Title:

Advanced power electronics for cable connection of offshore wind

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Abstract:

Several offshore wind farms are planned in a number of locations in Northern Europe. The introduction of offshore wind power brings the wind power into a new era, characterized by larger size of the farms, 200 – 1000 MW are planned, and increasing distances from the grid. Cable transmission is the only solution for the transmission from the farm to the shore. Often land cables are also required to reach a sufficiently strong interconnection point in the grid. Together this gives transmission distances of 50 – 100 km. The scale of these installations together with the interaction between the wind generators and the grid requires an overall understanding of the entire system. System knowledge and good models can identify the technical challenges but also find robust and economical solutions. Extruded AC or DC cables combined with power electronics such as HVDC Light and SVC Light gives the required flexibility and robustness. For short distances AC cables and FACTS devices such as SVC Light is normally found to be the best solution. For longer distances HVDC Light is increasingly attractive. This is particularly true given the increased size of the wind installations and the recent development of the HVDC Light technology. The technical benefits of the HVDC Light technology for wind power applications have been known for many years and also been demonstrated in small test installations. Examples of these benefits: Superior power quality mitigation in the AC grid, isolation of the wind generators from faults in the AC grid. The technical development has resulted in large converters offering drastically improved cost/performance including improved efficiency. The technology is also proven in a number of full-scale installations including offshore applications for gas platforms in the North Sea. All this together give a perfect fit between offshore wind farms advanced cable and power semiconductor technology.

Trend in offshore wind farms

Offshore wind farms have been in operation since the beginning of the 1990's. In the meantime the size have increased so the largest offshore wind farms have power ratings equivalent to medium sized power plants. The development is described in Figure 1

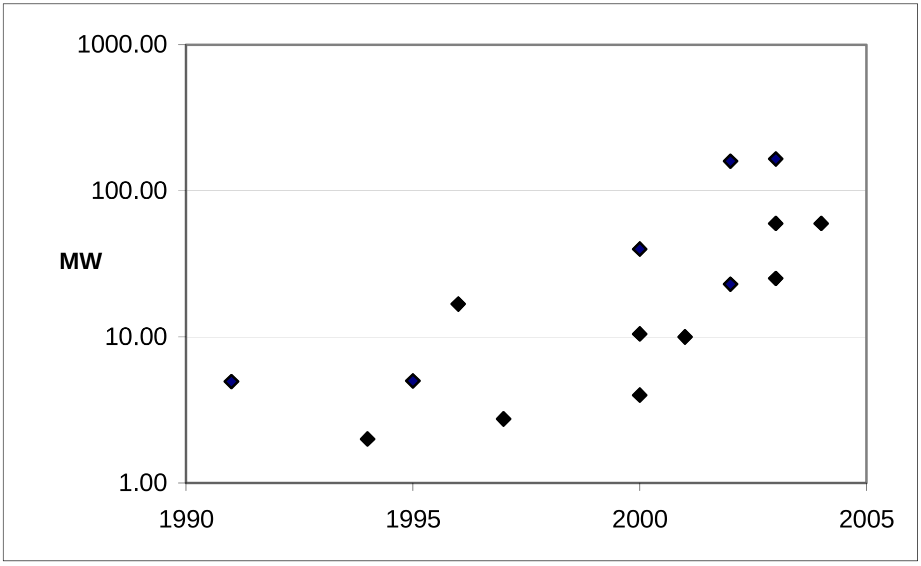

Figure 1 – Year of operation and power of established offshore wind farms

Based on the experiences and supported by the political aim for renewable energy sources, several offshore wind farms are planned in a number of locations in some countries in Northern Europe. Table 1 is a list of some of the planned offshore wind farms. The table shall not be taken as a complete list or accurate on the power ratings, just indicative for the amount and size of the planned offshore wind farms. The ratings even change in different sources because many permits allow a certain number of wind turbines and with the turbine development the size of those wind farms may increase.

Country / Wind farm	Rating [MW]	Country / Wind farm	Rating [MW]
Denmark		**Netherlands**	
Horns Rev 2	200	Egmont an zee	108
Omø Stålgrunde or Nysted 2	200	Ijmuiden	100
Germany		Mouth of Western Scheldt River	100
Borkum Riffgat	130	**Sweden**	
Borkum Riffgrund	600 - 1000	Kriegers Flak	600
Borkum 3	ca 60	Lillgrund	96 - 144
Borkum 4	400	Utgrunden 2	90
Borkum Riffgrund West	up to 1800	**United Kingdom**	
Butendiek	240	Barrow offshore wind	90
Dan-Tysk	1500	Burbo	90
Helgoland 1-3	each 800-1000	Cromer	90
Möwensteert	210	Gunfleet sands	90
Nordergründe	150 - 600	Kentish flats	90
Nordsee AWS	500 - 1000	London Array	3 x 275
Offshore Helgoland	200	Lynn and Inner Dowsing	90
Pommersche Bucht	1000	Rhyl Flats	90
Sandbank 24	400	Shell falt	270
Schleswig-Holsteinische Nordsee	500 - 1000	Solway Firth	180
Ireland		Southport	90
Arklow total project	520	Svarweather sands	90
Kish Bank	250	Tesside	90

Table 1 - Some planned offshore wind farms in Northern Europe

As the ratings of the megawatt wind turbines not have stopped to increase, it is likely that the size of the wind farms will continue to increase.

