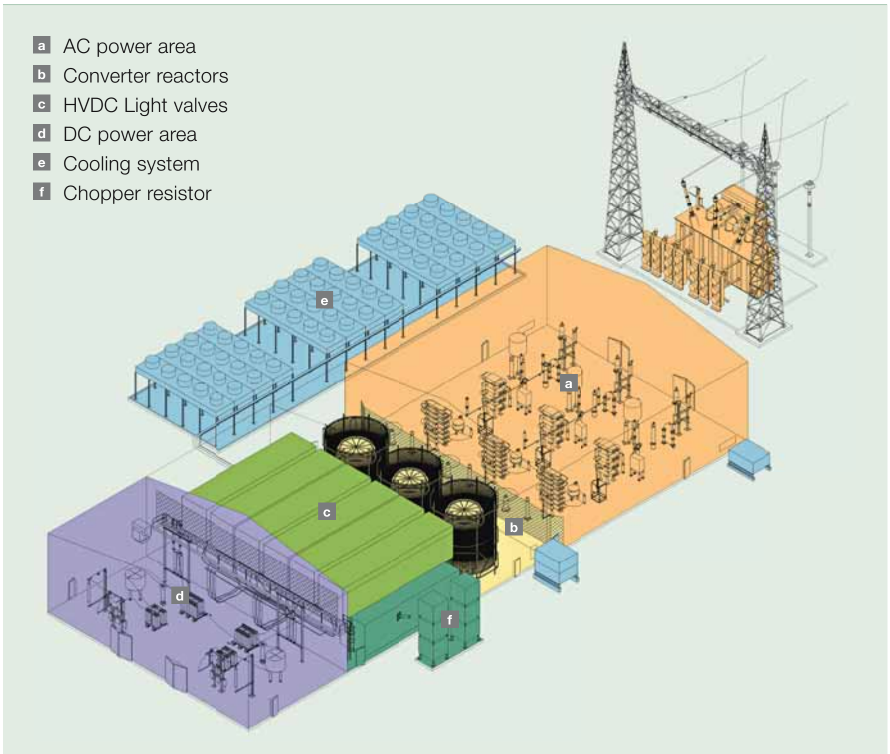
An HVDC Light VSC station can generate a voltage whose amplitude and phase can be controlled as desired. This feature is especially useful when it comes to starting an offshore network. The offshore station VSC can be used initially as a generator in frequency control mode. It then creates an AC voltage with the desired amplitude and frequency, which is ramped up smoothly to prevent transient overvoltages and inrush currents. The wind turbine generators (WTGs) are automatically connected to the offshore network after detecting the correct AC voltage for a given time.

Independent fast control of the active and reactive power using ABB's HVDC Light system.

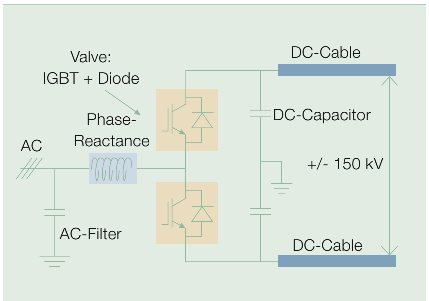
This functionality cannot be realized with classical thyristor-based HVDC transmission, as it requires a strong line voltage for the thyristors to commutate against. To overcome this, the transmission system must be complemented with an auxiliary generator, a synchronous compensator or a static synchronous compensator (STATCOM) at the wind farm. Besides being bulky, these components are also expensive.

Similarly, an HVDC Light connection can be used for network restoration after a blackout has occurred. When a blackout occurs, the converter will automatically disconnect itself from the grid and continue to operate in "house-load" mode. This is possible because the converter transformer is equipped with a special auxiliary

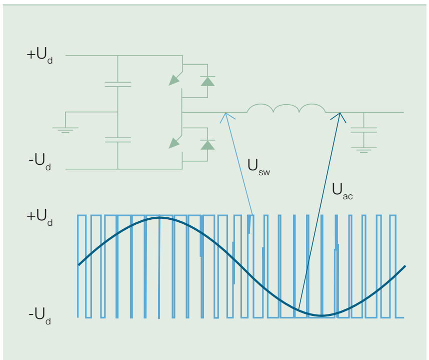
4 An HVDC converter station



5 HVDC Light principles



6 Pulse width modulation (PWM)



power winding that supplies the converter station. If needed, the converter can also be started manually in black-start mode[2].

Meeting strict grid codes

As the global share of installed wind power increases, the grid code requirements[3] are becoming stricter. Most current grid codes set requirements on so-called "fault ride through" or "low-voltage ride through," meaning that a wind turbine or park must be able to survive sudden voltage dips down to 15 percent (and in some cases down to zero) of the nominal grid voltage for up to 150 ms. It is anticipated that frequency response requirements (ie, the wind farm power output should be increased as the grid frequency decreases and vice versa) will also be imposed. In a wind farm connected via an HVDC Light transmission system, frequency response control can be introduced via a telecommunications link, which also transmits the instantaneous main grid frequency as well as other variables, between the onshore grid and the wind farm. Since the amplitude, frequency and phase of the voltage on the wind farm bus can be fully controlled by the VSC, the grid frequency can be "mirrored" to the wind farm grid without any significant delay.

Germany's first commercial offshore wind farm will be connected to the grid using HVDC transmission.