Cable transmission

With the large offshore wind farms, wind power will come into a new era. Besides the larger size of the wind farms those are also characterized by increasing distances to the shore. For the transmission to the shore cable transmission is the only solution. Furthermore there is often need for a long transmission on land to reach a sufficiently strong interconnection point in the grid. Overhead lines are the most attractive alternative from the traditional utility point of view. That is from a technically / economic point of view. However, during the latest decencies the public opinion has had an increased reluctance against new overhead lines. Under the best assumptions overhead transmission lines may be the bottleneck in the time schedule, postponing a project for several years. This leaves underground cables as the only realistic alternative for the connection to the grid, and then many projects end up in required transmission distances of 50 – 100 km.

When discussing an AC cable transmission it is a problem that the reactive consumption of the cable varies with the transferred power. But as long this can be compensated without coming to a point where the transfer capacity of the cable is fully utilized, the cable operation will be in a relatively stable point of operation. However, the low inductance between the ends of the cable will make the solution sensitive for voltage differences between the end locations. Differences of only a few percent will induce large reactive powers in the cable. The generating side (the wind farm) and the receiving end (the grid) must take care of this, to comply with grid codes. A solution can consist of different means like frequently operating on load tap changers with many steps, SVC or other facts devices, smart secondary voltage regulation in the wind turbines etc. Furthermore the contractual responsibility will be more complex by including the supplier of the grid connection as well as the turbine manufacturer. The split responsibility will be inconvenient for the owner of the wind farm and may make the grid acceptance more difficult. The complexity may increase the time schedule for the total project.

As the capacitance for a cable is much higher than for an overhead line, and the reactive power is increasing with voltage and transmission capacity, it is only possible to use AC cable transmission for short distances, and to utilize the thermal transmission capacity an AC cable must ideally be compensated with distributed compensation along the cable. A possible solution is compensation by several FACTS devises distributed along the cable, but the in practice the submarine cable for transmission to the shore can only be compensated at the platform for the wind farm and on shore, effectively limiting the possible power transfer for a given cable length. The problem is increased by the fact that the no joints have been constructed for extruded AC cables for higher voltages than 245 kV. There are many factors of importance for such a cable transmission, more generally described in other papers at this conference 1). As an example for a 70 km transmission, the power limit for a possible 3-phase cable is approx. 280 MW. Increasing voltage increase cable dimensions requiring the cable system must be laid as three single-phase cables and because the need of joints in case of cable damage, mass impregnated cables must be used, increasing the reactive power and thus requiring larger reactive compensators.

The scale of the installations together with the interaction between the wind generators and the grid requires an overall understanding of the entire system, which among all the demands require system knowledge and good models to identify the technical challenges but also to find robust and economical solutions.

Reactive compensation can be located in the turbines or be a separate compensator with continuous variation capability. The latter can generally be grouped in Synchronous condensers and FACTS devices, the latter either classic SVC solutions or Statcoms. When the turbines include the reactive compensation it must be taken into account that the compensation also should be active at no wind condition and must also compensate the collection grid. Synchronous condensers are handicapped by the maintenance need, the footprint and large weight usually ending up in less economical solutions. In some applications it will also be a disadvantage with the increased short circuit level.
Classic SVC solutions have larger footprint than the Statcom solutions and are generally less flexible. This normally requires more system analysis. This means that a Statcom is less sensitive to system changes than a classic SVC and this flexibility and robustness can be important for offshore wind farms. Furthermore the classic SVC have larger footprint, which is important offshore as well as in situations where the compensator on shore must be located in sensitive coastal areas. For offshore use it is important that the ABB Statcom, SVC Light®, is same design as HVDC Light®, and as described later, proven offshore. The combination of extruded cables and SVC Light give the required flexibility and for longer distances HVDC is increasingly attractive. For DC cables there is no influence of the reactive power and thus no critical cable length. In addition HVDC requires only two cables

compared to three cables for AC and the HVDC cables are in addition smaller in size and lighter. For offshore applications HVDC Light® is the most attractive HVDC solution. This is particularly true given the recent development of the HVDC Light® technology. This is better understood is the two HVDC technologies are compared.