If a reduction in the main grid voltage occurs, power transmission capability is reduced by a similar proportion because of the current limit of the inverting VSC. In a "standard" HVDC Light transmission system connecting two utility grids, a similar scenario is solved by instantaneously reducing the input power of the rectifying VSC through closed-loop current control. However, if, in a relatively weak wind farm grid, the input power of the rectifying VSC is quickly decreased, the wind farm bus voltage may increase significantly, causing the VSC and/or the wind turbines to eventually trip. One possible solution is to signal to the WTGs, via the grid voltage in the wind farm, that their output power should be reduced as quickly as possible. However, due to the low DC capacitance value, the DC voltage may reach an unacceptably high level – such as 30 percent overvoltage at which the protection is set to trip – in just 5 to 10 ms if power transmission is interrupted. The WTGs must therefore be able to detect this condition and reduce the output power within this time frame. An alternative is to employ a DC chopper[4] to dissipate the excess energy that cannot be transmitted by the inverting VSC. There will then be no abrupt change in the output power from the wind turbines and the disturbance seen by them will be minimized.

Reducing the WTG power output is considered a relatively prompt and effective method, depending of course on the response of the WTGs to voltage variations. A DC chopper, however, offers a more robust solution in that its operation is the same regardless of WTG type. Furthermore, an HVDC Light link, combined with a chopper, decouples the wind park grid from the fault and electrical transients that occur in the main grid, thereby reducing the mechanical stresses on the equipment in the wind turbines. This innovative solution will be supplied by ABB to Germany's E.ON for what will be one of the largest offshore wind farms in the world.

NordE.ON 1: the first of its kind

Germany's first commercial offshore wind farm cluster, known as Borkum 2, will be situated approximately 130 km off its North Sea coast. This will be the first project in which offshore wind power is connected to the grid using HVDC transmission. This modern, environmentally friendly technology, with its very low electromagnetic fields, oil-free cables and compactly dimensioned converter stations, cuts transmission losses by as much as 25 percent. The link, initially rated at 400 MW, will make an important contribution to Germany's goal of increasing the share of renewable energies in power generation from its current level of 15 percent to between 25 and 30 percent by 2030. With a construction time of just 24 months, the network link is expected to be fully operational by September 2009.

The offshore platform is shown in 7. Included in the AC power area are the transformers, circuit-breakers and harmonic filters. The HVDC Light transformers require only minor design modifications compared with standard power transformers of this size because the harmonic filter almost completely removes the electrical disturbances from the converter. The converter reactors are used for filtering, and are also important in providing reactance to control the HVDC Light system. The alternating current is rectified using HVDC Light valves. For each phase, two containers are provided, which house the IGBT valves,

Footnotes

1) This means the active power leaving the DC link must be equal to the active power coming into the DC link, minus the losses in the HVDC Light system.

2) The transmission link can be started from a de-energized condition without power generation from the wind turbines on the offshore side.

3) These are the set of rules that regulate the interconnection of wind parks to the utility grid.

4) A chopper is a resistor in the DC circuit with high energy capability, which evacuates the surplus energy during network faults when power transmission is not possible.

Converters

DC capacitors and bushings. The sophisticated MACH 2™ protection, instrumentation and control system, with built-in redundancy, is located in two containers below the valves. In the DC power area, 128 km of marine cable and 74 km of land cable connect to the other HVDC Light converter station. A cooling system ensures that the HVDC Light valves operate at the correct temperature. The chopper resistor is used for fast active power reduction in the event of AC network faults.

7 An offshore platform for the "Borkum 2" wind farm cluster

a AC power area
b Converter reactors
c HVDC Light valves
d DC power area
e Cooling system

Future prospects for HVDC-connected parks

Significant improvements have been made over the years in performance of wind-conversion systems. These allow wind turbines to be connected to the transmission grid, safeguarding against surges in power generation. However, some of the standard equipment in today's wind turbines may now be redundant because HVDC Light can effectively decouple turbines from the transmission grid. By taking advantage of the controllability offered by HVDC Light and its ability to optimize the electrical system in a wind park, it may be possible to utilize simpler (and therefore cheaper) and more robust wind conversion systems in the turbines.

Because HVDC Light can decouple the wind park from the grid, several possibilities exist for the internal collection grid in a wind park. An HVDC Light converter station normally follows the AC voltage of the connected grids. The magnitude and frequency of this voltage are determined by the control systems in the generating stations. However, the offshore converter station could also be used to optimize wind power production by controlling the grid frequency and voltage to a reference value set by a wind farm control system. No extra equipment is required to ensure variable frequency operation at one end and fixed grid frequency at the other. In general, the design principles adopted for normal transmission system applications also apply for wind farm applications.

Transporting power to where it is needed demands the most up-to-date technology and innovation.

Similarly, the internal grid in a wind park could be designed for DC operation at a suitable voltage level. Doing this leads to better utilization of the cables and lower losses per MW of generated power, mainly because reactive power is absent. The only drawback is the amount of development needed as DC grids are not in use today, with the exception of some specific applications.

Paving the way for other projects

The design, construction and operation of a large scale power plant, positioned far out to sea in harsh environments, requires significant skills and experience. Transporting the power to where it is needed demands the most up-to-date technology and innovation, and a combination of these comes in the form of HVDC Light. As a unique solution, it will soon lead to several gigawatts of offshore wind generation in Europe. It is hoped the valuable lessons learned by the engineers working on this project will help to reduce the technical – and eventually the financial – risks faced by offshore wind farm developers when it comes to choosing a suitable and reliable transmission system.

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