Comparison HVDC technologies

There are today two established HVDC technologies, the classic technology based on Thyristors and the voltage source technology based on transistors (IGBT). The new technology is marketed by ABB under the name HVDC Light®. There are fundamental differences between the two technologies, in particular relevant for offshore wind power applications that are summarized in this table:

	HVDC Classic	**HVDC Light®**
Size range single convertor	150 – 1500 MW	50 – 550 MW
Convertor/Semiconductor technology	Line commutated/Thyristor	Self commutated/IGBT
Relative volume	4 - 6	1
Type of cable	Mass Impregnated Paper Oil/Paper	XLPE
Control of active power	Yes	Yes
Control of reactive power	No (only switched regulation)	Yes, continuous control
Voltage control	Limited	Extensive
Fault ride-through	No	Yes
Black start capability	No	Yes
Minimum short circuit capability in AC grid	>2.0 x rated power	No requirement
Power reversal with-out interruption	No	Yes
Generator needed on off-shore platform	Yes	No
Minimum DC power flow	5-10% of rated power	No minimum DC power
Typical losses per convertor	0.8%	1.6%
Operating experience	> 20 years	5 years
Operating experience off-shore	No	Yes

Table 2 Comparison of HVDC technologies

The classic HVDC technology has been developed over 50 years. It is fair to say that the classic technology reached a stage of maturity already in 1990 and the only remaining development step is to build very large systems for China (> 3000 MW) and very large distances (> 1500 km). The HVDC Light® technology was introduced commercially in 1999 and has developed substantially since the first installation.

It is a general trend that wind turbines have improved performance at grid faults to cope with ever more demanding grid codes. At the introduction of HVDC Light most wind turbines used asynchronous generators with squirrel cage rotors. Today most turbines include power electronics and better ride-through performance. Parallel with this development other solutions have improved the situation 3), but simultaneously other advantages of HVDC Light® have been more interesting followed by an interesting economic development.

HVDC Light® technology and development

The new voltage source technology, by ABB named HVDC Light®, has a short history but also a still a significant development potential. The technology was for the first time introduced in a project in a small test installation in 1997 and the first commercial installation was completed in 1999 with the 50 MW project in Gotland. This project is a 70 km long underground cable connecting a wind farm with remote load centers. Although the project is small in size by today's standards it is very important in demonstrating the technological features of the technology e.g.

- Stabilization of voltages and reactive power. This reduces the stresses on both wind turbines and the connected grid.
- Mitigation of flicker problems.
- Power flow control to optimize the overall performance and losses in the adjacent AC grid.

Since 1999 a total of 8 HVDC Light® projects have been completed and another 2 projects are under construction. It is interesting to study the development of not only of rating in kV and MW but to study the development of two other key numbers, complexity in terms of number of components needed for a given rating and losses.

Here the development has been quite dramatic. Both the number of components and the losses has been reduced with more than 60% since the development of the first plant in 1999. This has been accomplished without changing the voltage of the components but mainly by refining the switching schemes and configuration of the convertors. The latest development step includes an intelligent switching scheme that adopts the switching to the need rather than a fixed switching frequency. This has given another reduction of the number of components with 33 %.

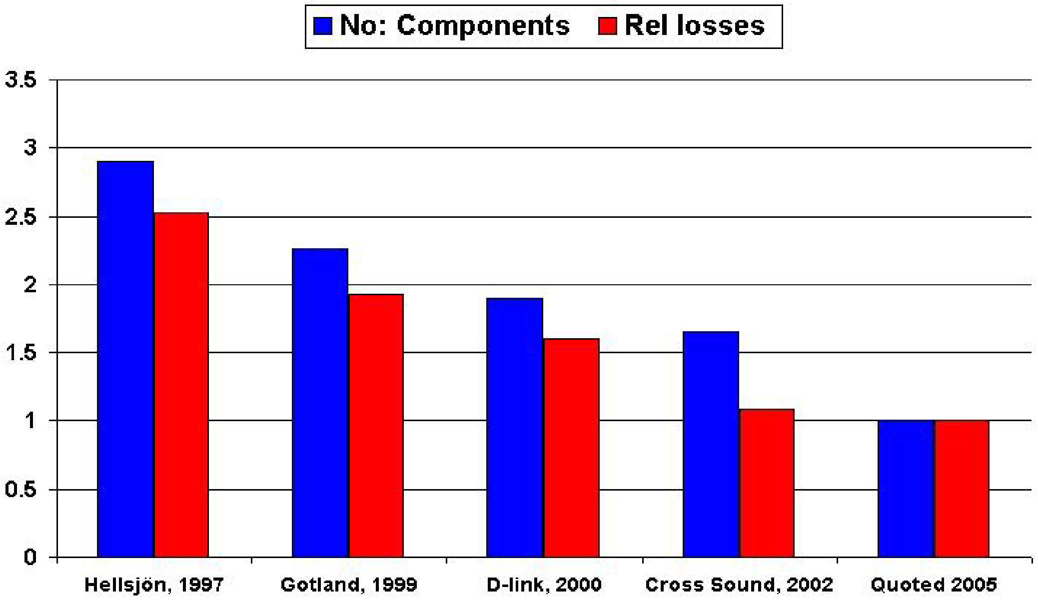

Figure 2: Development of HVDC Light® ratings and losses

The new convertor design gives the following benefits:

- Well-proven semiconductor technology with large number of components in service with identical voltage.
- Simple and robust convertor design.
- Good dynamic properties.
- Low losses
- Reduced costs

Economics

So when is HVDC Light® an attractive solution for offshore wind power? The first conclusion is that when HVDC is considered for off shore wind power, the most attractive technology is the voltage source technology in ABB version named HVDC Light®. The evidence is in the table describing the differences between the technologies. A recent study performed by Econnect 2) regarding the technological options related to the UK offshore projects also use voltage source convertors as the HVDC alternative. This study concludes that for the UK projects in a number of projects HVDC would be feasible particularly if "joint connection" is applied. "joint connection" is to combine the transmission for a number of wind parks. The total interconnection cost for the studied projects are in the range of 250 kEuro/MW to 370 kEuro/MW with an average cost of 270 kEuro/MW. The joint connection alternative shoved an average of 240 kEuro/MW. The studied range in power and transmission distance is 64 to 1000 MW and 30 – 100 km. The study suggests that HVDC (Voltage source convertors) should be considered particularly in the joint connection alternatives that also gives the lowest overall costs. This study does not cover potential transmission reinforcement costs or the cost for power flow equipment.

It is clear that the competitiveness of the HVDC alternative increases with the size of the projects but also with the transmission distance. We would suggest the following screening questions as in table 4:

Need for power transmission 200 - 1000 MW
Need for accurate and fast control
Distance more than 50 km
Difficult to obtain permits for OH-lines
Difficult to find/reach interconnection point in the grid
Difficult to build a substation near the coastline (for reactive power compensation)
Weak AC network
Risk for dynamic instability
Power quality issues
Need for grid black start capability
Need for high availability although occurrence of thunderstorms, windstorms/hurricanes or heavily icing conditions may apply
Need for compact offshore module
Risk of low harmonic resonances
Need for fast voltage and reactive power control to enhance network security

Table 3 Screening questions. When is HVDC transmission an interesting alternative.

A typical case for HVDC Light® in an offshore application could be:

350 MW transmission with 70 km sub sea cable and 30 km land cable

Assume this case fulfils at least five of the criteria above such as:

- Need for 50 – 1000 MW
- Transmission distance > 50 km
- Difficult to find/reach interconnection point in the grid
- Risk for dynamic instability
- Need for fast voltage and reactive power control to enhance network security

The direct investment cost for HVDC Light® option including converters, cables and installation of cable and converters will be in the range of 110 – 140 MEuro. The range is primarily given be differences in installation costs and local market conditions. For the AC cable option there is similarly a range in cost 110 – 140 MEuro. This corresponds in both cases to 310 – 400 kEuro/MW and gives similar results as in the previously quoted study.

The two alternatives are thus similar in cost and a detailed study for the individual case will determine the best solution.

But other factors should also be considered such that may show beneficial for the HVDC option:

- Grid reinforcement costs may be significant in the AC case but are very unlikely for a HVDC voltage source solution
- Cost for power flow equipment in the AC case
- Possibilities to go much further on land with underground cable at very moderate cost in the HVDC case.
- Increased transmission capacity in existing AC grid (HVDC case)

When these factors are included in the evaluation the overall competitiveness for the HVDC alternative will increase. Assume for example these realistic additional factors for the overhead option:
This case also illustrates that for larger power levels and/or longer distances the HVDC option is ea serious alternative.

Conclusions

The report illustrates that HVDC in the form of voltage source convertors and extruded cables is already today a viable option to feed power from offshore wind parks. This technology is today already established as the best solution to feed power to remote off shore platforms and we are convinced that it will also be proven to be the best solution to feed power from large offshore wind parks or groups of wind parks. Beyond the direct cost advantage there is a significant potential in using the freedom to choose interconnection point in the grid with the HVDC Light® solution. This is possible since there is no practical limitation in cable length and the requirements on the interconnected grid are minimal.

References:
1) Stefan G Johansson: AC Cable solutions for Offshore Wind Energy
2) Econnect project 1312, Jan 2005
3) Lars Gertmar, Hans Christian Christensen, Erik Koldby Nielsen, Leif-Erik Wraae:
New methods and hardware for grid-connection of wind turbines and parks.